Aeolian Sand Transport on a Ridge and Runnel Beach: Preliminary Results from Leffrinckoucke Beach, Northern France

Authors: Vanhée, Stéphane, Anthony, Edward J., and Ruz, Marie-Hélène

Source: Journal of Coastal Research, 36(sp1) : 732-740

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.732

Journal of Coastal Research	SI 36	732-740	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Aeolian Sand Transport on a Ridge and Runnel Beach: Preliminary Results from Leffrinckoucke Beach, Northern France

Stéphane Vanhée, Edward J. Anthony and Marie-Hélène Ruz

Coastal Geomorphology and Shoreline Management Unit, JE 2208,
Université du Littoral Côte d'Opale,
2 Chaussée des Darses, 59140 Dunkerque,
France.

ABSTRACT

The aeolian transport conditions on a macro-tidal ridge and runnel beach in northern France were monitored over two 30-minute experiments, representing respectively conditions of onshore and offshore to shore-parallel wind flow. Several anemometers, a portable weather station, acoustic grain impact counters (saltiphones), temperature and ground moisture probes, and aeolian sand traps were deployed in order to determine the effects of topographic, moisture and bedform variations on aeolian sand transport. The instruments were deployed across a ridge/runnel/ridge system on the mid- to upper beach, and on the upper beach terrace linking this ridge and runnel system to the dune front. The results show that the near-ground wind velocities are slowed by the pronounced ridge and runnel topography of the upper beach. The ridge and runnel system segments the fetch, whatever the wind direction. The experiment involving an onshore wind was associated with negligible rates of sand trapping in spite of suitable wind conditions. Significant trapping occurred during the offshore to shore-parallel wind experiment, but this was limited to the upper beach terrace and upper ridge and runnel, and there was little downwind transport below this upper ridge/runnel/ridge set. These preliminary experiments and the field observations suggest that the important degree of wave-tidal bedform development over the beach surface and the high moisture levels in the runnels and sometimes on the ridges, both common characteristics of ridge and runnel beaches, tend to limit sand mobilisation. It is tentatively suggested from this data set that this ridge and runnel beach is characterised by a moderate and balanced exchange of sand with the dune front.

ADDITIONALINDEXWORDS: *onshore-offshore winds, beach topography, dunes.*

INTRODUCTION

Aeolian sediment transport on beaches depends on a large range of environmental variables that interact in complex and time-varying ways. Most studies on beach-dune sand exchanges have focused on onshore transport, which is important in the growth and maintenance of foredunes. Some workers have shown, however, that offshore winds may dominate over onshore winds in magnitude and frequency along many coasts (AUGUSTINUS *et al*., 1992; GARES *et al*., 1993; NORDSTROM *et al*., 1996), resulting sometimes in significant sand supply from foredune to beach. Notwithstanding the fact that beach-dune systems are inextricably linked, the net transport direction is very important in the long-term sediment budget of either the beach or the dune (PSUTY, 1988; NICKLING and DAVIDSON-ARNOTT, 1990; DAVIDSON-ARNOTT and LAW, 1996), especially where fresh supplies of sand from marine sources are limited.

Among the other numerous environmental variables affecting aeolian sand transport on beaches is topography, which affects air flow patterns (BAUER *et al*., 1990; NICKLING and DAVIDSON-ARNOTT, 1990). Where pronounced on the beach, topographic variations may also indirectly affect sand transport patterns via ground moisture variations, which are important in aeolian sand transport on beaches (JACKSON and NORDSTROM, 1997). Beach surface moisture conditions in aeolian sand transport across beaches has been recently investigated These may be associated either with water table outcrop or with intertidal troughs on the beach. On planar beach profiles, the water table outcrop zone is one of zero transport and is generally located on the lower beach (NORDSTROM *et al.*, 1996). As the tide falls, decoupling of the water table with the tide may lead to a permanently wet lower beach (MASSELINK and TURNER, 1999), thus inducing zero aeolian sand transport. Situations where beach intertidal bars and troughs influence aeolian transport patterns have, to our knowledge, never been investigated.

Ridge and runnel beaches are characterised, as their name implies, by intertidal ridges or bars, alternating with runnels or troughs, and are found in environments of fine sand exposed to fetch-limited waves and tidal ranges larger than about 3 m (KING, 1972). The number of ridge and runnel sets may range from two to six. The runnels are commonly humid and sometimes contain channel flow that may cut across the ridges further down the beach. The runnels and the back slopes of the ridges generally exhibit abundant wave-tidal bedforms. Ridge and runnel beaches are commonly associated with aeolian dunes, as on the northern coast of France, the Belgian coast, and parts of the coasts of Britain and Ireland (MULRENNAN, 1992; MASSELINK and ANTHONY, 2001; J.D. ORFORD, pers. comm., 2001). In this paper, the preliminary results from experiments on aeolian sand transport across a ridge and runnel beach dominated by shore-parallel to offshore winds are presented. Several experiments were carried out on this beach in 2000 and 2001. Very few were associated with sand trapping. The role of the beach morphology in influencing patterns of sand transport, especially via wind flow, ground moisture variations and surface bedform development, is discussed from the results of especially two experiments (03/05/2000 and 08/10/2001), involving respectively onshore and dominantly offshore to shore-parallel wind conditions. A tentative interpretation of the longer-term beach-dune sand exchange budget is then briefly presented.

