Available online at www.sciencedirect.com
SCIENCE DIRECT®

ELSEVIER

Geomorphology 60 (2004) 73–87

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Influence of high water levels on aeolian sand transport: upper beach/dune evolution on a macrotidal coast, Wissant Bay, northern France

Marie-Hélène Ruz[a,*], Catherine Meur-Ferec[b]

[a] *Coastal Geomorphology and Shoreline Management Unit, EA 3599, Université du Littoral-Côte d'Opale, 2, chaussée des Darses, 59140 Dunkerque, France*
[b] *Institut des Mers du Nord, Université du littoral-Côte d'Opale 21, Quai de la Citadelle, 59140 Dunkerque, France*

Received 2 November 2002; received in revised form 25 May 2003; accepted 18 July 2003

Abstract

Aeolian sand transport measurements and detailed topographic surveys were carried out during 1 year along a macrotidal upper beach/dune system experiencing rapid coastal retreat. Aeolian transport measurements, coupled with wind records, showed extreme spatial and temporal variability along a spatially limited upper beach sector. Analysis of wind velocity, rainfall, and water level showed that aeolian sand transport may occur all year long on the upper beach with the most energetic conditions occurring during winter and spring. Analysis of volume change revealed that aeolian sedimentation on the upper beach occurred only during the summer period, while the rest of the year was characterised by upper beach and dune scarp erosion. This erosion, due to storm events combined with high water levels, completely eliminated summer aeolian sand accumulation. Our results show that aeolian transport and upper beach/dune evolution on this macrotidal beach is strongly controlled by the magnitude and frequency of occurrence of high water levels. This study illustrates the fact that upper beach/dune evolution cannot be completely understood and satisfactorily modelled if only potential aeolian sand transport is considered.

Keywords: Aeolian sand transport; High water levels; Storm surges; Coastal retreat; Macrotidal beaches; France

---

1. Introduction

Beaches and coastal foredunes systems in many parts of the world have experienced erosion in recent decades (Bird, 1985), and coastal dune retreat is a major concern along developed coastlines. Coastal dunes act as sand reservoirs, which may supply sediment to adjacent beaches (Psuty, 1988; Pye, 1991; Sherman and Bauer, 1993), and therefore can delay coastal retreat and protect low-lying backshore areas against marine invasion.

Along sandy shorelines, coastal dunes are often extensive when sediment supply (fine to medium sands) is large and when onshore winds predominate. Aeolian sand transport from the beach to the dune is enhanced by wide beaches of fine grain size. Macrotidal sandy beaches are thought to represent optimal

---

* Corresponding author.
E-mail address: Ruz@univ-littoral.fr (M.-H. Ruz).

0169-555X/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2003.07.011

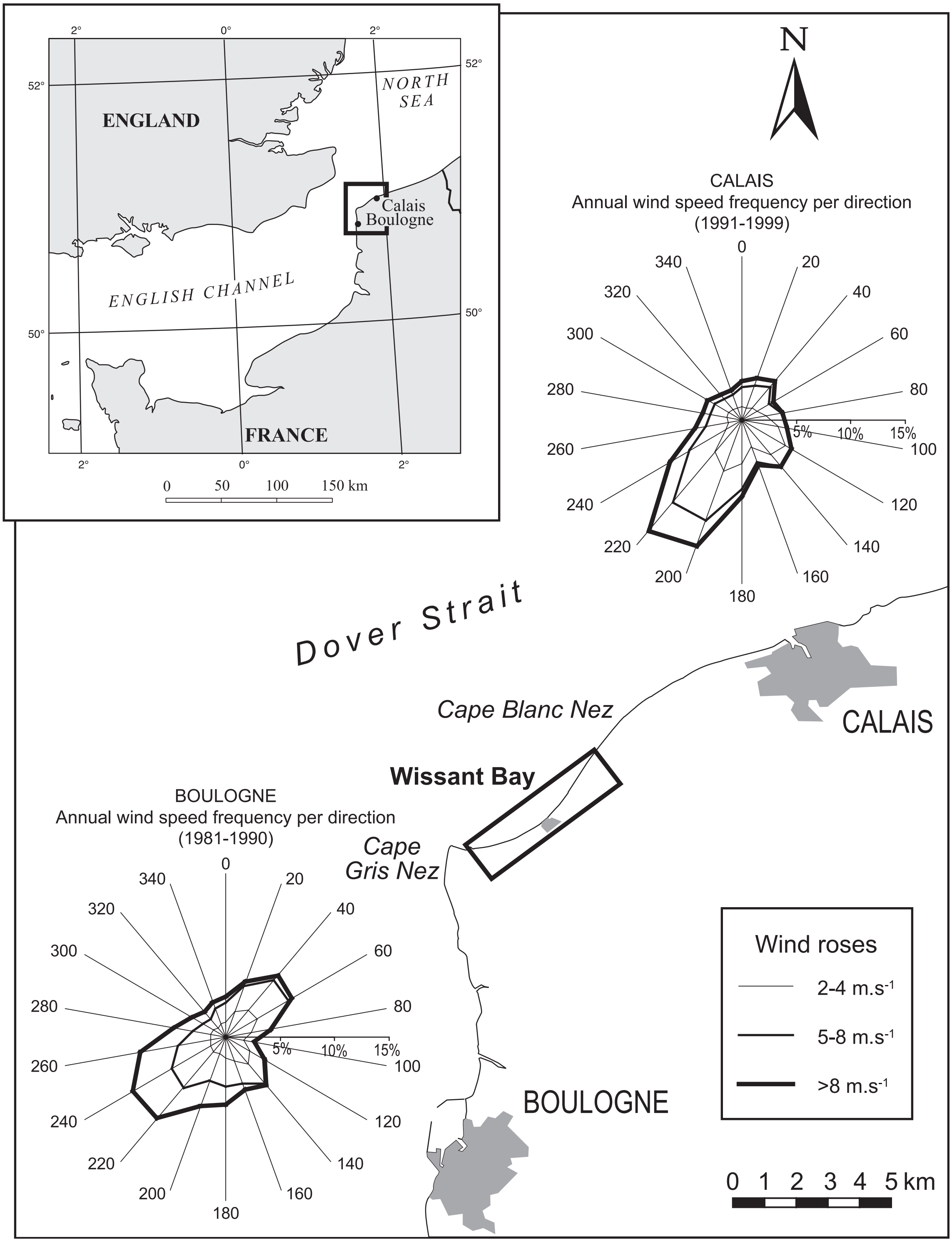

Fig. 1. Location of the study area in Wissant Bay, northern France.

conditions for coastal dune development (King, 1972; Carter, 1988). Macrotidal beaches of the northern coast of France are characterised by a wide beach/surfzone consisting of parallel bars and troughs (Sipka and Anthony, 1999; Masselink and Anthony, 2001). These ridge and runnel beaches are associated with extensive coastal dune fields (Anthony, 2000; Battiau-Queney et al., 2000). This study was carried out along Wissant, a macrotidal beach located in the Dover Strait (Fig. 1). Along this beach, optimal conditions for aeolian sand transport and foredune development are apparently found: a wide foreshore exposed at low tide, homogenous, well-sorted fine sands, a shallow beach gradient, and dominant onshore winds. However, the central part of the beach is characterised by coastal dune erosion. An aeolian sand transport study was conducted on the upper beach and near the dune foot, in order to gain insight into sediment transport rates on the eroding section. These short-term measurements were used to determine efficient wind conditions for potential aeolian sand transport on a seasonal basis.

It is well known that topographic variations, air and surface relative humidity, air and surface temperature, salt crust formation, surface roughness, beach slope, sediment characteristics and vegetation, are all environmental variables that influence aeolian sand transport on beaches (Nickling and Davidson-Arnott, 1990; Sherman and Hotta, 1990; Arens, 1996a).

