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Morphodynamics of beach/dune systems: examples from the coast of France

Fonctionnement morphodynamique des systèmes plage/dune : exemples sur les côtes françaises

François Sabatier*, Edward J. Anthony**, Arnaud Héquette**, Serge Suanez***,
Jonathan Musereau****, Marie-Hélène Ruz**, Hervé Régnauld*****

Abstract

Four representative sectors encapsulating the morphological and hydrodynamic diversity of the French coast are used to illustrate the morphodynamics of beach/dune systems at various timescales. These beach/dune systems cover the four shoreline sectors composing the French coast, i.e., the southern North Sea, the English Channel, the Atlantic Ocean, and the Mediterranean, and range from storm-dominated short-fetch to swell settings, and from micro- to macrotidal. The short-term processes affecting the beach/dune systems are strongly hinged on wind incidence and storm intensity, while sediment supply, modulated by marine processes, notably storms and tides, and by the regional wind directions, constitutes the primary control on long-term patterns of development. Beach morphology, notably the presence of bar/berm-trough systems, and water levels attained during storms, constitute key elements in the process of sand supply to the dune systems, which vary from low, poorly developed forms in the Mediterranean, to the well developed, but largely presently stable to erosive systems characterising the other three sectors. The comparative study of these systems shows that there is no linear relationship between storm intensity and the rate of dune erosion (except on Vougot site, English Channel), because of the influence of various parameters, notably the antecedent beach state.

Key words: storms, erosion, aeolian sediment transport, shoreface, spatio-temporal scale.

Résumé

Quatre sites représentatifs de la morphologie et de l'hydrodynamisme des côtes françaises sont décrits pour illustrer la morphodynamique du système plage/dune à différentes échelles de temps. Ces systèmes plage/dune couvrent les quatre secteurs qui composent les côtes françaises, i.e., le sud de la Mer du Nord, la Manche, l'Océan Atlantique et la mer Méditerranée, et s'étendent depuis les côtes à fetchs courts dominées par la houle jusqu'à celles dominées par la houle et depuis des contextes micro à macro tidaux. Les processus à court terme qui affectent le système plage/dune sont fortement reliés à la fréquence des vents et à l'intensité des tempêtes, tandis que les apports sédimentaires, modulés par les processus marins, particulièrement les tempêtes et les marées, ainsi que par la direction régionale du vent, constituent le premier contrôle du développement à long terme. La morphologie de la plage, surtout la présence des systèmes à barres et bâches, et les niveaux d'eau atteints durant les tempêtes, constituent l'élément clef dans le processus d'apports de sables aux systèmes dunaires qui varient depuis des dunes basses peu développées en Méditerranée jusqu'à des systèmes bien développés mais largement stables ou en érosion aujourd'hui sur les trois autres sites. L'étude comparative de ces systèmes montre qu'il n'y a pas de relations linéaires entre l'intensité des tempêtes et le taux d'érosion de la dune (excepté sur le site de Vougot, Manche), à cause de l'influence des nombreux paramètres, et notamment de l'état de la plage antérieure aux tempêtes.

Mots clés : tempête, érosion, transit éolien, avant côte, échelle spatio-temporelle.

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Version française abrégée

Les dunes jouent un rôle essentiel dans le bilan sédimentaire des plages, la biodiversité littorale, la protection des inondations de tempêtes et les activités récréatives. Ces structures sédimentaires entretiennent des relations sédimentaires avec la plage et le fonctionnement de ces deux unités est étroitement lié : l'ensemble constitue le système plage/dune. En France, les dunes sont présentes sur toutes les façades maritimes et dans des contextes géomorphologiques variés mais une revue exhaustive reste impossible car finalement ces structures sédimentaires demeurent encore relativement peu étudiées. L'objectif de cet article est donc de présenter quatre exemples de fonctionnement morphodynamique du système plage/dune le long des côtes françaises afin de distinguer le rôle des forçages qui contrôlent leur évolution.

Le premier site d'étude, la plage de Vougot, situé sur la partie occidentale de la Manche est représentatif de la morphologie des côtes du nord Finistère caractérisées par des successions de plages de baie aux systèmes dunaires bien développés. La dune protège aujourd'hui des inondations de tempête un polder situé en arrière et en contrebas. Cette dune s'est développée à la fin de l'Age de Bronze et jusqu'au 18^e siècle, date à partir de laquelle sa morphologie est devenue proche de celle d'aujourd'hui. Depuis plusieurs décennies cependant, elle enregistre une érosion chronique à cause de la construction d'une digue portuaire qui a modifié les dynamiques sédimentaires du secteur. Le budget sédimentaire entre 2004 et 2008 d'un transect dune/plage indique peu de variations morphologiques. La dune recule de 2,5 m et révèle les pertes les plus importantes (fig. 2). L'érosion de la dune, qui s'accompagne aussi d'un abaissement de la plage, est particulièrement bien reproduite à partir de l'approche proposée par Ruggiero et al. (2001). Ces résultats suggèrent une relation linéaire entre la hauteur du jet de rive atteint durant les tempêtes (max. 7,5 m NGF) et l'érosion dunaire (fig. 3). Les gains se localisent en haut de plage lors des périodes de beau temps (printemps – été) grâce aux vents dirigés vers la terre mais les étés particulièrement pluvieux qui limitent le transit éolien (fig. 4), se traduisent par des ré-engraissements naturels réduits.

Le second site d'étude se situe sur la partie occidentale de l'île d'Oléron (Océan Atlantique), à proximité de la localité de Vert-Bois. Une vaste opération d'aménagement et de végétalisation artificielle initiée au début du 19^e siècle est en partie à l'origine de l'extension de ce complexe dunaire. Aujourd'hui cependant cette dune connaît une érosion préoccupante dont nous tentons de décrire les relations avec les forçages. Deux tempêtes aux caractéristiques très proches (hauteur de houle, durée, force et direction des vents) induisent des réponses morphologiques très différentes (fig. 5). Ces différents impacts sont d'abord provoqués par la hauteur et la fréquence des niveaux d'eau atteints en relation avec les variations marégraphiques. Ensuite, nous suggérons que la morphologie anté-tempête joue aussi un rôle déterminant sur la réponse du système plage/dune à un forçage

externe. A l'échelle pluriannuelle il est cependant difficile de considérer un seuil d'efficacité des tempêtes (table 1). Les flux sédimentaires vers la terre sont aussi importants car en plus d'un déficit de la plage, la dune se déplace lentement vers le continent (fig. 5).

Le troisième site est plus régional puisqu'il s'agit des Côtes Nord de la France où les dunes sont généralement stables, même si des points d'érosion existent dans cette région au régime macrotidal et au fetch limité. La morphologie particulière de ces plages qui montrent une alternance de barres et de bâches sur l'estran contrôle les transits éoliens. A marée basse, les sables des zones basses du profil (bâches) sont souvent humides ou saturés en eau, ce qui interdit le transit éolien, tandis que les zones hautes, situées sur les barres, montrent un sédiment sec facilement mobilisable par le vent (fig. 6). Un modèle conceptuel simple résume ce fonctionnement : l'alimentation des dunes se produit essentiellement à partir d'une zone relativement étroite en haut de plage car la partie basse montre un fetch éolien segmenté. L'alimentation des dunes, démontrée à l'échelle longue (Holocène) à partir d'un transfert partiel de sable depuis l'avant-côte jusqu'à la plage par le déplacement des méga dunes hydrauliques qui tapissent le fond de la Manche et de la Mer du Nord, est analysée à partir de mesures courantologiques vers 5-6 m de fond (fig. 7). Le transit dominant est essentiellement orienté parallèlement au rivage, ce qui induit un transit longitudinal et non pas transversal, vers la plage. Le flux sédimentaire est surtout contrôlé par le courant de marée mais les vagues jouent aussi un rôle important sur l'augmentation des contraintes de cisaillement au fond, et donc du transport sédimentaire. Cependant, même si le courant orbital des houles augmente théoriquement le transit vers la plage, le transit parallèle au rivage domine.