STUDYAREA

The extreme northern coast of France (Figure 1) is bounded throughout by ridge and runnel beaches. These are associated with a coastal barrier comprising two to three generations of sub-shore-parallel dunes. This barrier stretches from Cape Blanc Nez (Figure 1) to the Netherlands. The development of these dunes has been related to massive sediment supplies from a sand-rich nearshore zone (ANTHONY, 2000), consisting of numerous tidal banks, the Flemish Banks. Observations along much of the northern French coast show that the dunes are presently in a state of meso-scale (decades) stability or even recession (VASSEUR and HÉQUETTE, 2000). Large stretches of the dunes in this North Sea sector of the French coast have been massively transformed or obliterated by urban and port development (Figure 1), but the subsisting dune barrier is still important for protection of the low-lying, densely populated back-barrier plain.

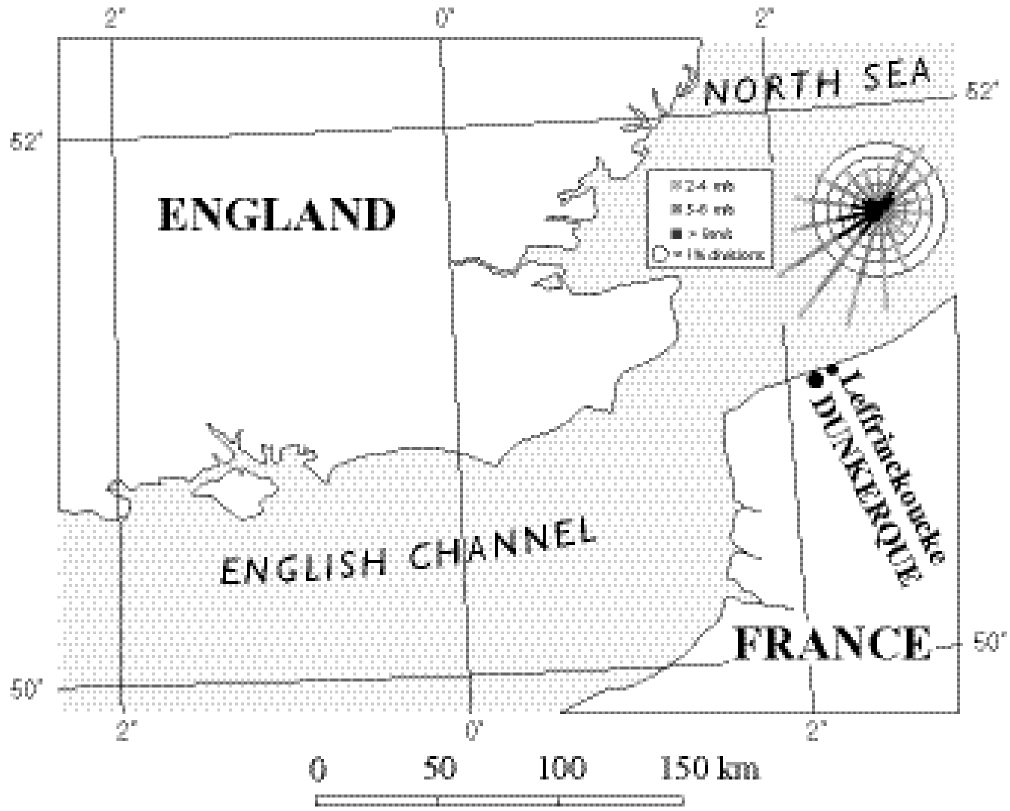

Figure 1. The experimental site of Leffrinckoucke Beach, northern France, and the regional wind field.

The experimental site is that of Leffrinckoucke beach (Figure 1), which is backed by coastal dunes that shows signs of mild erosion to stability. The beach is subject to a macro-tidal tidal range that increases from 3.5 m during mean neap conditions to 5.6 m during mean spring conditions. At exceptional low spring tides, the beach shows up to six sets of intertidal ridges and runnels. The overall gradient of this intertidal part of the beach is uniform, about 0.01, and the seaward slopes of the ridges have gradients of 0.02–0.04. A gently sloping terrace, flooded only during high spring tides and by storm setup, generally links the intertidal ridge and runnel system to a relatively steep, narrow foredune front. The beach is characterised by homogeneous fine to medium (D_{50} = 0.17–0.32 mm), well to very well sorted quartz sand. The sand tends to be slightly coarser and less well sorted on the upper beach. The ridges generally consist of coarser sediments than the runnels but the differences are small due to the homogeneity of the material. The ridges and runnels are associated with a wide variety of bedforms. These are especially well developed in the runnels where wave and current ripples are particularly abundant. The ridge crests commonly exhibit plane beds that give way further downslope to simple wave-formed ripples, and then more complex wave-current linguoid ripples as the ridge merges into the next runnel. The channels in runnels exhibit a wide variety of micro- and meso-scale bedforms ranging from complex current ripples to channel antidunes, sand waves and scour pits.