Few studies, however, include an analysis of the influence of water level variations on potential aeolian sand transport and coastal dune evolution. As noted by Arens (1997), the uncertainty in effective beach width due to differences in water level should be addressed in order to improve existing deterministic models. In this study, hourly tide levels and surges were analysed and compared with detailed topographic surveys carried out over one year (May 1998–May 1999). Changes in sand volume were combined with meteorological factors, notably rainfall and storm surge, that might explain the observed morphological variations.

2. Study area

Wissant is a 5.5-km-long sandy beach located in a bay open to the northwest, and limited by Cape Gris-Nez to the southwest and by Cape Blanc-Nez to the northeast (Fig. 1). The little town of Wissant is a seaside resort located in the central part of the bay (Fig. 2). The mean tidal range at Wissant is 5.84 m, with a maximum tidal range of 8.15 m at spring tide (SHOM, 1997). At low tide, the beach is 400–500 m wide and has a very gentle gradient (0.6–1%). The upper beach, extending from the dune toe to the mean high tide level, is approximately 20 m wide. The beach consists of fine homogeneous well-sorted sands (mean grain size 0.25 mm) and is characterised by irregular ridge and runnel morphology and by strong bedform development (Sipka and Anthony, 1999; Reichmüt and Anthony, 2002). The beach is backed by coastal dunes 100–350 m wide and 6–22 m high above Hydrographic Datum (HD, the French Hydrographic Datum corresponds to the lowest astronomical tide level).

The coastal dunes have experienced both erosion and accumulation during the last 50 years (Battiau-Queney et al., 2000). In the central part of the bay (Dune d'Aval), the dune front retreated by up to 250 m between 1949 and 1997. Northeast of Wissant resort, in contrast, sand accumulation occurred during the same period of time and coastal dune development resulted in shoreline advance of up to 90 m (Marquet, 2000). In the central part of the bay, coastal retreat resulted in the complete loss of the foredunes. The inland dunes, now exposed at the shoreline, exhibit an erosional scarp 2–3 m high (Fig. 2). Back-dune vegetation (mainly *Hippophaë rhamnoïdes*, *Festuca* sp., *Ligustrum vulgare*, *Sambucus nigra*) is therefore now found in a seaward position. Due to the rapid coastal retreat, an outcrop of organic-rich freshwater peat is exposed on the upper beach 15–20 m seaward of the dune toe (Fig. 2). In order to encourage sand accumulation and prevent dune scarp erosion, sand fences are usually installed before summer (by the end of May) and retrieved at the beginning of autumn by the *Conservatoire du Littoral*, which owns 42 ha of coastal dune in Wissant Bay.

The climate in the region is typically temperate oceanic with a mean annual temperature of 10.3 °C. The mean annual precipitation is 674 mm. Rainfall is abundant from September to December. Wind velocity and directional frequency data for the two nearest weather stations run by Meteo France at Boulogne and Calais–Marck are shown in Fig. 1. The most

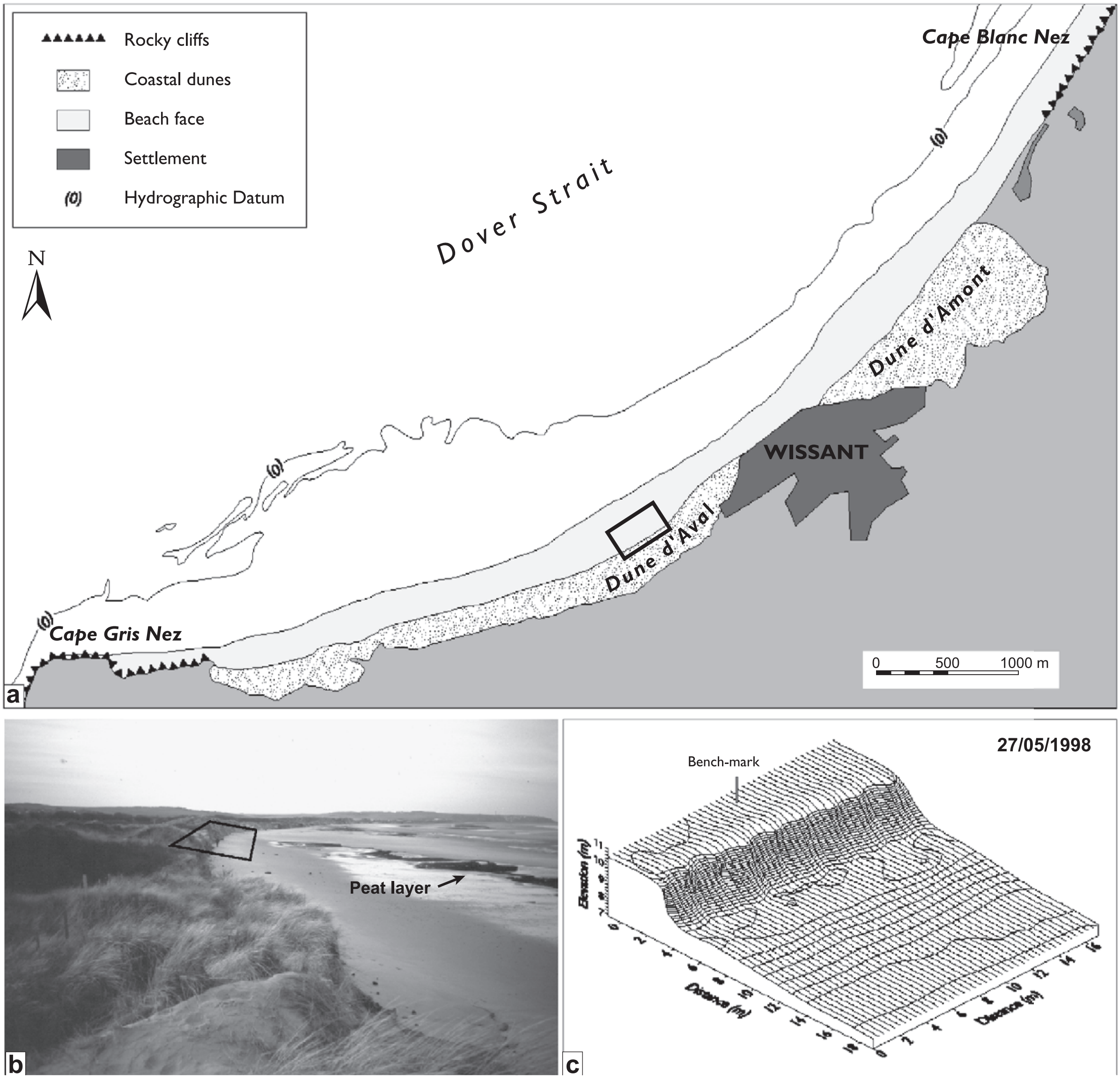

Fig. 2. Study area. (a) Geomorphology of Wissant Bay and study site location (boxed). (b) Oblique photograph of the study site; the box delimits the DTM. Aeolian sand transport measurements were mainly carried out within the DTM limits. (c) DTM showing the initial morphology of the study area (May 1998).

frequent winds are from the southwest and the west, with a moderate northeastern component at both stations. Winds with the greatest velocity are from the southwest and they occur in autumn and early winter. Dominant deep-water waves are from the southwest. Most waves have a significant height of less than 1.2 m with periods of 5–7 s. Long-period waves can reach 12 s and exceed heights of 5 m. Storm surges resulting from low atmospheric pressure and strong onshore winds can induce sea-level increases of up to 1.5 m. Strong tidal currents and frequent southwesterly waves induce a dominant longshore transport from the southwest to the northeast (Clique and Lepetit, 1986).