Enfin le quatrième site présente aussi une analyse régionale dans un contexte de fetch court mais dans un environnement microtidal puisqu'il s'agit des plages de Camargue (Mer Méditerranée). Lorsqu'elles sont présentes, les dunes de ces plages en érosion sont souvent dégradées et sont incapables de protéger des crues de tempêtes les terres situées en arrière. Ces dunes anciennes se sont mises en place durant la construction holocène du delta, lorsque le rivage actuel connaissait des conditions différentes (orientation du rivage, bilan sédimentaire positif). Sur le profil de plage d'un secteur en érosion, lors des épisodes de vent de terre, le transit éolien dégraisse la plage en transportant les sables vers la mer (fig. 8). Pendant les vents de mer, l'engraissement de la dune par la plage n'est possible qu'au début de la tempête, avant que le niveau d'eau ne soit supérieur à la berme car à partir de ce seuil la plage est inondée et le transit éolien stoppé. Dans les petits fonds (- 3 m), le transit sédimentaire de l'avant-côte est dirigé vers le large durant les tempêtes (fig. 9) ce qui est conforme à l'évolution mesurée à long terme. L'analyse du transit éolien théorique, fondé sur la rose des vents à laquelle nous avons intégré les phases de submersions de tempêtes, dévoile aussi une légère dominance du transit vers la mer. Par conséquent, la succession de ces éléments défavorables aux transits depuis la

plage vers la dune explique la faiblesse des cordons dunaires sur les secteurs en érosion de Camargue.

Pour conclure, nous insistons sur le rôle du niveau de l'eau lié aux tempêtes, à la marée et à la morphologie qui contrôle partiellement l'érosion des dunes et limite le transport éolien. La morphologie anté-tempête joue très probablement sur l'érosion des dunes durant les tempêtes mais ce paramètre demande encore à être approfondi tout comme les processus épisodiques des échanges entre l'avant côte et le système plage/dune.

Introduction

Sand dunes are common features of the coastal zone and, together with the associated beach systems, are primordial in the shore sediment budget. They are also valuable ecosystems embodying several key conservation issues. Natural dunes also play a crucial management role by protecting low backshore areas from storms. In France, coastal dunes are variably developed along the sandy shores of the North Sea, the English Channel, the Atlantic Ocean and the Mediterranean Sea. These shores exhibit a wide variety of hydrodynamic and geomorphic contexts, ranging from macro- to microtidal, open and embayed settings, barriers, fringing beaches, and deltaic outlets, and variations in regional wind incidence angles. They are associated with various sources and modes of sediment inputs, from the shoreface, from commonly heavily managed rivers, and via variably developed littoral drift cells. This diversity is at the basis of marked variability in coastal dune morphology. The aim of this paper is to present examples of the morphodynamics of these beach/dune systems based on recent work carried out at four sites from the four maritime façades of the French coast. Similarities and differences between the different systems are identified and the role of the different forcing mechanisms assessed. The first two sites, located respectively in the western English Channel, and on the Atlantic coast, illustrate the mechanisms of dune erosion in a macrotidal environment affected by significant changes in wave energy due to storms. The coastal dunes of the third site, the southern North Sea coast, illustrate the influence of macrotidal bar-trough (ridge and runnel) topography on sand transport to dunes in a mixed storm and tide-dominated sand-rich shoreface. The fourth site illustrates patterns of beach/dune morphodynamics in the microtidal, storm-dominated Mediterranean setting of the Rhône delta.

The study sites

The northern coast of Finistère (Brittany), in the English Channel, is characterised by large coastal beach/dune systems situated on a low coastal platform (fig. 1A). In some cases these dunes stretch several kilometres seaward of abandoned cliffs, and bar swampy depressions. The dune of Vougot beach, located in the district of Guissény, illustrates this kind of morphology. It consists of a massive dune, 0.2 to 0.4 km wide and 2 km long, that extends in a SW-NE direction from the abandoned cliff of Zorm. It attains an ele-

vation of 13 m NGF (altimetric reference NGF – Nivellement Général Français – which refers to mean French sea level datum). The dune presently protects 100 hectares of polders that were former salt marshes disconnected from the sea by a dike constructed in 1834 (fig. 1A). The formation of the inner part of the dune commenced just after the Bronze Age. The external part of the dune accumulated later during the Iron Age. It continued to develop locally up to the 17th and 18th centuries (Guilcher and Hallégouët, 1991). The dune consists of fine homogeneous well-sorted sand (mean grain size 0.20 mm). The grain size of the tidal beach increases seaward from 0.25 to 0.315 mm.

The eastern part of the studied dune has experienced erosion for several decades. The study of shoreline changes over the last 54 years (1952-2006) has shown that erosion was caused by the construction of the jetty of Curnic in 1974 (fig. 1A), which has completely modified the hydrodynamics and sediment circulation (Sparfel and Suanez, 2007; Suanez *et al.*, 2007). Before the construction of the jetty, sediment circulated from Centre Nautique beach to Vougot beach within a general west to east sediment transport cell. After the building of the jetty, sediment became trapped in the western part of Centre Nautique beach, inducing rapid accretion, while Vougot beach, which was no longer supplied, started experiencing erosion. From 1982 to 2006 the total retreat of the dune attained 20 m. The speed of retreat began to increase in 2000 and is presently comprised between -1 and -1.2 m.yr⁻¹ (Sparfel and Suanez, 2007; Suanez *et al.*, 2007).

Wind data are derived from the nearest weather station run by Météo-France at Brignogan, situated about 30 km from the study site. Deep-sea wave data have been calculated by running a numerical model over the period 1979-2002 for a depth of 64 m offshore of Vougot beach (fig 1A). The most frequent annual winds are from west-southwest with a moderate northeastern component (fig. 1A). Dominant deep-water waves are from west-northwest. Both wind and waves are characterised by seasonal variations. The winter period (December to February) is characterised by strong winds (> 8 m.s⁻¹ for more than 30% of the time) blowing from northwest to southwest. These winds are associated with west-northwest waves (96%) which can reach heights ≥ 10 m and periods of up to 18 s during the largest storms. During spring (March to May), waves are less energetic (36% of wave heights between 2 to 4 m, and 34% of wave periods between 8 and 12 s) while winds from the northeast become more important (20%). The summer period (June to August) is characterised by relatively low energy conditions. During the autumn (September to November), energetic conditions again prevail to attain values close to those of the winter period. Dominant winds are from northwest to southwest (35%).

The second study area, Vert-Bois beach, is located in the middle part of the Atlantic coast of France (fig. 1B), where the continental shelf extends 120 km offshore and displays a very low gradient (1-2‰). The beach is specifically located on the southwest coast of Oléron Island and is relayed in the northern part of the island by Dune de St-Trojan (fig. 1B).