Leffrinckoucke beach is dominantly exposed to offshore to shore-parallel winds from a south to southwesterly window (180-270°N, Figure 1). These winds are related to the westerly depressions that affect the English Channel and southern North Sea in spring, summer, autumn and early winter. Northerly, onshore winds, occur in winter and are generated by frontal circulations peripheral to depressions over the British Isles and the North Sea.

METHODS

Each experiment was carried out over a 30 minute period at low tide. This duration was imposed by two constraints: the rapidity of tidal translation across the beach, and the time-consuming nature of the deployments and the wiring of equipment. Wind speed was measured using a total of 12 Gill-type 3-cup anemometers with a threshold speed of about 0.3 m/s. The anemometers were deployed on three masts aligned on a shore-normal transect between the upper beach terrace and the first ridge/runnel/ridge set. Field experience showed that beyond this set, aeolian transport was nil as a result of high ground moisture levels. The anemometers were deployed at heights of 0.25 m, 0.5 m, 0.75 m and 1 m on masts 1 and 3, and 0.25 m, 0.5 m, 0.75 m and 2 m on mast 2. Wind speeds were measured every 5 seconds and wind directions every minute by all the anemometers. An independent portable weather station recording wind speed and directions every minute was deployed on a 2 m high mast at the foot of the dune. Ground moisture was measured by a hand-held Theta-probe that functions on the basis of time domain reflectometry (see ATHERTON *et al*., 2001 for a description of this method). In order to count the impacts of sand grains mobilised by the wind, 2 saltiphones (ARENS and VAN DER LEE, 1995) were also deployed. These instruments incorporate a microphone and an electronic grain count system situated at a height of 0.11 m. They recorded grain impacts every second. Saltiphones give a precise time frame of the duration and intensity of aeolian transport bursts, and are also particularly useful in giving an idea of aeolian transport of sand over the humid runnels. The 12 anemometers and 2 saltiphones were wired to a 24-channel Delta 3000 data logger. During the 30 minute experimental runs, trapping rates of blown sand were quantified from traps designed following OWENS (1927). Trapping rates were normalised to kg/m/h. For each experiment, a profile survey of the beach along the deployment transect was carried out using a high-precision electronic total station. In the experiment carried out on 8/10/2001, a hand-held radiometer that remotely measures temperatures was used to monitor changes in the temperature of the beach surface. Sand samples of the beach surface subjected to aeolian transport were collected and analysed in the laboratory following each experiment using the sieving method, and classical grain size characterisation parameters were obtained.