3. Methods

3.1. Aeolian sand transport measurements

Aeolian sand fluxes were estimated using modified Leatherman-type vertical sand traps (Pye and Tsoar, 1990). These traps are inexpensive and commonly used, with trapping efficiency estimated at about 70% (Marston, 1986). The traps were installed on the upper beach during four separate field experiments (August 1998, January 1999, June 1999 and November 1999). Upwind apertures of the sand traps were opened for a period of 30 min. Trapped sand was oven dried, and the resulting weight was converted to a rate of transport in units of kg m^{-1} h^{-1}. Sediment samples were collected on the beach a few metres upwind of each trap. These were washed, dried, and sieved. Inclusive graphic statistics were calculated using the Folk and Ward (1957) procedure. Additional sand samples were collected from the beach surface (depth < 5 mm) in order to determine moisture content. These samples were weighed, oven-dried, and re-weighed to determine the weight of water evaporated. Moisture content, w, was expressed as percent by weight of a sediment sample (Namikas and Sherman, 1995).

In order to collect simultaneous local wind data during aeolian sand transport measurements, a Davis Weather monitor II station was used in the field. Wind direction and wind speed were recorded at 1-min intervals. The vane and the anemometer were fixed to a mast at a height of 2 m installed close (2–5 m) to the sand traps. In this study, measured sand transport rates were used to determine efficient winds for potential aeolian sand transport along this coastal zone.

3.2. Topographic surveys

In order to assess topographic change along this retreating upper beach/dune sector, an accurate survey (± 1 cm in elevation) was carried out with an electronic theodolite along a representative sector 19 m long and 17 m wide (Fig. 2). Four digital terrain models (DTM) were constructed for: 27 May 1998, 25 August 1998, 5 January 1999 and 25 May 1999. These periods roughly correspond to summer, autumn/winter and winter/spring. During surveying, heights were recorded at 2 m intervals and at obvious changes in micro-morphology, and transformed into an equidistant grid with pixels 0.5 m × 0.5 m with each point having x, y and z coordinates. Elevations are in metres above HD. Volume changes were calculated using terrain modelling software (Golden Software's Surfer®).

Coastal dune retreat was measured from semi-permanent stakes spaced every 7 m and initially located approximately 5 m landward of the dune front along a 130-m-long representative sector (Fig. 2). Measurements from stakes to the upper limit of the dune scarp were carried out in May, July, August, November 1998, and in January and May 1999.

3.3. Meteorological data and water level analysis

Wind data were analysed for the surveyed period (27 May 1998–25 May 1999). Hourly mean wind speed and direction measured at a height of 10 m were obtained from Calais–Marck meteorological station. Wind data from Calais were assumed to be more representative of the local climate, as the coastline has the same orientation and the meteorological tower is located in a low-lying area (6 m HD) 2 km inland from the coastline. The Boulogne station is installed at an altitude of 73 m along a rocky coast oriented south–north. Wind frequencies were recorded for sectors of 10°. Wind speed and wind direction were analysed on a seasonal basis corresponding to the periods over which volumetric changes were estimated using the DTMs. Hourly mean precipitation greater than 0.2 mm recorded at the Calais–Marck meteorological station were also analysed for the surveyed period.

Predicted hourly tidal levels at Wissant were obtained from the Service Hydrographique et Océanographique de la Marine (SHOM) and analysed in order to determine the periods of time when the dune toe could be reached by high tides. As there is no tide gauge at Wissant, differences between predicted and observed water levels at Calais harbour were analysed. Positive differences usually indicate sea level setup at the coast induced by strong onshore winds. It was assumed that when storm surges were recorded at Calais, Wissant experienced similar events. Water level analyses also allowed estimation of the beach fetch for aeolian sand transport measurement. In this study, the term "fetch" relates to the stretch of beach surface over which the wind blows before reaching the point where sediment transport and wind characteristics were recorded. It corresponds to the maximum fetch as defined by Bauer and Davidson-Arnott (2002).

The most favourable conditions (“optimal” conditions) for potential aeolian sand transport were determined by combining the analysis of efficient winds, rainfall, beach morphology and water level data. These “optimal” conditions represent the maximum number of hours during which aeolian sand transport potentially can occur on the emerged upper beach. It was assumed that sand transport ceased during rainfall.

4. Results

4.1. Aeolian sand transport

4.1.1. August 1998

On August 21, four sand traps were deployed on the upper beach at mid-tide (tidal range of 6.41 m). A sand trap (T1) was located on the top of the dune scarp; another was installed at the dune toe (T2), downwind of the sand fences. The third trap (T3) was 5.5 m seaward of the dune toe and the fourth (T4) was 8 m from the dune toe (results are presented in Table 1). The wind blew from the southwest (240°) with a speed ranging from 8.9 to 11 m s^{-1} (mean wind speed was 10 m s^{-1}). For such alongshore wind conditions, the fetch was in excess of 2 km. Although mean grain sizes of beach surface sediments were very similar for each sand trap (Table 1), variations in measured transport rate were very different. At the end of the experiment, the sand trap T1 was empty, indicating that no transport occurred from the upper beach to the upper edge of the 2-m-high dune scarp. Transport was limited at the base of the dune scarp (T2) due to the influence of sand fences upwind. Maximum transport rate was measured on the dry upper beach (T3), not submerged during the previous high tide. The moisture content of the samples collected on the upper beach surface increased from the dune toe to the foreshore (Table 1), ranging from 0.25% to 5% and even reaching 18.7% 11 m seaward of the dune toe. The presence of the partially buried peat layer at this level of the beach contributed to maintaining a large water content in the overlying sediments as groundwater seeped from the seaward edge of the peat outcrop.

4.1.2. January 1999

Sand traps were deployed on the upper beach on January 6 at low tide (tidal range of 6.57 m). Wind was blowing obliquely offshore from the south–

Table 1
Data summary for the aeolian sand transport measurements

Date and time	Sand trap	Trap location	Wind direction (deg)	Mean wind speed (m s^{-1})	Beach fetch (m)	Mz (mm)	Moisture (%)	Trapping rate (kg m^{-1} h^{-1})
8/21/98, 16:10	T1	Top of the dune scarp	240	10	>2000	0.252		0
	T2	Dune toe	240	10	>2000	0.248	0.2	3.7
	T3	5.5 m seaward dune toe	240	10	>2000	0.245	2.3	40.7
	T4	8 m seaward dune toe	240	10	>2000	0.235	5.0	11.4
1/6/99, 11:18	T5	3 m seaward dune toe	220	4.7	3	0.248	4.4	0
	T6	4.5 m seaward dune toe	220	4.7	4.5	0.248	4.4	0
1/6/99, 11:48	T7	100 m seaward dune toe	180	8.2	< 100	0.263	4.5	0.1
6/8/99, 15:10	T8	Dune toe	240–250	8.8	>1000	0.246	–	2.3
	T9	5 m seaward	240–250	8.8	>1000	0.240	–	7.7
	T10	10 m seaward	240–250	8.8	>1000	0.236	–	15.8
6/8/99, 16:00	T11	30.7 m seaward dune toe	260	8.6	>500	0.260	–	20.7
	T12	36 m seaward dune toe	260	8.6	>500	0.266	–	28.7
	T13	40 m seaward dune toe	260	8.6	>500	0.266	–	29
11/18/99, 15:00	T14	5 m to the dune toe	360	8.7	< 400	0.250	0.5	6.5
	T15	5 m to the dune toe	360	8.7	< 400	0.250	0.3	15.6
	T16	8 m to the dune toe	360	8.7	< 400	0.240	7	9.7
	T17	9 m to the dune toe	360	8.7	< 400	0.248	6.2	9

southwest (200–220°). Two sand traps (T5 and T6, Table 1) were deployed on the upper beach, 3 and 4.5 m seaward of the base of the dune scarp. During the experiment, the mean wind speed was 4.7 m s^{-1}, and the wind direction was constant. Moisture content between the two sand traps was 4.4%. No sand was captured in the two traps. The small wind speed as well as the moisture content may explain this absence of aeolian transport during this measurement.