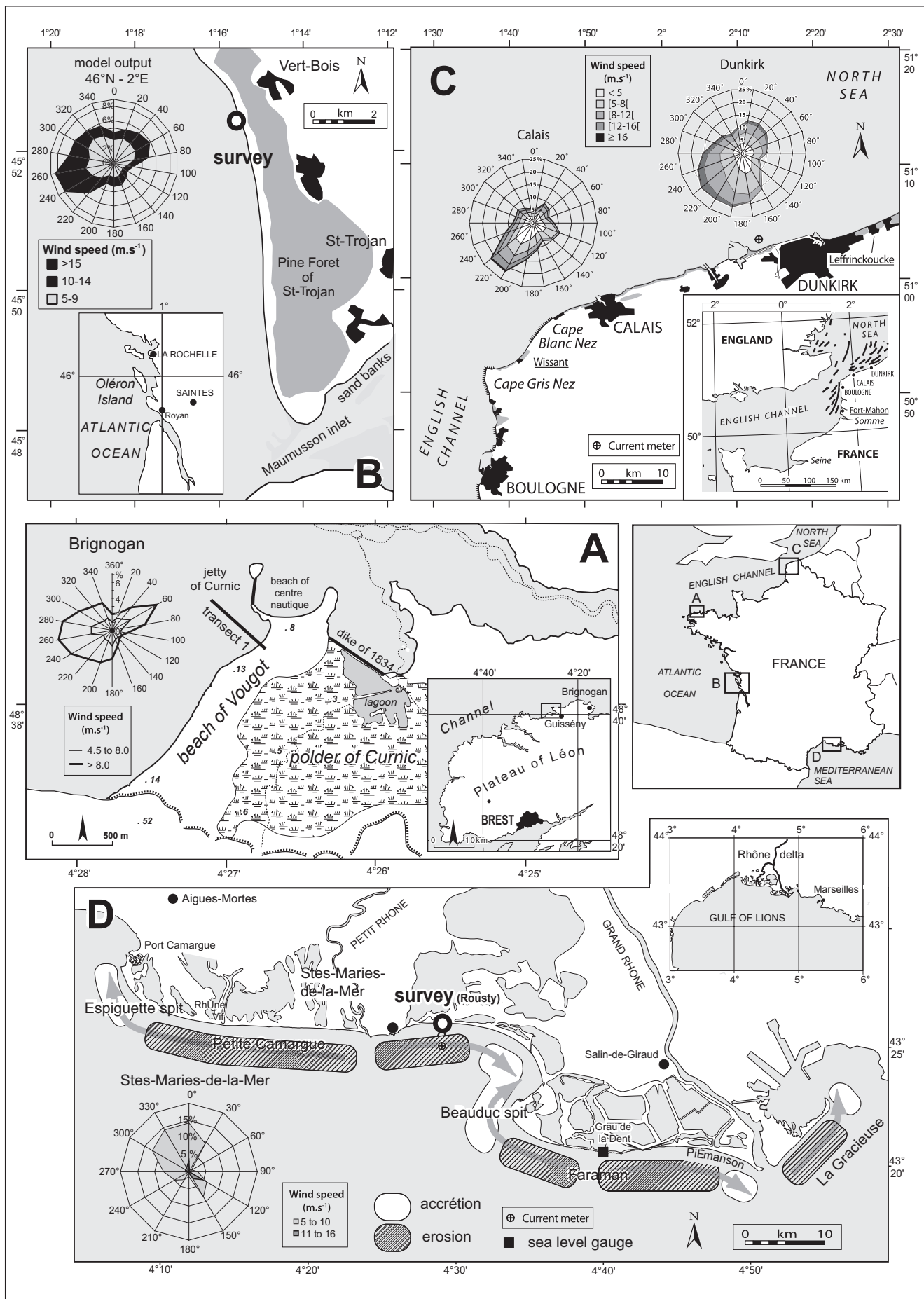


Fig. 1 – **Locations of study sites.** A: Vougot (Western English Channel); B: Vert-Bois (Atlantic coast); C: northern coast of France (North Sea); D: Camargue (Rhône delta, Mediterranean Sea).

Fig. 1 – **Localisation des sites d'études.** A : site de Vougot (Manche occidentale) ; B : site de Bois-Vert (Océan Atlantique) ; C : côte du Nord de la France (Mer du Nord) ; D : Camargue (Mer Méditerranée).

The following morpho-sedimentary characteristics are based on the most recent bathymetric surveys available for this coast, from Bertin *et al.* (2008). This high-energy dissipative beach is composed of fine sand ($D_{50} = 180\text{-}200 \mu\text{m}$). The system is dominated by longshore transport (towards the south) ranging from $50,000 \pm 20,000 \text{ m}^3\cdot\text{yr}^{-1}$ to $140,000 \pm 30,000 \text{ m}^3\cdot\text{yr}^{-1}$. According to statistical data from Météo-France (fig. 1B), the wind direction is annually balanced between SW (more frequent) and NE (less frequent) but westerly winds predominate when wind speeds exceed $15 \text{ m}\cdot\text{s}^{-1}$. Waves with $1 \text{ m} < H_s < 2 \text{ m}$ are predominant and represent more than 60% of the annual wave climate while waves with $H_s > 5 \text{ m}$ represent about 3%; wave directions are predominantly W to NW.

The dune of St-Trojan prograded from the mid-19th century to the end of the 20th century, as long as sediment supply along the coast was prevented by a pine forest from being mobilised inland. On west European coasts, dating of late Holocene sand sequences shows a significant agreement with reported wind intensification and sand mobilisation during and after the cooler period of the 'Little Ice Age' (Wintle *et al.*, 1998; Orford *et al.*, 2000; Clarke *et al.*, 2002). Today the dune is in retreat. Between 1996 and 2001, a rate of 4 to 6 m per year was measured by M.-C. Prat (2001), whereas J. Musereau *et al.* (2007) observed a retreat of 1 to 3 m per year since 2005. The reasons for this shift of the beach and dune morphodynamics observed on a large timescale are varied: inhabitants no longer fix the dune using pine forests as in the past; the region has been experiencing a decrease in sediment supply since the early 1980's (Prat and Salomon, 1997; Prat, 2001; Prat, 2004), as confirmed by the work reported in this paper. The upper beach is frequently flattened and temporarily covered by limestone pebbles. The sand dune cliff varies from 0.5 to 2.0 m in height and is in places directly in contact with the fixed dune (fig. 5A). Here, onshore aeolian sand transport is quite negligible, partly in relation with the recent reduction of the size of the mobile dune. Seaward, the development of sand bars, although typical of the Atlantic coast of France, is prevented by the presence of a rock barrier, the Rocher du Jard, which sometimes emerges at low tide.

The coast of Northern France, facing the eastern English Channel and the Southern Bight of the North Sea (fig. 1C), largely consists of wide, gently sloping, sandy bar-trough beaches (Anthony *et al.*, 2005; Reichmüth and Anthony, 2007, 2008; Sedrati and Anthony, 2007), and of low-elevated coastal dunes that rarely exceed 15 m high (Ruz *et al.*, 2005; Anthony *et al.* 2006). The shoreface is characterised by the presence of numerous linear sand banks (Augris *et al.*, 1990; Beck *et al.*, 1991), sub-parallel to the shoreline, the evolution

of which mainly depends on the action of tidal currents and storm waves (Tessier *et al.*, 1999). The hydrodynamic context is one of exposure to short-fetch, relatively low-energy waves punctuated by storm activity, and a tidal range of approximately 5 to 8 m at spring tides, increasing towards the English Channel. Due to the flood-dominated asymmetry of the tidal currents, the net regional sediment transport in the coastal zone is directed to the east-northeast (Beck *et al.*, 1991; Héquette *et al.*, 2008a). Sand is abundant on the shoreface, generally consisting of fine to medium quartz (Anthony and Héquette, 2007; Héquette *et al.*, 2008b).

Abundant accumulation of fine sand occurred on this coast during the Holocene as a result of large-scale tide-dominated circulations in the English Channel and southern North Sea that have gradually sorted the heterogeneous seabed sediments that were deposited under past changing sea levels (Anthony, 2002). Due to the nature of the regional bedrock geology, which largely consists of carbonate rocks, and to the small size of the rivers in the study area, the Holocene and contemporary fluvial sediment supply to the coast is very limited. The primary source of sand of the coastal deposits is consequently the adjacent seafloor of the English Channel and southern North Sea. Sand derived from the eastern English Channel was transported via a tide-dominated sand transport pathway hugging the French coast, leading to the infilling of the Flemish coastal basin (a large embayment on the North Sea coast that progressively filled up during the late Holocene to become the Flemish coastal plain) and to the ubiquitous development of coastal dune systems. Nowadays, extensive stretches of dune coastline are relatively stable, as shown by a number of studies (Vasseur and Héquette, 2000; Battiau-Queney *et al.*, 2003). Dune erosion also occurs with retreat rates that locally reached several metres per year during the second half of the 20th century (Corbau *et al.*, 1993; Clabaut *et al.*, 2000; Aernouts and Héquette, 2006), while the shoreline has also been advancing seaward at some locations during the last decades (Chaverot *et al.*, 2008). We present here a synthesis of the results of investigations carried out on sediment transport processes on the shoreface, beach and coastal dunes of this part of the French coastline, and which provides insight into the interactions between these coastal units in a macrotidal setting.

The fourth site concerns the microtidal Camargue (Rhône delta) coast in the Mediterranean. Build-up of the Rhône delta plain began at about 7,000 years BP and took place in several stages which are still visible in the present morphology, including for example palaeochannels, sand ridges, sand dunes and spits (Provansal *et al.*, 2003, Vella *et al.*, 2005). The current shoreline assumed its present morphology at the beginning of the 18th century (fig. 1D), actively shaped by a series of well defined littoral drift cells (Sabatier and Suanez, 2003; Sabatier *et al.*, in press). Areas undergoing erosion represent more than 60% of the coast and are leading to withdrawal and backshore concentration of human activities. Consequently, these zones are very sensitive to natural hazards (Sabatier *et al.*, in press). Moreover, they are subject to sea surges during storms due to their low elevations. In order to better understand the effectiveness of

dunes against storm surges (Sabatier, 2008), it is important to investigate the dune/beach system and its imbrications with the shoreface. The Camargue coastline presently undergoing significant erosion does not present any continuous natural dune formations (Augustinus *et al.*, 1990; Suanez, 1997). On the Faraman, Saintes-Maries-de-la-Mer and Petite Camargue erosional shores, the dunes have either developed under form-process dynamics different from those of the present (near former river mouths and/or coastal spits: Vella *et al.*, 2005), or linked to management, namely sand accumulation against dikes (Faraman and Petite Camargue), sand fencing to favour dune development (Saintes-Maries-de-la-Mer and Petite Camargue), and artificial dune construction (close to the Rhône Vif and the Gracieuse spit) (Suanez and Sabatier, 1999). The few well-developed modern dunes are located on beaches bordering the Grand Rhône river mouth and on the Espiguette and Beau-duc spits (fig. 1D).