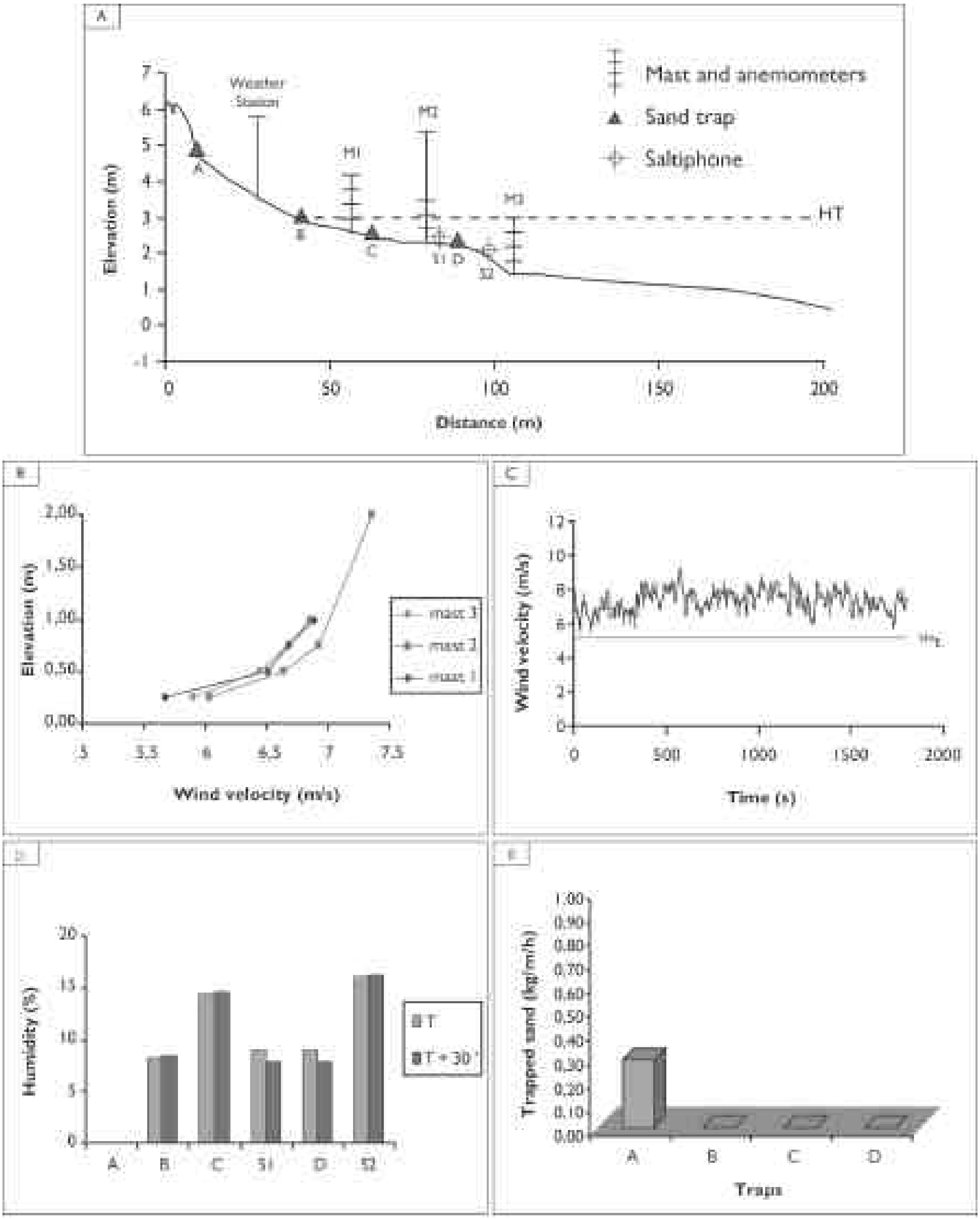

Figure 2. Data for the 03/05/2000 experiment. A. Beach profile and deployment configuration; B. Wind velocity profiles from the three masts; (C) Wind velocity record from mast 2 and threshold velocity line for sand mobilisation; (D) Humidity variations across the profile (see locations on profile) at the start (T) and end (T+30') of the experiment; (E) Trapping rates of blown sand across the profile.

RESULTS

03/05/2000 (6h – 6h30 UMT)

The upper beach during this experiment exhibited a conspicuous single ridge linked to a mildly developed runnel that merged downslope with a mid-beach zone (Figure 2A) flattened by early spring storms. The ridge was linked to a gently sloping upper beach terrace that merged landward with the steep dune front slope. Ripple marks were present on the inner, landward part of the ridge and on the upper beach terrace, and were inherited from a preceding high spring tide (tidal range: 5.16 m) associated with moderate winds. The wind velocities measured by the weather station at the foot of the dune ranged from 5.5 to 9.3 m/s, with a mean of 7.36 m/s, while the direction was onshore, from north to northeast (5-25°N). The wind velocity, ground humidity, and trapping data are shown in Figure 2B-E. The wind speed records from the anemometers on all three masts showed a near-log increase in velocity, with small velocity differences between the three masts (Figure 2B). Velocities were highest on mast 2 and nearly identical on masts 1 and 3, especially at the 0.25 m and 0.5 m heights. The lowest moisture values were obtained at the foot of the dune and the values increased regularly downslope to the bottom of the only marked ridge present on the profile that day (Figure 2D). The saltiphone impact counts were too insignificant to be depicted here. Only two minor impact pulses occurred shortly after the start of the experiment. Blown sand was only trapped, very moderately (0.3 kg/m/h), at the foot of the dune in trap A (Figure 2E). None of the other traps located downslope on the ridges trapped sand.

08/10/2001 (11h14 – 11h44 UMT)