A sand trap (T7) and the anemometer were reinstalled on the lower beach, 100 m from the dune toe. Wind speed was greater on this portion of the beach, with a mean speed of 8.2 m s^{-1} and wind direction was from the south (180°). The sand was slightly coarser than on the upper beach (mean grain size of 0.26 mm) and moisture content was 4.5%. After a 30-min exposure, a very small amount of sand was captured in the trap (Table 1). This small transport rate could be related to the relatively large water content and the limited fetch (less than 100 m).

4.1.3. June 1999

Two experiments were conducted in June 1999. One experiment was carried out on the upper beach and the other on upper foreshore, 35 m seaward of the dune toe. Measurements were carried out at low tide (tidal range of 4.57 m) in both cases. During the first experiment, one sand trap was deployed at the base of the dune scarp (T8), another was located 5 m seaward (T9) and the third was 10 m seaward (T10). Mean wind speed during the 30-min experiment was 8.8 m s^{-1}. Wind direction was from the southwest sector (240–250°). Near the dune toe (T8) and 5 m seaward (T9), little sand was collected in the traps while the amount of sand captured 10 m seaward (T10) was twice that collected in T9 (Table 1). Despite a beach fetch larger than 1 km, little sand was transported on the dry upper beach during this experiment.

Three sand traps and the weather station were then redeployed on the upper foreshore, 35 m seaward of the dune toe (T11, T12, T13). Mean wind speed was 8.6 m s^{-1}, and at this level of the beach, wind direction was from the west–southwest (260°), resulting in a beach fetch of more than 500 m. Although the conditions were similar to those of the previous experiment, transport rates were greater (Table 1). Sand transport was limited at the base of the dune scarp relative to that on the foreshore. Unfortunately, samples taken for the determination of moisture content were lost. However, measurements were carried out at low tide and on a sunny day, therefore beach surface sand was generally dry.

4.1.4. November 1999

Sand traps were deployed at low tide on the upper beach (tidal range of 3.85 m). Two sand traps, 4 m apart, were installed 5 m seaward of the dune toe (T14 and T15) and two others were located 8 m (T16) and 9 m (T17) from the base of the dune, aligned with the two previous ones. During this experiment, the wind was from the north, blowing directly onshore, with a mean wind speed of 8.7 m s^{-1}. Moisture content was small near the dune toe (0.3–0.5%) and increased seaward (Table 1). Maximum transport rate was obtained near the dune toe. A few metres seaward transport rate was smaller, probably because of greater moisture content.

Under the same wind conditions, two sand traps located only a few metres apart (T14 and T15) captured very different amounts of sand (Table 1). Despite onshore wind conditions, aeolian transport was not very large. During this experiment, the peat outcrop acted as a sand sink with accumulation against the peat and formation of adhesion ripples.

From these results, efficient wind conditions for aeolian sand transport on this upper beach appear to be onshore- to alongshore-blowing winds (240–60°) and wind speed of 5 m s^{-1}. Such a threshold limit is commonly accepted for aeolian sand transport (Carter, 1988).

4.2. Topographic changes and forcing parameters

4.2.1. Period 1 (27/05/98–25/08/98)

In May 1998, the upper beach had a slope gradient of 5.35% and the dune front was cut into a 2-m-high dune scarp. The dune toe was at 8.4 m above HD and the seaward limit of the upper beach was at 7.6 m HD. Along the 200-m-long area affected by erosion, sand fences perpendicular to the beach were erected by the end of May in order to favour aeolian sand accumulation. Sand fences were 3–4 m long and were spaced approximately every 5 m. Between late May and August 1998, net sand accumulation (up to 0.35 m) occurred around sand fences, mainly close to the dune toe (Fig. 3a), which reached an elevation of 8.6 m

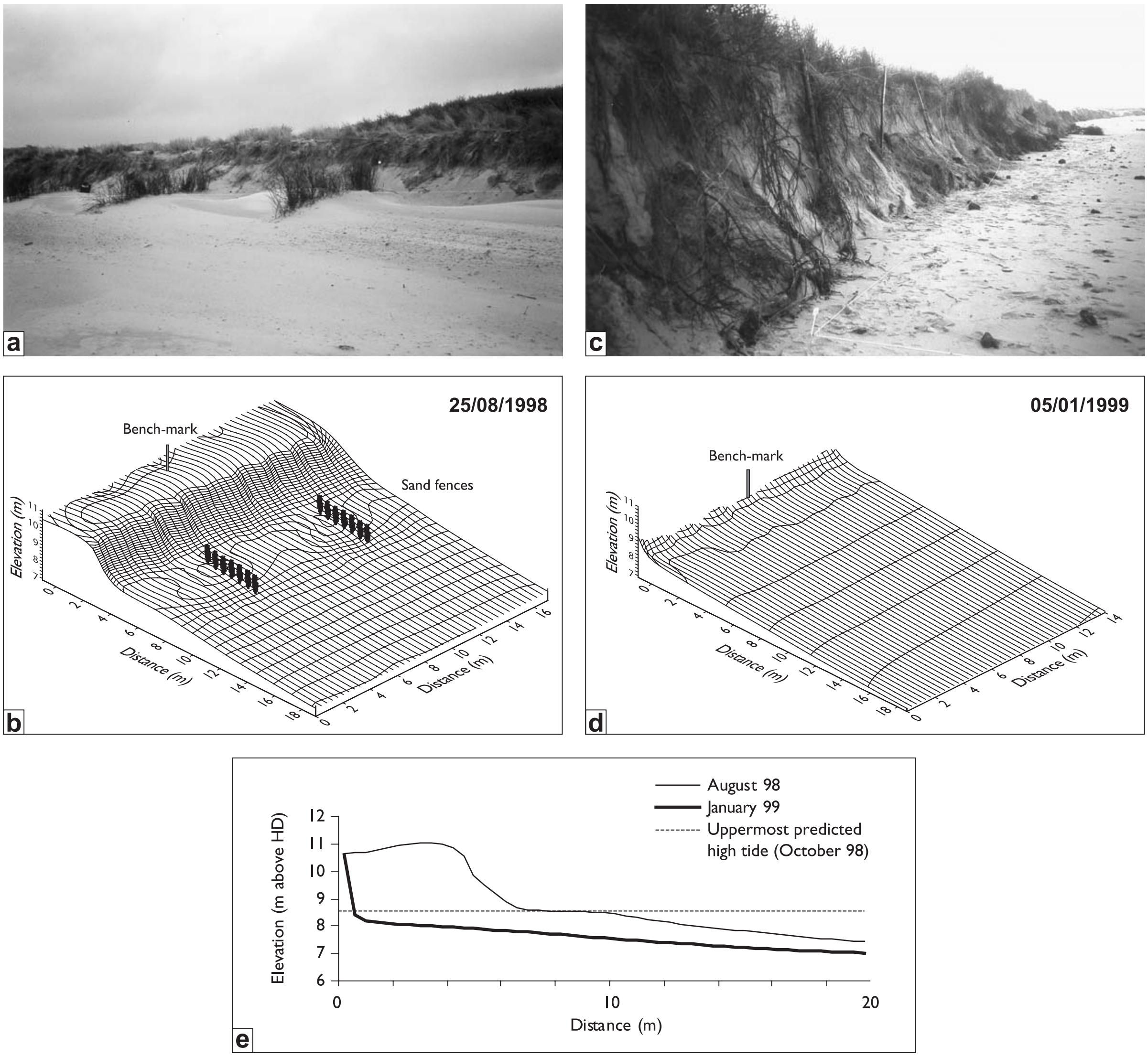

Fig. 3. Upper-beach/dune evolution between late August 1998 and January 1999. (a) Sand accumulation around sand fences in late August 1998. (b) DTM showing the upper beach morphology in late August 1998 (25/08/98). (c) Erosional scarp after storm events combined with high water levels (January 1999). (d) DTM showing the eroded upper beach in early January 1999 (05/01/99). (e) Upper beach profile variations between August 1998 and January 1999.

above HD. DTM comparison revealed an accumulation of more than 20 m^3 in the surveyed area, which represents a mean accumulation of about 1 m^3/m of beach width.