The wind rose shows two dominant directions, from the N-NW and from the S-SE, creating two types of wave energy contexts: low-wave energy during offshore winds, and storm waves associated with sea surges during onshore winds. The astronomical tide is very low (0.3 m) but water levels can reach 1.0 m NGF during exceptional storms which favour dune toe attacks by wave action. The fine grain sizes (around 0.2 mm) render dune and beach sands very sensitive to aeolian processes. Erosional shores are oriented west-east, in line with the dominant wind directions which induce offshore and onshore aeolian sediment transport on the beach/dune systems (Augustinus *et al.*, 1990). The typical morphology of Camargue's eroding beaches displays a berm (around 1 m NGF) and a lower-lying back-berm (around 0.50 m NGF) (fig. 9). When dunes are present, they are low and never exceed 5 m NGF in elevation; thus the morphology of the beach/dune system manifests two crests (the dune and the berm) separated by a depressed zone (the back-berm). Wherever shoreline retreat has reduced the beach width between the dune and/or a dike, this morphology disappears and the beach is planar with a gentle slope (around 1 to 3°). In order to understand the beach/dune system along the eroding shores of Camargue, a multi-scalar approach is required. Methods employed included the use of episodic and in situ sand transport measurements, analysis of the annual wind rose and potential sediment transport, and comparison with the long-term evolution (> 10 years). From a coastal management point of view, it is essential to know whether natural conditions are favourable or not to dune development since they can protect the deltaic plain from storm surges, and can therefore be considered as a possible coastal protection option.

Vougot Dune, English Channel: an eroding system

In order to contribute to a better understanding of morphodynamic processes inducing retreat of the dune, a morphological survey of the zone between the neap tide low water level and the top of the dune was conducted. Meas-

urements using DGPS with accuracies of 0.015 min (x, y) and 0.01 min (z) were carried out along three cross-shore transects once a month from July 2004 to May 2008. Quantification of sediment budgets based on the method of 'vertical surface calculation' was achieved on two different sections of the transects: the tidal beach/dune system and the dune defined by the eroded steep face. Only the results obtained for transect 1 (fig. 1A), which is the most characteristic of dune retreat, are presented in this paper.

Regarding the whole transect (tidal beach/dune system), there are few morphological changes (fig. 2A). The most important variations concern the upper beach and the dune (from 0 to 18 m) where profile changes reach ± 0.7 m (fig. 2A). The sediment budget calculated for the whole transect over the monitoring period shows a deficit of about $25 \text{ m}^3 \cdot \text{m}^{-1}$ (fig. 2B). This result confirms the tendency to erosion observed since the 1980s and shows that the retreat of the dune is mainly due to the sediment deficit of the tidal beach which leads to marine submersion of the dune foot. The same evolution is observed for the dune *stricto sensu* where the deficit of sediment reaches $11 \text{ m}^3 \cdot \text{m}^{-1}$ over the whole period, and leads to a retreat of about 2.5 m (fig. 2C). Strong seasonal morphological changes are noticed, showing the important role played by meteorological forcing agents. The winter periods of 2005, 2006 and 2008 (and to a lesser extent 2007) were characterised by episodes of sediment loss, while intermediate periods (spring and summer) experienced sediment supply to the foredune, inducing accretion near the dune foot (fig. 2C).

The analysis of hydrodynamic and meteorological conditions recorded during the survey period was carried out in order to determine wave-induced erosion of property backing beaches using the Property Erosion Model (Ruggiero *et al.*, 2001). This model has been developed on dissipative beaches with slopes ranging from 0.005 to 0.047. It is based on predicted extreme water level elevations due to the combined processes of tide, surge and wave runup which are compared with measured elevations of the junctions between the beach face and the toe of the foredune. Therefore, wave-induced erosion of the foredune occurs primarily when extreme water levels exceed the elevation of the toe of the foredune. From the morphodynamic characteristics of Vougot beach ($0.1 < \xi_0 < 0.9$ and $\tan\beta 0,016$), a runup parameter was calculated using formulations by Stockdon *et al.* (2006). We also studied favourable conditions for potential aeolian sand transport that may induce sediment supply to the foredune. This study was carried out by analysing wind and rainfall conditions recorded over the survey period.

Results show a good relationship between extreme water levels and foredune erosion (fig. 3). More than 80% of erosion phases are well correlated with water levels exceeding the elevation of the toe of the foredune, which is consistent with the Property Erosion Model. In this context, retreat is observed with the dune scarp cut into a vertical bluff. These processes take place during winter, and are associated with swash fluctuations due to storm events. The winters of 2006 and 2008, characterised by several wave-induced erosion episodes, illustrate these processes quite well. Nevertheless,

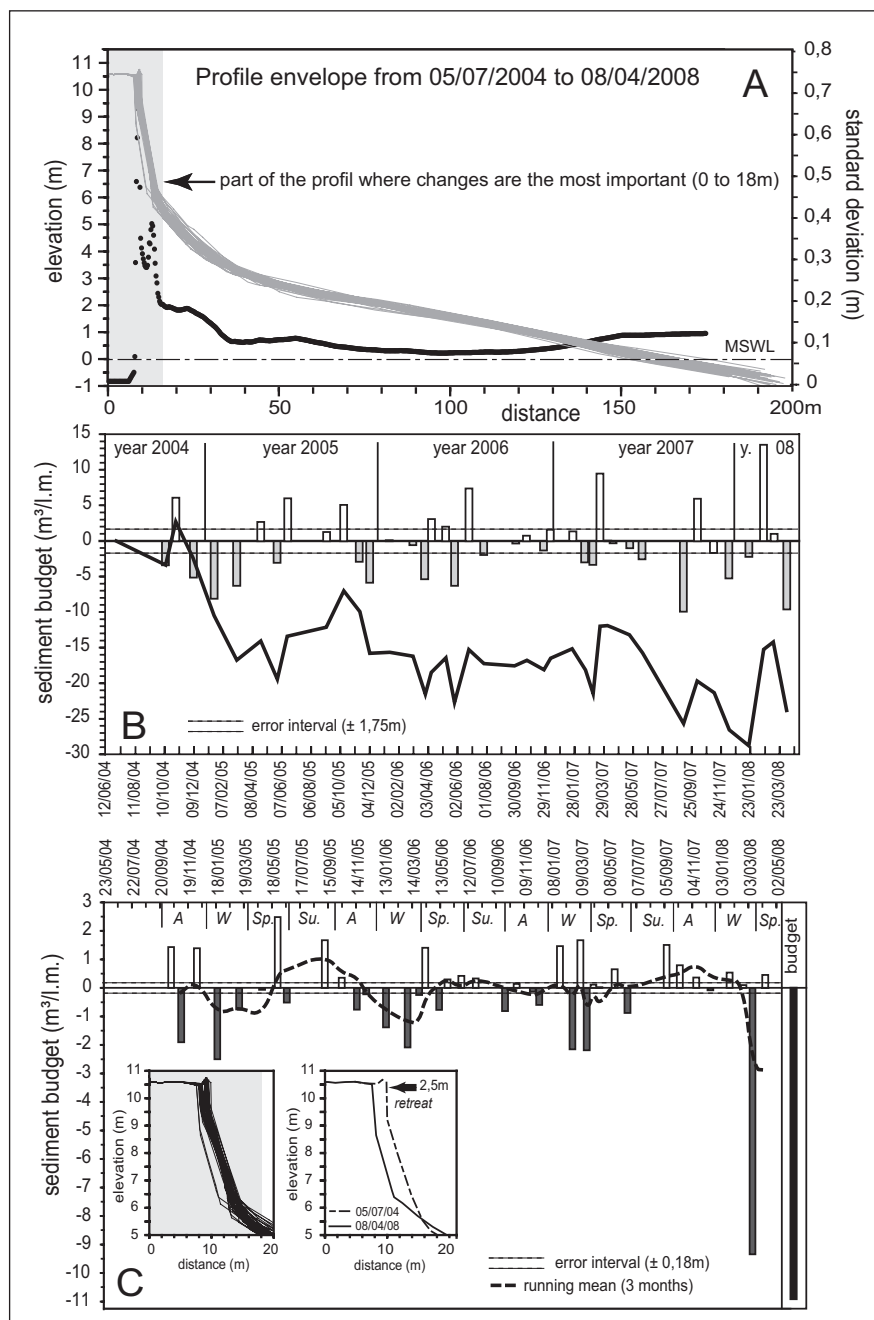


Fig. 2 – Morphological and sedimentary changes on a tidal beach and foredune for transect 1 from June 2004 to April 2008. A: envelope of the entire beach profile (from 0 to 175 m), and identification of the zone of greatest change; B: sediment budget of the entire beach profile (from 0 to 175 m); C: profile envelope of foredune and sediment budget calculated on this section of the profile (from 0 to 18 m).