The instrument deployment on the beach profile and the data from this experiment are shown in Figure 3. The experiment was carried out during normal tidal range conditions (tidal range: 4.53 m). The dune front was linked to the beach by a gently sloping terrace (Figure 3A). This terrace lacked bedforms and was fronted by a steeper slope down to the uppermost runnel. Further downslope, the beach exhibited a well developed 70 m-wide ridge (Figure 3A). This ridge exhibited plane beds upslope of mast 3, and, downslope, current ripples that became progressively better expressed towards the runnel. The wind direction was predominantly from southwest (obliquely offshore with a 45° angle to the beach) but there were marked fluctuations. between minutes 10 and 22. The wind first sharply veered to the northwest (onshore) and then to the southwest, and then nearly north (onshore) before stabilising again at southwest. The velocities measured by the weather station ranged from 3.6 to 8 m/s, with a mean of 5.65 m/s. Wind speeds consistently increased between the 0.25 m and the 1 m or 2 m (mast 2) levels. However, the near-ground velocity (0.25 m) diminished downwind from mast 1 to 2, before increasing on mast 3 (Figure 3B). Moisture levels were higher than those of the 03/05/2000 experiment, but the data showed a comparable regular decrease up the beach (Figure 3D). It is significant to note that even the ridge surface showed high moisture content. The beach surface temperature record, obtained near mid-day, on a sunny Autumn day, showed significant cross-shore variations during the initial phase of the experiment (Figure 3E). These fluctuations were closely hinged on the beach topography (lower temperatures in the runnel and higher temperatures on the ridges and the foredune slope), while more uniform temperature conditions were observed at the end of the experiment. Unlike the 03/05/2000 experiment, the saltiphones recorded abundant impact counts (Figure 3F). There appears to be a gross visual correlation between wind speed (mast 2, Figure 3C) and the saltiphone counts. The latter show a significant drop at about 10-12 minutes and 20-22 minutes after the start of the experiment. These phases correspond to sharp changes in wind direction (from offshore to onshore). The saltiphone data, however, show no statistical correlation with the wind velocity data for reasons that are beyond the scope of this paper. Although the wind speeds were comparable to those of the 03/05/2000 experiment, much greater trapping of blown sand occurred during this experiment, especially over the upper beach platform downslope of the foot of the dune (Figure 3G). Very little trapping occurred on the landward part of the ridge crest, while a significant amount of sand was trapped further downslope on this ridge.

DISCUSSION

Beach topographic variations are known to cause variations in wind boundary layer development that may affect wind transport of sand under conditions of cross-shore flow (SVASEK and TERWINDT, 1974; BAUER *et al*., 1990). The preliminary data from the two experiments on Leffrinckoucke beach suggest that the ridge and runnel topography affects the wind flow patterns on the upper beach, where conditions for aeolian sand mobilisation are most readily met. Another significant aspect shown by the data is the marked difference in the rate of trapping of blown sand during the two experiments, despite similar wind speed conditions.

The wind speed records from both experiments show the classical surface retarding effect on wind flow near ground level (Figures 2B, 3B). The data suggest that at a height of 0.5 m above the beach face, all the profiles were in the full flow field of the wind during both offshore and onshore wind conditions. The slight increase in velocity on profile 2 above this height during the 03/05/2000 experiment (Figure 2B) may reflect slight upward deflection of the onshore air