Measurements from benchmarks to the top of the dune scarp revealed an erosion of 0.35 m between the end of May and the end of August. Between May and July the mean retreat was 0.13 m, while between July and August the mean retreat was 0.22 m. This erosion is thought to be mainly due to sand slumping on the dune scarp. It is commonly observed that the material eroded at the top of a dune scarp slides down and masks the lower slope and the upper beach (Carter et al., 1990). During the summer period, anthropogenic erosion (people climbing the 2-m-high dune slope) was probably responsible for this evolution. It is possible that sand from the dune slope contributed to the accumulation recorded at the dune toe and on the upper beach.

During this monitoring period, fair weather conditions were prevalent. Mean wind speed was 5.35 m s^{-1} and dominant winds originated from the south–southwest with a frequency of 53%. Calm conditions (0–1 m s^{-1}) occurred 7.7% of the time. The strongest winds (>12 m s^{-1}) occurred only during 25 h (1.14% of the time) and these originated from the south–southwest. No major storms occurred, the maximum-recorded hourly wind speed being 14 m s^{-1}. Onshore winds prevailed 29% of the time. Efficient onshore winds, strong enough to induce sand transport (>5 m s^{-1}), blew 15% of the time with a mean speed of 6.6 m s^{-1} (Table 2). They originated mainly from the southwest, blowing parallel to the beach. Direct onshore winds, which can potentially initiate sand transport from the foreshore to the upper beach, blew only 2.5% of the time. During this summer season, the amount of rainfall was small (96 mm). Under efficient wind conditions, rainfall, which may inhibit or limit aeolian sand transport, occurred during 15 h.

The highest predicted high tide reached an elevation of 8.22 m above HD (tidal range of 7.5 m). A maximum surge of 0.40 m was recorded at Calais. This surge was related to moderate (10 m s^{-1}) southwesterly winds. During this event (21 August 1998), the predicted high tide at Wissant was at 7.65 m above HD and therefore, even with the surge component, the high tide would not have reached the dune toe. Under efficient winds conditions, the upper beach (DTM limits) was partially submerged by high water over a combined duration of 20 h, representing 17 high tides. Despite surges up to 0.40 m, the absence of very high tides reaching the dune toe, as well as moderate wind conditions, prevented wave erosion along the upper beach and allowed aeolian sand accumulation upwind of the sand fences. During this first period, "optimal" conditions for potential aeolian sand transport occurred 14% of time.

4.2.2. Period 2 (26/08/98–06/01/99)

From August 1998 to January 1999 dramatic changes occurred along this coastal sector. Along the 130-m-long surveyed coastline, retreat of up to 6 m was observed, with the dune scarp cut into a vertical bluff (Fig. 3c). The base of the dune scarp,

Table 2
Seasonal analysis of "optimal" conditions for potential aeolian sand transport, and volume changes recorded in the DTM

Period	Number of data (h)	Efficient winds (Effw)	Efficient winds without rain	Dune toe elevation (m)	High water levels reaching the dune toe	Upper beach elevation (m)	High water levels reaching the upper beach	"Optimal" conditions	Mean wind speed (m s^{-1})	DTM volumetric variations
27 May 1998–25 August 1998	2184	343 h (15.7%)	328 h (15%)	8.40–8.60	0 h	7.59–7.45	129 h (5.9%) (20 h during Effw)	308 h (14.1%)	6.6	+20 m^3
26 August 1998–06 January 1999	3205	955 h (29.8%)	830 h (25.9%)	8.60–8.20	19 h (10 h during Effw)	7.45–7.06	329 h (10.2%) (90 h during Effw)	730 h (22.7%)	8.10	Loss of 392 m^3
07 January 1999–25 May 1999	3329	1295 h (38.9%)	1152 h (34.6%)	8.20–7.90	38 h (18 h during Effw)	7.06–6.7	468 h (14%) (176 h during Effw)	958 h (28.7%)	8.10	Loss of 116 m^3
May 1998–May 1999	8718	2593 h (29.7%)	2310 h (26.5%)	8.40–7.90	57 h (28 h during Effw)	7.45–6.7	926 h (10.6%) (286 h during Effw)	996 h (22.9%)	7.6	Loss of 488 m^3

Efficient winds correspond to alongshore to onshore winds with a mean wind speed higher than 5 m s^{-1}. "Optimal" conditions for potential aeolian sand transport were calculated combining the analysis of efficient wind, rainfall, and water level hourly data for the survey period. These conditions correspond to efficient winds, without rainfall, blowing on a totally emerged upper beach. Elevations are in metres above Hydrographic Datum.

lying at 8.60 m above HD in late August, was at 8.20 m HD by January. The upper beach was flattened and its level was lowered by about 0.75 m (Fig. 3e). The sand fences disappeared, probably washed out by storm waves (Fig. 4). DTM comparison showed net erosion with a deficit of 392 m^3 within the survey area. This represents an erosion of nearly 20 m^3/m of beach width. Benchmark measurements revealed mean scarp retreat of 4 m, with a maximum retreat of 6.10 m, 100 m west of the DTM. Within the DTM limits, dune scarp retreat was 3.9 m. Between the end of August and the beginning of November, the dune scarp retreated 1.8 m. Maximum retreat occurred between November 1998 and January 1999, with a mean retreat of 2.17 m.

Mean wind speed was 5.9 m s^{-1} during this period. Dominant winds blew from the south–southwest (22% of the time) and southwest (14.5% of the time). Efficient winds for potential aeolian transport blew almost 30% of the time, with a mean wind speed of 8.1 m s^{-1} (Table 2). Total precipitation during this period was 390 mm and efficient winds without rain occurred during 830 h (26% of the time). Strong winds (>12 m s^{-1}) blew 4.62% (147 h) of the time,