Fig. 2 – Changements morphosédimentaires de la plage intertidale / cordon dunaire au niveau de la radiale 1, sur la période allant du mois de juin 2004 à avril 2008. A : Enveloppe de profils de plage allant de 0 à 175 m de distance, et identification de la zone la plus mobile au sein du profil ; B : bilan sédimentaire calculé sur 175 m de distance ; C : enveloppe de profils du cordon dunaire et évolution du bilan sédimentaire calculé sur cette section du profil allant de 0 à 18 m.

the greatest event recorded remains the 10th March 2008 storm during which extreme water levels reached about 7.5 m above sea level, i.e. 2 m higher than the level of the foot of the dune, inducing strong erosion (more than $9 \text{ m}^3 \cdot \text{m}^{-1}$ lost during this event).

In contrast, supply to the foredune occurs essentially during spring and summer when surface sand is dry and wind speeds are strong enough to initiate sand displacement (fig. 4). Sediment transport during spring is mainly oriented from the northeast and sediment transport is therefore subparallel to the coast. During the summer, winds shift to the west-northwest, inducing efficient conditions for supply to the foredune. It is mainly during this period that net sand accumulation occurs (fig. 4B), mostly at the toe of the dune and the upper beach. This accretion process may become modified when the summer period is rainy, inducing an increase in moisture content. As was the case during the rainy summer of 2007 (fig. 4C), supply to the foredune during these conditions is very low. Nevertheless, as various authors have shown, the dynamics of upper beach/dune systems also function at a micro-timescale (Hesp, 2002; Ruz and Meur-Ferrec, 2004; Suanez and Stéphan, 2006; Anthony *et al.*, 2006, 2007a). Therefore, loss of sediment due to a storm erosion event might be followed a few days later by accumulation processes inducing rapid morphological change.

Vert-Bois beach, Atlantic coast: decoupling of beach and dune erosion

Two storms were chosen to sort out the relative importance of wind, tide and waves in the behaviour of beach and dune. One occurred on the 9th December 2007, and the other on the 10th March 2008. These results are later considered within the perspective of a recent history of storms (2005-2008), which is then compared with rates of coastal retreat. The 9th December 2007 and 10th March 2008 storms were quite similar in magnitude, with, respectively, absolute wind speeds of 16 and $17 \text{ m} \cdot \text{s}^{-1}$ and wave heights of 5.8 and 5.2 m (fig. 5B). They also share the fact that they were both characterised by more than 24 hours of waves over 4 m high and more than 50 hours of waves over 3 m (52 hours in 2007 and 56 hours in 2008). In spite of these similarities, the first storm impacted only the beach while the second caused significant damage to the dune (fig. 5C). During the first storm, the maximum wave height and wind speed were rea-

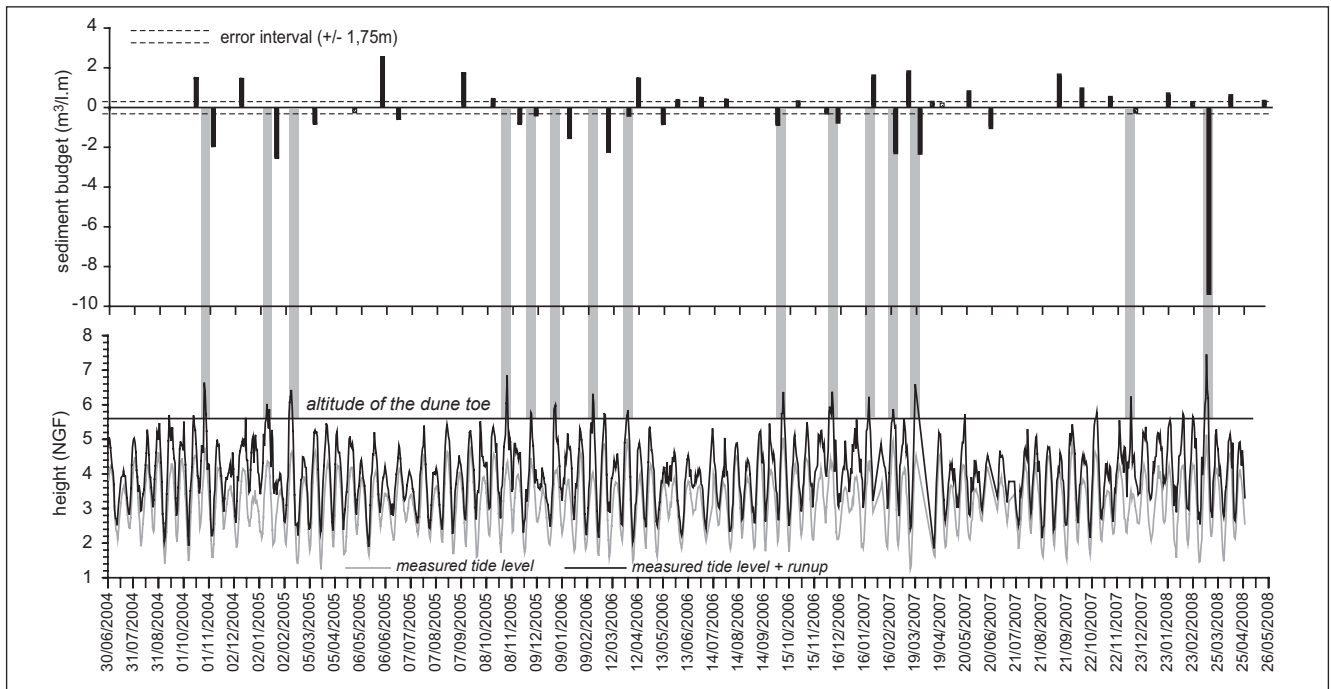


Fig. 3 – Relation between foredune erosion and extreme water levels. Measured tide records have been provided by the tide gauge station of Roscoff situated about 35 km to the east of Guissény; wave data were obtained using numerical models and have been provided by LNHE-EDF for the period July 2004–December 2005, and SHOM-Brest for the period January 2006–March 2008 (lat. 48.6540°; long. -5.946°; 64 m depth). On the basis of the morphodynamic characteristics of the beach ($0.1 < \xi_0 < 0.9$), the runup parameter was calculated using formulations by Stockdon *et al.* (2006).

Fig. 3 – Relation entre l'érosion du cordon dunaire et les niveaux d'eau extrêmes à la côte. La marée observée provient du marégraphe de Roscoff situé à environ 35 km de Guissény ; les données de houle ont été obtenues par simulation numérique auprès du LNHE-EDF pour la période juillet 2004–décembre 2005 et du SHOM-Brest pour la période janvier 2006–mars 2008 (lat. 48.6540°; long. -5.946°; 64 m de profondeur). Le jet de rive est calculé à partir de l'équation de Stockdon *et al.* (2006) qui s'applique aux caractéristiques du site d'étude ($0.1 < \xi_0 < 0.9$).

ched during only one high tide, with an astronomical tide level of 4.8 m. On a few occasions after the storm, the upper beach underwent aeolian sand deposition and beach recovery began promptly. During the second storm, the maximum wave heights and wind speeds coincided during several spring high tides, with astronomical tide levels around 5.2 m. Maximum wind speed was reached at the beginning of the storm ($17 \text{ m}\cdot\text{s}^{-1}$ at 7 a.m. on the 10th) and the dune front was depleted by winds before it was reached by the higher tide and waves (about 12 hours later). It probably had a weakened resilience during the wave height peak. This kind of combination and such duration are a distinctive feature of this storm. High waves were able to reach the dune toe several times and active erosion occurred (fig. 5C). Thus, the second storm caused much greater damage and dune sand loss.