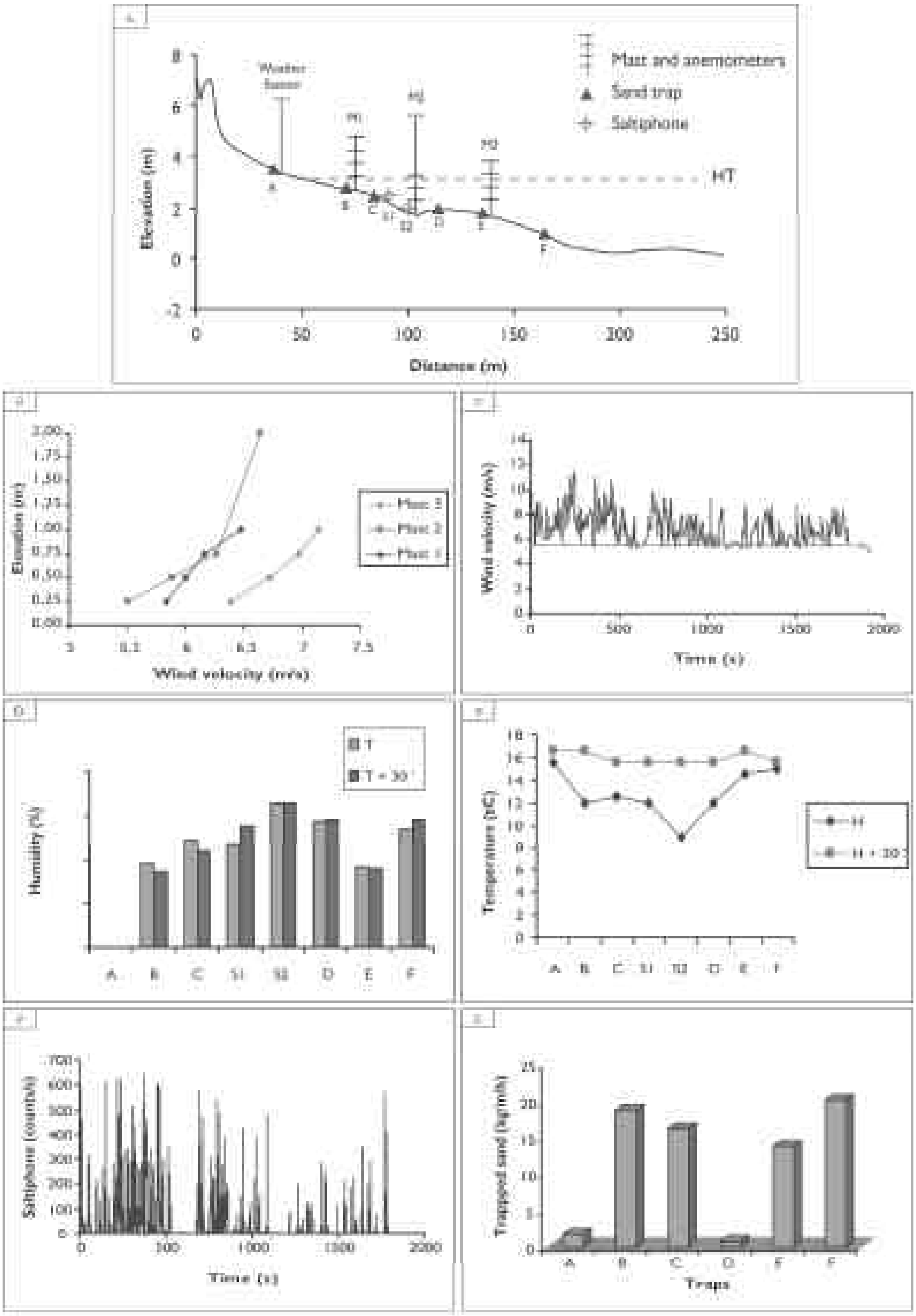

Figure 3. Data for the 08/10/2001 experiment. A. Beach profile and deployment configuration; B. Wind velocity profiles from the three masts; (C) Wind velocity record from mast 2 and threshold velocity line for sand mobilisation; (D) Humidity variations across the profile (see locations on profile) at the start (T) and end (T+30') of the experiment; (E) Beach surface temperature variations (see locations on profile) at the start (T) and end (T+30') of the experiment; (F) Impact counts from saltiphone 1; (G) Trapping rates of blown sand across the profile.

flow by the steep face of the conspicuous mid-beach ridge during the experiment. In the 08/10/2001 experiment, two aspects need to be highlighted: a deceleration in velocity downwind from profile 1, on the upper beach terrace, to profile 2 in the runnel, and a marked velocity increase from profiles 2 to 3 (Figure 3A,B). The velocity decrease in the runnel and the subsequent increase downwind reflect, respectively, the influence of the ridge and runnel topography on the air flow, and, below mast 2, the full air flow descending down the beach. A similar seaward increase in velocity during offshore wind conditions has been noted by NORDSTROM *et al*. (1996).

Theoretical transport rates using the Bagnold (BAGNOLD, 1941) equation from the wind velocity data exceed, for both experiments, the rates measured using traps, especially for the 03/05/2000 when hardly any trapping occurred. This overestimation is commonly reported in the literature (BAUER *et al*., 1990). For the 03/05/2000 experiment, the onshore wind speed conditions were theoretically suitable for transport of sand, since the threshold velocity (5.12 m/s, Figure 2C) for mobilisation of the coarsest sand (0.24 mm) on the beach that day was often exceeded. The negligible saltiphone counts clearly indicate, however, that suspension of sand, at least where these saltiphones were deployed, was much more limited than would suggest the wind velocities. This was visually confirmed in the field. The reasons for the insignificant aeolian sand transport were most likely the high upwind moisture content and roughness conditions of the beach surface, which limited the dry fetch length as the wind blew onshore from the sea. Much of the ridge surface and the runnel between masts 1 and 3 showed high moisture contents (Figure 3D) at a time when the early morning temperatures were still too low to allow evaporative processes over the beach surface. The moisture levels hardly varied during the 30 minute experiment. As a result of the spring tide conditions, flooding of the beach surface occurred up to trap B (Figure 2A) during the previous high tide at night, and favoured the formation of low-flow shallow water current ripples that increased beach surface roughness. Minimal transport occurred only over the dry sloping surface of the upper beach terrace, suggesting that the effective (dry) fetch for this particular experiment was only about 30 m. This is quite a limited fetch, given the width of the beach. NICKLING and DAVIDSON-ARNOTT (1990) and JACKSON and COOPER (1999) have suggested that under conditions of limited sediment supply, a limited fetch length may restrict the development of steady-state transport. In this experiment, the overall field conditions (beach surface moisture and roughness) did not allow for significant sand mobilisation, and transport was further restricted by the fetch conditions.