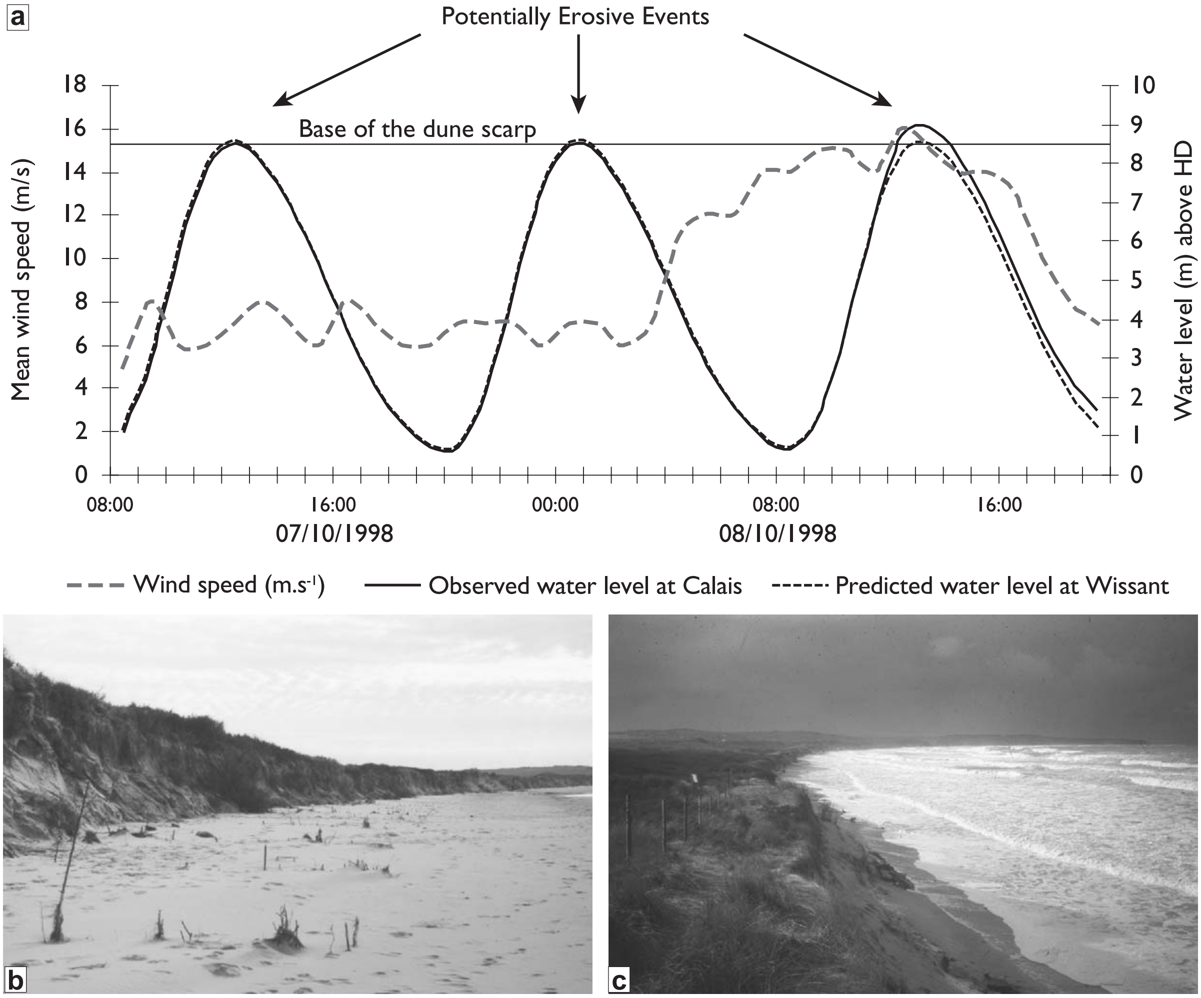

Fig. 4. Example of a storm event and resulting upper beach morphology. (a) Storm event combined with a surge, 8 October 1998. (b) Upper beach morphology after this storm event (15 October 1998). (c) Inundation of the upper beach during a high water level (3 November 1998, predicted high tide at Wissant: 8.18 m HD, surge of 0.22 m recorded at Calais harbour).

mainly onshore (90 h) with a west to northwesterly direction.

This period was characterised by very high spring tides. The highest predicted high tide at Wissant reached an elevation of 8.56 m above HD (tidal range of 7.89 m, 7 October 1998). In addition, strong onshore winds induced storm surges up to 0.45 m high at Calais. The upper beach was partially flooded 10% of the time, and high water levels reached the dune toe during 19 h (Table 2). Four major storms with winds >14 m s^{-1} occurred during this period, with the maximum recorded hourly mean wind speed being 18 m s^{-1} (November 1998). The first storm occurred at the beginning of September and the most significant storm event occurred on October 8 (Fig. 4a). During this event, direct onshore winds (350°) with a mean wind speed of 14 m s^{-1} blew for 8 h and induced a water level setup of 0.45 m at Calais harbour. At Wissant, this surge, combined with the high tide (predicted water level of 8.5 m above HD at Wissant), resulted in the submergence of the base of the dune toe (Fig. 4a). Furthermore, it is highly probable that strong onshore winds generated storm waves responsible for dune front erosion. This event likely initiated the erosion of the sand that accumulated during the summer and induced the lowering of the upper beach and erosion of the dune scarp (Fig. 4b). Subsequent high water levels could therefore easily reach the dune front (Fig. 4c), inhibiting aeolian sand transport and resulting in sediment deficit evidenced by beach lowering and dune scarp retreat.

4.2.3. Period 3 (07/01/99–25/05/99)

Between January and May 1999, erosion was still taking place within the DTM limit. The dune front retreated by 0.9 m and remained cut into a steep scarp. In May 1999, the base of the scarp was less than 8 m above HD (7.9 m) and the seaward limit of the upper beach was 6.7 m above HD. Due to erosion, the dune scarp, originally located within the DTM limits, retreated beyond the landward limits of the DTM in May 1999. The DTM comparison shows a deficit of 116 m^3, this volume corresponding to a mean erosion of 6 m^3/m of beach width along the upper beach. This volume calculation underestimates the actual loss of sand because it does not include the volumes eroded by dune scarp retreat landward of the DTM limits. West of the DTM, erosion was less pronounced with a mean retreat of 0.31 m. Stability prevailed in the central part of the surveyed sector. On the upper

Fig. 5. The study site in June 1999. Note that without sand fences, accumulation on the upper beach is very limited; compare with the upper beach morphology during summer 1998 (Fig. 3a).

beach, sand fences had not been reinstalled for the summer period and accumulation was very limited (Fig. 5).

The winter/spring period was characterised by dominant southwesterly winds and the mean wind speed was 5.48 m s^{-1}. Efficient winds for potential aeolian sand transport occurred 38.9% of the time (Table 2), and the mean speed was 8.25 m s^{-1}. Winds blowing parallel to the beach (240–250°) represented 20% of the observations. Direct onshore winds (320–340°) >5 m s^{-1} blew only during 51 h (1.6% of the time). Strong winds >12 m s^{-1} blew during 168 h and 100% of them were directed onshore, mainly originating from the southwest (93% of the time). Two major storms occurred during this period, one on 22 February 1999 and the other on 1 March 1999. The highest predicted water level was at 8.41 m above HD (tidal range of 7.72 m). As the upper beach was very low during this time (< 7 m above HD), numerous high water levels reached the dune toe (Table 2) and the upper beach was at least partially submerged for 468 h (14% of the time). Consequently, aeolian sand transport during efficient wind conditions was completely or partially restricted as the width of the upper beach was considerably reduced. The high frequency of tidal inundation would therefore limit aeolian sediment transport, even if efficient wind conditions prevailed.

5. Discussion

Field measurements reveal great spatial and temporal variability in aeolian sand transport on the study site (Table 1). Such variability has been observed in many studies (Bauer et al., 1996; Gares et al., 1996; Jackson and Nordstrom, 1997; Meur-Férec and Ruz, 2002). In addition to variations in wind direction and wind speed, which are factors controlling aeolian sand transport (Davidson-Arnott and Law, 1990; Nickling and Davidson-Arnott, 1990; Nordstrom and Jackson, 1993; Bauer and Davidson-Arnott, 2002), several other environmental variables may describe the observed variability in aeolian sand fluxes (for an overview, see Nickling and Davidson-Arnott, 1990; Sherman and Hotta, 1990).

At this particular site, our results suggest that wind direction (which controls fetch distance), as well as moisture content and dune front morphology are local parameters that may explain observed transport rates. Winds blowing strictly parallel to the beach were the most efficient ones for entraining sand, the maximum sand transport rate having been observed with such alongshore winds (Table 1). As underlined by Arens (1996a), during alongshore winds, the fetch and sand source can be considered to be virtually infinite. Bauer and Davidson-Arnott (2002) also demonstrated that when the angle of wind approach is shore parallel, longer fetch distances enhance aeolian sediment transport. At Wissant, under parallel wind conditions, the fetch distance is more than 2 km and therefore parallel winds can induce high sand transport rates (Table 1). However, transport is mainly limited to the bare upper beach, and potential accumulation on the foredune is low (Table 1, T1). Along the Netherlands beaches, Arens (1996b) also noted that although very high transport rates may be reached under parallel winds, the impact on foredune development could be small.