The storm duration may be the main factor responsible for this difference between these two events and this parameter is often used in the establishment of storm and erosion indices (Dolan and Davis, 1992; Sallenger, 2000). Another reason for this difference is that at a particular site erosion induced by a storm is affected by the antecedent beach profile (Thieler *et al.*, 2000; Morton, 2002). Thus, some storms are much more efficient in removing dune front sand than others. The main problem is that on a yearly basis the larger retreat rates are not necessarily linked with the intensity

and/or duration of each single erosive episode. Successive storm impacts in the same coastal region are common, but their cumulative impacts are poorly understood (Morton, 2002). In fact, the cumulative effects of storm groups, even if with a minor intensity, can often exceed the impact of one severe storm (Ferreira, 2006; Musereau *et al.*, 2007; Claudino-Sales *et al.*, 2008). Therefore, annual storm counts (frequency) do not necessarily reflect total annual storm energy. Although the 2008 storm has been one of the highest in magnitude for years, the shoreline retreat rate of the late 2007–early 2008 winter season is lower than that of the previous years (tab. 1). We consider that setting threshold conditions constitutes a useful tool for discriminating storm events that have greater erosion potential from others. As an example, an arbitrary sorting of storms has been carried out for Vert-Bois, based on (onshore) wind speed, wave height, and tide level (tab. 1). At a seasonal timescale, such a method of decoupling could be much more efficient than the calculation of values related to the wave climate (as means of wave height and period or wave power). Concerning the relationship between storms and medium-term (years) coastal dune morphodynamics, we suspect that, usually, storms do not relocate sediment far offshore, because within a few weeks the former profiles become re-established and normal beach behaviour resumes. This means that erosive events are more or less smoothed within weeks, unless they occur in succes-

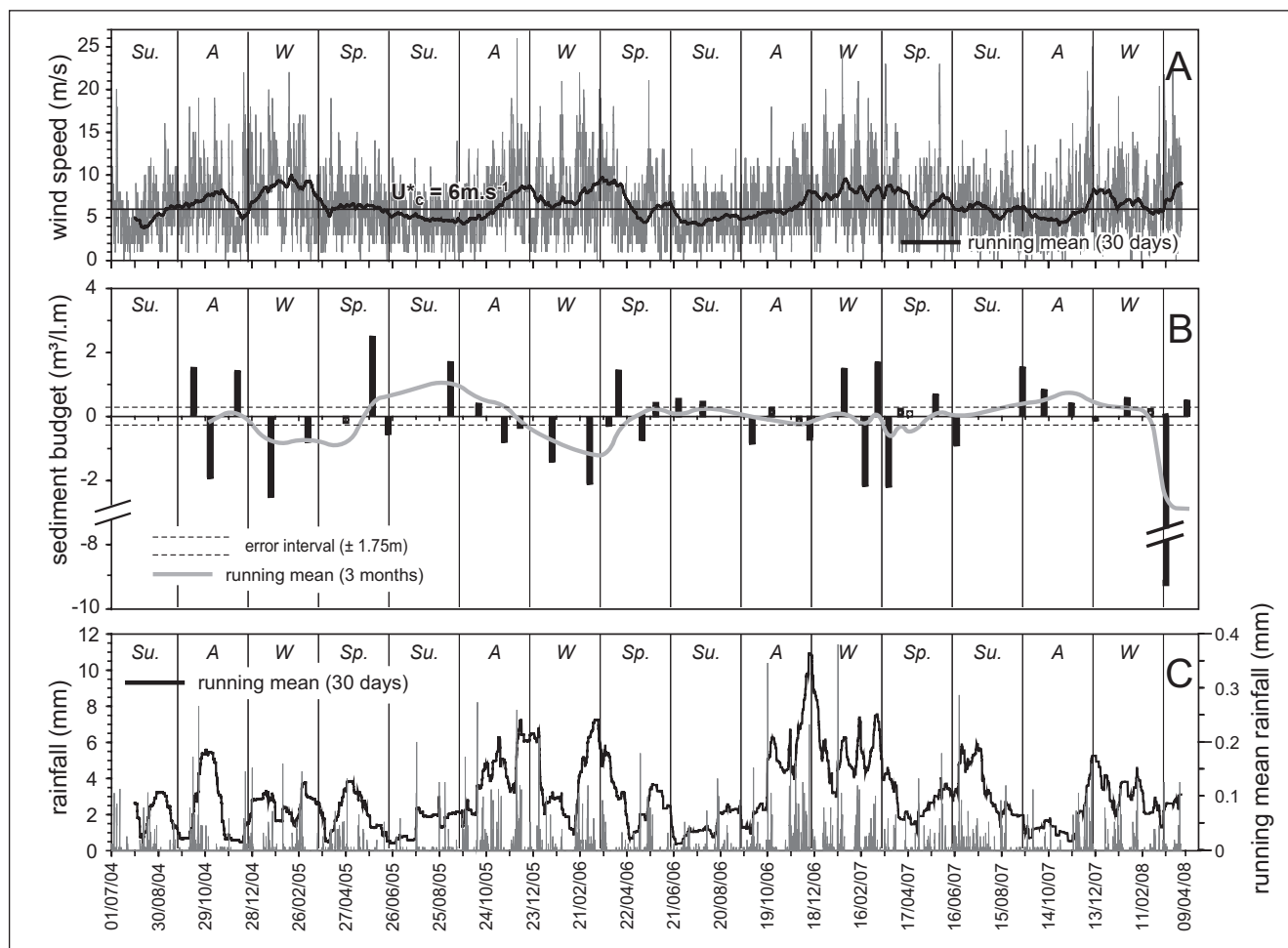


Fig. 4 – Evolution of the sediment budget of the foredune as a function of wind speed and rainfall recorded over the survey period. According to the Bagnold's formula (1941), the threshold velocity for a grain size of 0.25 mm is equal to 6 m.s^{-1} .

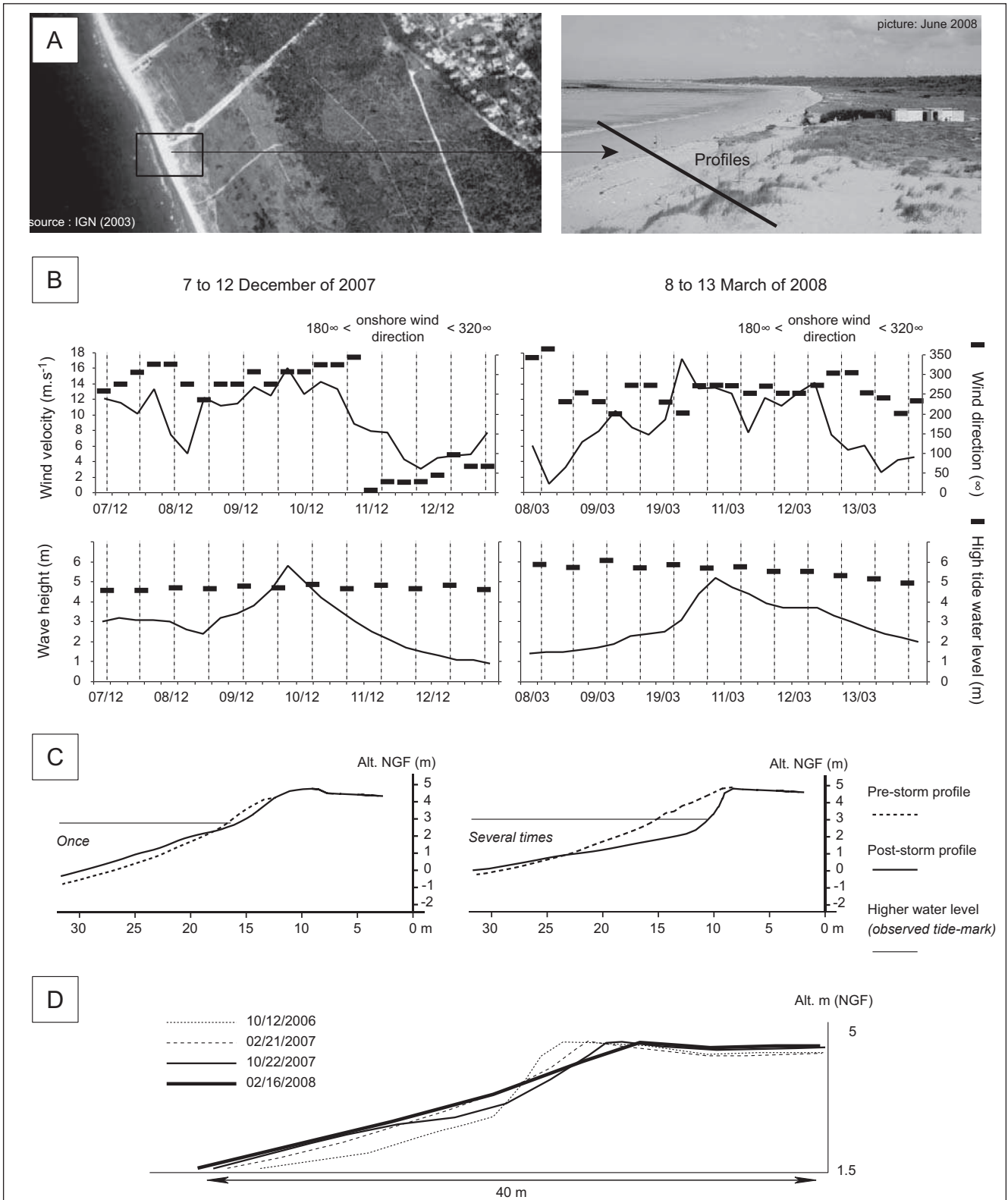
Fig. 4 – Evolution du bilan sédimentaire de la dune en fonction de la vitesse du vent et de la pluviométrie, enregistrées sur toute la période de suivi. La vitesse seuil d'arrachement est évaluée à 6 m.s^{-1} pour une granulométrie de 0,25 mm (formule de Bagnold, 1941).