The cross-shore variations in trapping during the 08/10/2001 experiment are strongly related to beach topography, with significant rates over the seaward part of the upper ridge and the upper beach terrace, and minor rates at the foot of the dune and over the landward part of this ridge. The variations also reflect the influence of the wind field. The oblique fetch associated with the dominantly offshore to shore-parallel wind field probably entailed a very narrow no erosion ‘lee of dune’ zone, as defined by NORDSTROM *et al*. (1996), associated with low wind velocities near the foot of the dune. Low wind velocities at the foot of the steeply sloping dune front during offshore wind flow may be expected due to divergence of flow lines. Although no mast was deployed at the foot of the dune, a subsequent recent experiment showed that wind velocities in this ‘lee of dune’zone are weaker than on the open beach. Traps B and C, at the base of the terrace, were located downwind of a significant oblique fetch (100 m) over a dry (nil ground surface humidity at trap A), low-gradient and bedform-free upper beach terrace. This zone, between the foot of the dune and the base of the terrace (Figure 3A), appeared to have served as the ‘erosion zone’, in the zonation of offshore aeolian sand transport domains on beaches proposed by NORDSTROM *et al*. (1996). This erosion zone most probably sourced the accumulation of sand in traps B and C. The difference in trapping rates between traps B,C and trap D, on the crest of the ridge (Figure 3A) may suggest that the uppermost runnel acted as an efficient sink for sand blown offshore or alongshore, an aspect confirmed by the abundant impact counts recorded by the saltiphones deployed in the runnel (Figure 3F), and by the field observations. The runnel constitutes a zone of decreased air flow, of high moisture content, and of deposition. The more significant trapping over the lower ridge surface (traps E, F), compared to the ridge crest near the runnel, suggests that much of the ridge crest (zone of trap D location) acted as an efficient fetch surface (enhanced by shore-parallel wind flow during part of the experiment) for sand mobilisation and downslope deposition. The beach surface on this upper ridge crest is commonly characterised by plane beds due to intense swash washout. This surface also dries out rapidly following tidal emersion and shows higher temperatures (Figure 3E). The downslope increase in the rate of sand trapping also conformed with the increase in wind velocity downwind of mast 2. Field observations showed that the humid runnel downslope of trap F acted as an efficient sink for sand, with hardly any transport below this level.

CONCLUSIONS

In conclusion, the preliminary experiments carried out on Leffrinckoucke beach show that the cross-shore topographic, bedform and moisture content variations inherent to intertidal ridge and runnel beach morphology have a strong influence on sand transport patterns. Understanding the variability of these transport patterns therefore requires careful consideration of the particular profile of ridge and runnel beaches and of ridge and runnel profile variability.

The general overall imprint is that of offshore to shore-parallel winds, which would tend to starve the dunes of sand while feeding the beach. However, this transport system is severely limited by the relatively low frequency of strong winds on this coast and by control of the ridge and runnel beach conditions on sand transport. The ridge and runnel morphology shows a segmented fetch and transport system that tends to limit offshore sand transport from the dune to the upper beach terrace and ridge. Although wind velocities tend to increase downwind, the uppermost runnel acts as a barrier to downslope sand transport by acting as a moist trapping surface. It must be noted that the fetch distance generated by this morphology incorporates much of the upper beach terrace surface itself, rather than the steep seaward face of the dune front where wind velocities are lower. Field observations show that this terrace may become a largely no-erosion zone, or one of much more limited fetch than would suggest the 08/10/2001 experiment, when bedform development and salt crusting (sometimes observed in the field) become particularly important following high spring tide flooding. Below the uppermost beach runnel, the uppermost ridge has its own source zone and fetch, and trapping of sand blown by westerly to south-westerly winds may be particularly important on the downslope part of this ridge where higher moisture levels and wave-current ripples encourage deposition.

Onshore winds are more limited in frequency. However, data being processed from experiments from this and other beaches show that the upper runnel also acts as a barrier to sand flow from the lower downslope ridge whenever onshore transport conditions are such as to favour mobilisation of sand from this ridge surface. This requires strong wind speeds (mean wind speed >9 m/s) because of both the high ground moisture levels that restrict the dry surface area (generally limited to the crest of the ridge, i.e., a width of a few meters, especially in the face of directly onshore winds) and the abundant bedform development on the ridge surface. These conditions mean that the effective fetch for supply of blown sand to the dune front is limited to the upper beach terrace surface, which fluctuates in width from 50 to 150 m, depending on wind approach from northeast to northwest. This would be considered as a sufficiently large fetch, if steady-state transport conditions are achieved (JACKSON and COOPER, 1999). However, any significant transport of sand from this surface to the dune is conditioned by various factors: the moisture level which depends essentially on tidal modulation, and the degree of bedform development, related to wave and tidal conditions. Wind characteristics set aside, transport would therefore be expected to be variable depending on these conditions, whose cross-shore distribution is hinged on beach topography. Identifying these patterns in order to build a coherent model of beach-to-dune sand supply, and eventually work out even a gross sediment budget, would require more experiments involving various other instrument deployment configurations. Various lines of evidence, including temporal observations of dune and beach morphology over the last few years, suggest gross stability of the beach-dune system, which functions under conditions of rather limited sand supply from offshore. This is happening in spite of the abundant nearshore stocks of sand locked up in subtidal ridges and banks. Mild dune scarping in winter in this area is often followed in spring and summer by limited embryo dune formation. Understanding past massive dune formation on this coast therefore requires looking at the conditions under which sand is sequestered or released by the subtidal realm.

ACKNOWLEDGEMENTS

Funding for this research has been provided by the European Research and Development Funds and by an INTERREG II programme ‘Kent – Nord-Pas de Calais’. Stéphane Vanhée benefits from a PhD grant jointly funded by the Conseil Régional Nord-Pas de Calais and the Communauté Urbaine de Dunkerque.