Under direct onshore winds that are potentially the most effective ones for dune development, transport from the foreshore to the upper beach was limited, despite a beach fetch up to 400 m at low tide (Table 1). Relatively high moisture content, related to ground water seepage in the vicinity of the peat layer outcropping at the seaward limit of the upper beach, seems to have been a limiting factor for aeolian sand transport. The effects of moisture have been recognized explicitly in several studies (Hotta et al., 1984; Sarre, 1987; Bauer et al., 1990; Kroon and Hoekstra, 1990; Sherman et al., 1998). Small amounts of moisture in the sand are able to significantly increase threshold shear velocity values and consequently decrease aeolian transport (Goldsmith et al., 1990; Namikas and Sherman, 1995). In addition, on such a macrotidal beach, the surface moisture following tidal inundation may also delay initiation of transport for several hours, especially in the runnels, retarding optimum transport conditions even though wind speed and direction may be favourable for aeolian transport (Vanhee et al., 2002).

Winds blowing offshore did not induce any sediment transport on the upper beach, which, under such wind directions, was in the lee side of the dune scarp. A sheltering effect of the dunes on wind velocities has been noted in several studies (Svasek and Terwindt, 1974; Kroon and Hoekstra, 1990). It has been shown that dune scarps are zones of flow separation and eddying, often resulting in a dead zone at the front of scarped foredunes (Sherman and Nordstrom, 1985; Bauer and Sherman, 1999).

These short-term measurements allowed us to determine efficient wind conditions for potential aeolian sand transport at a longer time scale (seasonal to annual) (Table 2). During summer, efficient winds were low to moderate (mean wind speed of 6.6 m s^{-1}), and were not very frequent (15%). During autumn, winter and spring, the frequency as well as the mean speed of efficient winds increased significantly (Table 2).

The analysis of volume change revealed an inconsistency: although "optimal" conditions for potential aeolian sand transport were more prevalent during the autumn and winter/spring periods, sand accumulation was observed only during the summer period, while a net sediment deficit resulted in upper beach lowering and dune scarp retreat during the two other periods (Fig. 6). During the summer period, sand fences erected on the upper beach captured wind-blown sand. This accumulation put the dune toe as well as the upper beach out of reach of tidal inundation during the highest tides in that period. During the autumn and winter/spring periods, although aeolian sand transport was potentially greater (optimal conditions prevailing 28.7% of the time between January and May 1999), beach and dune scarp erosion was predominant.

During the survey period, the most severe erosion likely took place when high spring tides coincided with periods of strong onshore winds. During such storm events, the level of the upper beach was planed down by waves and sand was probably transferred towards the lower foreshore and nearshore zone. Following storm events, the upper beach displayed a planar, low angle form, and the foot of the dunes could be reached by waves during smaller subsequent tides, inducing further erosion. Aeolian sand transport likely occurred during these periods, but no perennial sand accumulation was possible as high water levels flooded the upper beach, inhibiting aeolian sand transport or more dramatically inducing upper beach and dune scarp erosion.

The volume change analysis suggests that this upper beach/dune system is characterized by an apparently classical seasonal cycle of summer accumulation and fall/winter erosion occurring during storm surges. Dune scarping by storm waves is a common process affecting sandy shorelines (Carter et al., 1990; Pye, 1991; Pye and Neal, 1994; Arens, 1996b). In many cases, sediment removed during scarping is usually returned to the dune as part of the beach/dune recovery cycle (Sarre, 1989; Carter et al., 1990). This is not the case at Wissant, where erosion has prevailed for at least 50 years and was still proceeding rapidly in 1998–1999 (Paxion, 2001). The accumulation observed in the summer 1998 was mainly related to

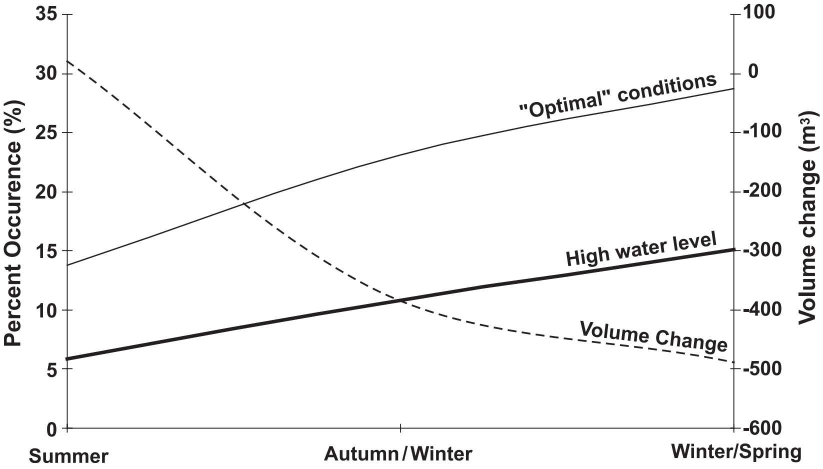

Fig. 6. Relationship between potential aeolian sand transport, water level, and resulting volume change illustrating that the upper beach/dune evolution is mainly controlled by the occurrence of high water levels although "optimal" conditions for potential aeolian sand transport occur all year long.

sand fences that captured the sand transported alongshore. Since that time, sand fences were not reinstalled due to financial restrictions, and accumulation on the upper beach is very limited during summer. This shows that alongshore-efficient winds inducing large sand transport rates do not necessarily cause large amounts of sand accumulation excepted when sand fences are erected on the upper beach.

6. Conclusions

Despite "optimal" conditions for potential aeolian sand transport prevailing, on an annual basis, almost 23% of the time, this upper beach/dune system is at present in a state of erosion. During winter and spring periods, although conditions for potential aeolian sand transport are frequent, high tidal levels associated with storm surges are major forcing parameters, dramatically altering aeolian sand transport and potential sand accumulation. During summer period, although winds are moderate and are mainly blowing offshore, sand accumulation prevails on the upper beach and at the dune toe when sand fences are erected. This study illustrates the fact that upper beach/dune evolution cannot be completely understood and satisfactorily modelled if only potential aeolian sand transport is considered.

Our results suggest that aeolian transport and upper beach/dune dynamics can be strongly controlled by the magnitude and frequency of occurrence of high water levels. In the central part of Wissant, water levels may regularly affect the upper beach and dune toe during high astronomical tides and even during moderate storm surges due to the low elevation of the upper foreshore. Aeolian sand transport may have occurred on the upper beach between inundation events, but no perennial sand accumulation could take place since high water levels resulted in upper beach and dune scarp erosion.

This study also shows that it is necessary to consider a multitude of factors, processes and responses across a range of spatio-temporal scales to fully understand upper beach/dune systems. Short-time measurements of aeolian sand transport can give some insights about local parameters that may encourage or restrict aeolian sand transport, and are useful to determine efficient winds on a longer time scale. A better understanding of the influence of aeolian sand transport on upper beach dynamics requires a combined analysis of changes in beach volume, meteorological data and water levels prevailing during the survey period.

Acknowledgements

This project received financial support through a contract from the "Observatoire de l'Environnement Littoral et Marin Manche-Mer du Nord (Espace Naturel Régional)". We are grateful to E. Anthony and A. Héquette for their helpful comments during the writing of this paper. B.O. Bauer and A. Neal provided very helpful critical reviews of an earlier version of the manuscript.

References

Anthony, E., 2000. Marine sand supply and Holocene coastal sedimentation in northern France between the Somme estuary and Belgium. In: Pye, K., Allen, J.R.L. (Eds.), Coastal and Estuarine Environments: Sedimentology, Geomorphology and Geoarcheology. Geological Society, London, Spec. Publ., vol. 175, pp. 87–97.

Arens, S.M., 1996a. Rates of aeolian transport on a beach in a temperate humid climate. Geomorphology 17, 3–18.