Years	Events	Hm (m)	Tm (s)	P (J.m^{-1})	Dune retreat (m)
2005-2006	5	0.7	9.0	24,271	2
2006-2007	8	0.9	10.3	27,318	3
2007-2008	4	0.8	9.5	30,180	1

Tab.1 – Frequency of forcing agents (global mean significant wave height -Hm-, global mean wave period -Tm-, cumulative Wave Power -P-), and dune retreat at Vert-Bois during winter to early spring (i.e. November to April). Hm, Tm and the cumulative Wave power are derived from data used in this study (available on <http://windguru.cz>). Thresholds are defined as follow: (onshore) wind speed $> 12 \text{ m.s}^{-1}$; wave height $> 3 \text{ m}$; tide level $> 4.7 \text{ m}$ during at least two tide cycles. $P = 1/16 \text{ gHm}^2$ (where ρ is the sea water density, g is the gravitational force).

Tab.1 – Fréquence des forçages (houle moyenne -Hm-, période moyenne -Tm-, énergie de la houle cumulée -P-), et recul de la dune de Vert-Bois pendant les derniers hivers (i.e. novembre à avril). Les données de Hm, Tm et de l'énergie de la houle sont disponibles à cette adresse : <http://windguru.cz>. Les seuils sont définis de la manière suivante : vent de mer $> 12 \text{ m.s}^{-1}$; hauteur de la houle $> 3 \text{ m}$; marée $> 4,7 \text{ m}$ durant au moins deux cycles. $P = 1/16 \text{ gHm}^2$ (où ρ est la densité de l'eau de mer, g la gravité).

sion. Even if recession caused by storms is generally followed by aggradation of the beach and/or aeolian sand deposition on the back dune, profile surveys of the upper beach and dune show a significant retreat of the dune front between October 2006 and February 2008 (fig. 5D). The re-emergence of bedrock also indicates that the sediment budget is negative in the intertidal zone. The rhythm of retreat is mainly controlled by the relationship between dune erosion and frequency of storm occurrence. As shown above, the analysis of such a relationship could be much more efficient if based on a previous decoupling of specific hazards (use of crossing thresholds), assuming that they have a greater potential for erosion than others.



The southern North Sea coast: beach/dune/shoreface articulations at various timescales

The topography of the beaches bounding the macrotidal southern North Sea varies spatially and temporally in terms of the number, spacing, and elevation difference of bars

(Masselink and Anthony, 2001). The intertidal bar-trough couplets commonly exhibit strong cross-shore variations in surface moisture contents and bedforms. The troughs are only exceptionally dry, while the bar slip-faces and seaward slopes are generally moist. Bar slip faces and seaward slopes, and the upper beach ramp linking the bar-trough systems to the foredune, may carry abundant wave-tidal

Fig. 5 – Forcing agents and profile survey of the beach and dune system associated with exceptional storms, and interpretation of the medium-term (years) coastal dune morphodynamics at Vert-Bois (on the left between the 7 and 12th December 2007; on the right, between the 8 and 13th March 2008). A: location of the survey; B: storm description from wind velocity and direction, wave height and water level; C: pre- and post-storm profiles, between 7 and 12th December 2007 and between 8 and 13th March 2008; D: behaviour of the upper beach/dune system between October 2006 and February 2008. Meteo-marine data are obtained from a (near) real-time monitoring of storms, based on wind and wave model data from various sources such as Météo-France, GFS model (NOAA), and NWW3 (FNMO) at the following coordinates: 45° 13'N - 1° 30'W – 26 m depth). High tide water level is obtained from the tide tables of the National Hydrographic and Oceanographic Service at the following coordinates: 47° 13' N - 01° 35'W. Profiles of the upper beach/dune system are realised between 1.5 m NGF (neap high tide sea level) to the dune top which culminates at around 5 m NGF.

Fig. 5 – Forçages et relevés topographiques de la plage de Vert-Bois lors de deux tempêtes exceptionnelles et interprétation pluri annuelle de la morphodynamique de la dune à Vert-Bois (colonne de gauche, entre le 7 et le 12 décembre 2007 ; colonne de droite, entre le 8 et le 13 mars 2008). A : localisation des mesures ; B : description des tempêtes à partir des paramètres suivants : la vitesse et la direction du vent, la hauteur des vagues et le niveau d'eau (hauteur d'eau prédite à pleine mer) ; C : profils réalisés avant et après chaque tempête (les 7 et 12 décembre 2007 puis les 8 et 13 mars 2008) ; D : comportement du système plage-dune entre octobre 2006 et février 2008. Les données météo marines sont issues de sorties de modèles de Météo-France, GFS (NOAA), et NWW3 (FNMO) aux coordonnées 45° 13' N - 1° 30' W – 26 m de profondeur). Les données de hauteur d'eau sont extraites des tables de marée du SHOM aux coordonnées 47° 13' N - 01° 35' W. Les relevés de terrain (profils) sont réalisés entre la limite supérieure des marées de morte-eau (1.5 m NGF) et le haut de la dune (environ 5 m NGF).

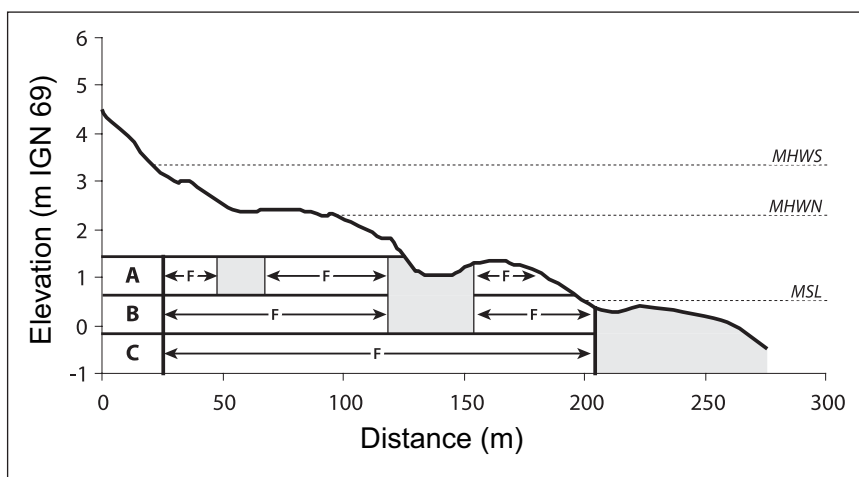


Fig. 6 – Modèle conceptuel de la segmentation du fetch éolien à marée basse sur une plage macrotidale avec une topographie intertidale de barres et de bâches bien développées (le profil est celui de la plage de Leffrinckoucke relevé le 08/10/01). MHWS : Niveau moyen des hautes mers de vive eau ; MHWN : Niveau moyen des hautes mers de morte eau ; MSL : Niveau moyen. Le gris montre des zones de transport nul, d'étendue variable dans le temps (zones humides de la plage, et notamment en dessous de MSL). A : conditions de marées de vive-eau caractérisées par un fetch très segmenté comprenant trois segments : une zone de contact entre le haut de plage et le pied de dune à fetch peu développé, un fetch de haut de plage, et un fetch de barre du haut de plage ; B : conditions de marées de morte eau associées à un fetch large de haut de plage et à un fetch de barre de haut de plage ; C : conditions de fetch exceptionnel et optimal durant lesquelles l'accrétion et le comblement des bâches élargissent considérablement la partie sèche du haut de plage au-dessus de MSL. L'érosion et l'aplatissement du profil induisent des effets opposés – un accroissement de l'humidité de surface et un développement important de figures sédimentaires qui conduisent à une réduction significative du fetch transversal. Des variations de fetch (segmenté) peuvent être causées par des changements dans la morphologie des barres et des bâches et par leur espacement. A noter que le fetch transversal peut être élargi considérablement par des vents à incidence oblique (tiré de Anthony et al., 2009).

bedforms, notably ripples. Bedform development may also be observed on bar crests and on the upper beach zone that normally show plane beds. This occurs especially during spring tides and storms, which also tend to increase surface moisture contents (Oblinger and Anthony, 2008). Wind and sediment transport measurements on several beaches of the region have shown that apart from the influence exerted by the undulating bar-trough topography on air flow, potential aeolian sand transport across these beaches appears to be influenced considerably by the marked variability in surface moisture contents (Anthony *et al.*, 2009). Surface roughness, due to bedforms, may also affect transport, especially over areas characterised by ripple development (Anthony *et al.*, 2009). The variability of these factors results in aeolian transport rates that range from less than 0.5 kg.m⁻¹.hr⁻¹ to more than 120 kg.m⁻¹.hr⁻¹.