LITERATURE CITED

ANTHONY, E.J., 2000. Marine sand supply and Holocene coastal sedimentation in northern France between the Seine estuary and Belgium. *In*: PYE, K. and ALLEN, J.R.L. (editors), *Coastal and Estuarine Environments - Sedimentology, Geomorphology and Geoarchaeology*. Special Publications of the Geological Society of London, 175, pp. 87-97.

ARENS, S.M. and VAN DER LEE, G.E.M., 1995. Saltation sand traps for the measurement of aeolian transport into the foredunes. *Soil Technology,* 8, 61-74.

ATHERTON, R.J., BAIRD, A.J. and WIGGS, G.F.S., 2001. Inter-tidal dynamics of surface moisture content on a meso-tidal beach. *Journal of Coastal Research*, 17, 482-489.

AUGUSTINUS, P.G.E.F., LAEVEN, M.P., RUWE, J., and DEVRIES, J.B., 1990. Dune formation and dune degradation in the Camargue, France. *Littoral 1990*, EUROCOASTAssociation, pp. 115-119.

BAGNOLD, R., 1941. *The Physics of Blown Sand and Desert Dunes*. London: Chapman and Hall, 265 pp.

BAUER, B.O., SHERMAN, D.J., NORDSTROM, K.F. and GARES, P.A., 1990. Aeolian transport measurement and prediction across a beach and dune at Castroville, California. *In*: NORDSTROM, K.F., PSUTY, N.P. and CARTER, R.W.G. (editors), *Coastal Dunes: Form and Process.* Chichester: Wiley, pp. 39-55.

DAVIDSON-ARNOTT, R.G.D. and LAW, M.N., 1996. Measurement and prediction of long-term sediment supply to coastal foredunes. *Journal of Coastal Research*, 12, 654-663.

GARES, P.A., NORDSTROM, K.F., SHERMAN, D.J., BAUER, B.O., DAVIDSON-ARNOTT, R.G.D., CARTER, R.W.G., JACKSON, D., and GOMES, N., 1993. Aeolian sediment transport under offshore wind conditions: implications for aeolian sediment budget calculations. *In*: HILDEBRAND, L.P. (editor), *Coastlines of Canada*. New York: American Society of Civil Engineers, pp. 59-72.

JACKSON, D.W.T. and COOPER, J.A.G., 1999. Beach fetch distance and aeolian sediment transport. *Sedimentology*, 46, 517-522.

JACKSON, N.L. and NORDSTROM, K.F., 1997. Effects of time-dependent moisture content of surface sediments on aeolian transport across a beach, Wildwood, New Jersey, USA. *Earth Surface Processes and Landforms*, 22, 611-621.

KING, C.A.M., 1972. *Beaches and Coasts.* 2nd Edition, London: Edward Arnold, 570 p.

MASSELINK, G. and ANTHONY, E.J., 2001. Location and height of intertidal bars on macrotidal ridge and runnel beaches. *Earth Surface Processes and Landforms*, 26, 759-774.

MASSELINK, G. and TURNER, I.L., 1999. The effect of tides on beach morphodynamics. *In*: SHORT, A.D. (editor), *Handbook of Beach and Shoreface Morphodynamics*. Chichester: Wiley, pp. 204-229.

MULRENNAN, M.E., 1992. Ridge and runnel beach morphodynamics: An example from the central east coast of Ireland. *Journal of Coastal Research*, 8, 906-918.

NICKLING, W.G. and DAVIDSON-ARNOTT, R.G.D., 1990. Aeolian sediment transport on beaches and coastal sand dunes. *Proceedings of the Canadian Symposium on Coastal Sand Dunes*, pp. 1-35.

NORDSTROM, K.F., BAUER, B.O., DAVIDSON-ARNOTT, R.G.D., GARES, P.A., CARTER, R.W.G., JACKSON, D.W.T. and SHERMAN, D.J., 1996. Offshore aeolian transport across a beach: Carrick Finn Strand, Ireland. *Journal of Coastal Research*, 12, 664-672.

OWENS, J.S., 1927. The movement of sand by wind. *Engineer*, 143, 37 pp.

PSUTY, N.P., 1988. Sediment budget and dune/beach interaction. *Journal of Coastal Research*, *Special Issue 3*, 1-4.

SVASEK, J.N. and TERWINDT, J.H.J., 1974. Measurements of sand transport by wind on a natural beach. *Sedimentology*, 21, 311-322.

VASSEUR, B. and HÉQUETTE, A., 2000. Storm surges and erosion of coastal dunes between 1957 and 1988 near Dunkerque (France), southwestern North Sea. *In*: PYE, K. and ALLEN, J.R.L. (editors), *Coastal and Estuarine Environments - Sedimentology, Geomorphology and Geoarchaeology.* Special Publications of the Geological Society of London, 175, pp. 99-107.