Arens, S.M., 1996b. Patterns of sand transport on vegetated foredunes. Geomorphology 17, 339–350.

Arens, S.M., 1997. Transport rates and volume changes in a coastal foredune on a Dutch Wadden island. J. Coast. Conserv. 3, 49–56.

Battiau-Queney, Y., Fauchois, J., Deboudt, P., Lanoy-Ratel, P., 2000. Beach–dune systems in a macrotidal environment along the northern French Coast (English Channel and Southern North Sea). J. Coast. Res. ICS, 580–592.

Bauer, B.O., Davidson-Arnott, R.G.D., 2002. A general framework for modelling sediment supply to coastal dunes including wind angle, beach geometry, and fetch effects. Geomorphology 49, 89–108.

Bauer, B.O., Sherman, D.J., 1999. Coastal dune dynamics: problems and prospects. In: Goudie, A.S., Livingstone, I., Stokes, S. (Eds.), Aeolian Environments, Sediments and Landforms. Wiley, Chichester, pp. 71–104.

Bauer, B.O., Sherman, D.J., Nordstrom, K.F., Gares, P.A., 1990. Aeolian transport measurements and direction across a beach and dune at Castroville, California. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), Coastal Dunes, Form and Process. Wiley, New York, pp. 39–55.

Bauer, B.O., Davidson-Arnott, R.G.D., Nordstrom, K.F., Ollerhead, J., Jackson, N.L., 1996. Indeterminacy in aeolian sediment transport across beaches. J. Coast. Res. 12, 641–653.

Bird, E.C.F., 1985. Coastlines Changes: A Global Review. Wiley, Chichester.

Carter, R.W.G., 1988. Coastal Environments; An Introduction to the Physical, Ecological and Cultural Systems of Coastlines. Academic Press, London. 617 pp.

Carter, R.W.G., Hesp, P.A., Nordstrom, K.F., 1990. Erosional landforms in coastal dunes. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), Coastal Dunes, Form and Process. Wiley, New York, pp. 217–250.

Clique, P.M., Lepetit, J.P., 1986. Catalogue sédimentologique des côtes françaises. Côtes de la Mer du Nord et de la Manche. De la Frontière belge à la Baie de Somme. Laboratoire National d'Hydraulique, Laboratoire Central d'Hydraulique de France. 133 pp.

Davidson-Arnott, R.G.D., Law, M.N., 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), Coastal Dunes, Form and Process. Wiley, New York, pp. 177–200.

Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. J. Sediment. Petrol. 27, 3–26.

Gares, P.A., Davidson-Arnott, R.G.D., Bauer, B.O., Sherman, D.J., Carter, R.W.G., Jackson, N.L., Nordstrom, K.F., 1996. Alongshore variations in aeolian sediment transport: Carrick Finn Strand, Ireland. J. Coast. Res. 12, 673–682.

Goldsmith, V., Rosen, P., Gertner, Y., 1990. Eolian transport measurements, winds, and comparison with theoretical transport in Israeli coastal dunes. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), Coastal Dunes, Form and Process. Wiley, New York, pp. 79–101.

Hotta, S., Kubota, S., Katori, S., Horikawa, K., 1984. Sand transport by wind on a wet sand surface. Proc. 19th Coastal Eng. Conf. ASCE, New York, pp. 1263–1281.

Jackson, N.L., Nordstrom, K.F., 1997. Effects of time-dependent moisture content of surface sediments on aeolian transport rates across a beach, Wildwood, New Jersey, U.S.A. Earth Surf. Process. Landf. 22, 611–621.

King, C.A.M., 1972. Beaches and Coast, 2nd ed. Edward Arnold, London. 570 pp.

Kroon, A., Hoekstra, P., 1990. Eolian sediment transport on a natural beach. J. Coast. Res. 6, 367–379.

Marquet, A., 2000. Etude sur la variabilité spatio-temporelle du trait de côte et sur les conditions météo-marines en baie de Wissant. Unpublished Master's thesis, Department of Geography, Université du Littoral, Dunkerque. 142 pp.

Marston, R.A., 1986. Maneuver-caused wind erosion impacts, south-central New Mexico. In: Nickling, W.G. (Ed.), Aeolian Geomorphology. Allen and Unwin, Boston, pp. 273–306.

Masselink, G., Anthony, E., 2001. Location and height of intertidal bars on macrotidal ridge and runnel beaches. Earth Surf. Process. Landf. 26, 759–774.

Meur-Férec, C., Ruz, M.H., 2002. Transports éoliens réels et théoriques en haut de plage et sommet de dune (Wissant, Pas-de-Calais, France). Géomorphologie 4, 321–334.

Namikas, S.L., Sherman, D.J., 1995. A review of the effects of surface moisture content on Aeolian sand transport. In: Tchakerian, V.P. (Ed.), Desert Aeolian Processes. Chapman & Hall, New York, pp. 269–293.

Nickling, W.G., Davidson-Arnott, R.G.D., 1990. Aeolian sediment transport on beaches and coastal sand dunes. Proc. Canadian Symp. on Coastal Sand Dunes. NRCC, Ottawa, pp. 1–36.

Nordstrom, K.F., Jackson, N.L., 1993. The role of wind direction in aeolian transport on a narrow sandy beach. Earth Surf. Process. Landf. 18, 675–685.

Paxion, K., 2001. La baie de Wissant: Cent ans d'évolution du rivage. Unpublished Master's thesis, Department of Geography, Université du Littoral, Dunkerque. 140 pp.

Psuty, N.P., 1988. Sediment budget and beach/dune interaction. J. Coast. Res. SI3, 1–4.

Pye, K., 1991. Beach deflation and backshore dune formation following erosion under storm surge conditions: an example from Northwest England. Acta Mech. 2, 171–181.

Pye, K., Neal, A., 1994. Coastal dune erosion at Formby Point, north Merseyside, England: causes and mechanisms. Mar. Geol. 119, 39–56.

Pye, K., Tsoar, H., 1990. Aeolian Sand and Sand Dunes. Unwin Hyman, London. 396 pp.

Reichmüt, B., Anthony, E., 2002. The variability of ridge and runnel beach morphology: examples from northern France. J. Coast. Res. SI32, 612–621.

Sarre, R.D., 1987. Aeolian sand transport. Prog. Phys. Geogr. 11, 157–182.

Sarre, R.D., 1989. The morphological significance of vegetation and relief on coastal foredune processes. Z. Geomorph. 73, 17–31.

Sherman, D.J., Bauer, B.O., 1993. Dynamics of beach–dune systems. Prog. Phys. Geogr. 17, 339–349.

Sherman, D.J., Hotta, S., 1990. Aeolian sediment transport: theory and measurements. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), Coastal Dunes, Form and Process. Wiley, New York, pp. 16–38.

Sherman, D.J., Nordstrom, K.F., 1985. Beach scarps. Z. Geomorph. 29, 139–152.

Sherman, D.J., Jackson, D.W.T., Namikas, S.L., Wang, J., 1998. Wind-blown sand on beaches: an evaluation of models. Geomorphology 22, 113–133.

SHOM, 1997. Annuaire des ports de France, Tome 1. Imprimerie de l'Etablissement Principal du Service Hydrographique et Océanographique de la Marine, Brest.

Sipka, V., Anthony, E., 1999. Morphology and hydrodynamics of a macrotidal ridge and runnel beach under modal low wave conditions. J. Rech. Océanogr. 24, 24–31.

Svasek, J.N., Terwindt, J.H.J., 1974. Measurements of sand transport by wind on a natural beach. Sedimentology 21, 311–322.

Vanhee, S., Anthony, E., Ruz, M.-H., 2002. Aeolian sand transport on a ridge and runnel beach: preliminary results from Leffrinckoucke Beach, northern France. J. Coast. Res. SI32, 732–740.