A simple conceptual model of effective fetch development, integrating the effects of the spring-neap tidal range and of gross bar-trough morphological variability over time, can be proposed for these bar-trough beaches (fig. 6). The model highlights the dominant effect of fetch segmentation induced by cross-shore differentiation in the moisture contents of these beaches. Despite their large intertidal widths, the ef-

Fig. 6 – A conceptual model of cross-shore fetch segmentation at low tide on macrotidal beaches that exhibit well developed intertidal bar-trough topography (profile shown is that of Leffrinckoucke, 08/10/01). MHWS = Mean high water springs; MHWN = Mean high water neaps; MSL = Mean sea level. Grey shading shows time-varying areas of no-transport (very moist or water-saturated areas – temporary or quasi-permanent troughs and the part of the beach profile below about MSL). A: spring tide conditions characterised by a highly segmented fetch comprising three segments: a poorly developed upper beach-dune foot fetch, an upper beach fetch ramp, and an upper bar fetch; B: neap tide conditions associated with a wide upper beach fetch, and an upper bar fetch; C: exceptional optimal fetch conditions during which accretion and infill of troughs considerably enlarge the dry upper beach zone above MSL. Erosion and flattening of the profile induce opposite effects: enhanced beach surface moisture and bedform development associated with significant cross-shore fetch reduction. Variations in (segmented) fetch may be caused by changes in bar-trough morphology and spacing. Note that the cross-shore fetch may be considerably enlarged by obliquely-incident winds (after Anthony *et al.*, 2009).

fective dry fetch of these beaches is segmented across-shore and, therefore, dry sand sources for the foredune may be highly restricted to a narrow upper beach zone. Neap tides with restricted tidal and wave effects on the upper beach bar, and especially on the upper beach slope linking the bar-trough system to the foredune, tend to favour dry and smooth bed fetch conditions conducive to sand supply to the foredune, while spring tides may limit sand supply from the upper beach to the foredune. Under adequate sand availability, the most favourable conditions for short-term beach-to-dune sand supply occur when strong onshore, and especially obliquely onshore (fetch-lengthening) winds, coincide with neap tides, while longer-term optimal aeolian sand supply from beach to dune is hinged on the development of a large upper beach platform associated with trough infill or minimal trough development (fig. 6). Such optimal fetch conditions can only occur under conditions dominated by wave-induced accretion and infill of the troughs above mean sea-level. Erosion and flattening of the profile may, on the other hand, lead to enhanced beach surface moisture contents and bed-form development associated with significant cross-shore fetch reduction. Whilst short time-varying aeolian transport over these macrotidal beaches can be explained by the extent of effective fetch, over longer timescales, the development, or conversely, the erosion of coastal dunes is strongly dependent on the upper beach elevation and beach sediment budget. Investigations in the bay of Wissant, for example, have shown that dune erosion is not solely a response to storm intensity and water levels, but is also controlled by the elevation of the upper beach (Ruz and Meur-Férec, 2004). These authors clearly demonstrated that even moderate storm events may result in severe coastal erosion when the beach level is lowered, while storm impact is moderate when the upper beach elevation is high.

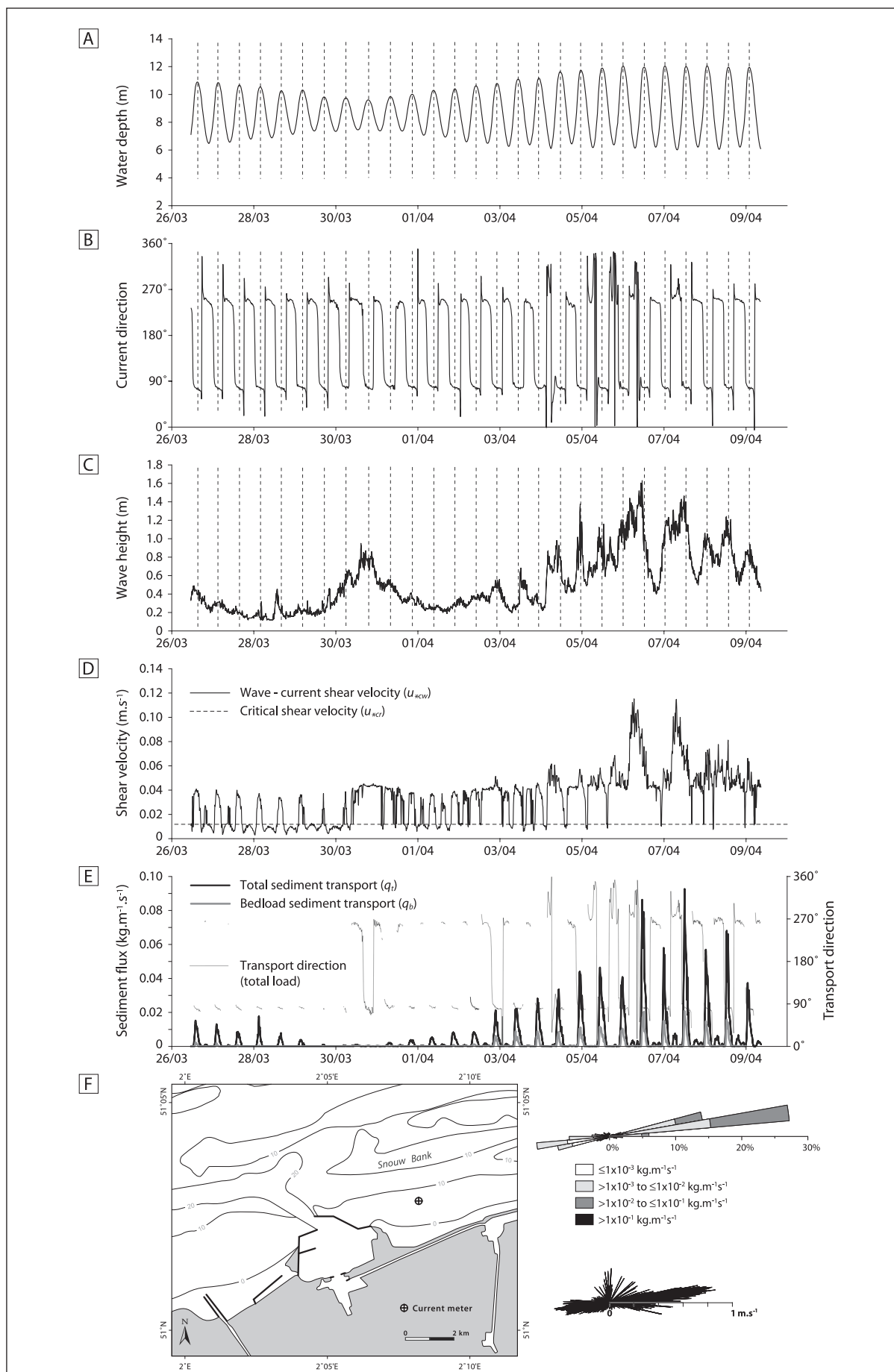
In addition to studies carried out in the intertidal and supratidal zones, analyses of nearshore bathymetry changes have revealed that shoreline evolution is also strongly influenced by medium timescale (10^1 - 10^2 years) shoreface morphodynamics (Corbau *et al.*, 1993; Aernouts, 2005; Aernouts and Héquette, 2006), which are, to a large extent, controlled by the longshore and onshore migration of tidal sand banks (Garlan, 1990; Tessier *et al.*, 1999). Investigations near Calais and in the bay of Wissant have shown that shoreline evolution is clearly linked to nearshore sediment budget, sectors of rapidly eroding coastal dunes being characterized by shoreface erosion, while prograding shorelines correspond to nearshore areas of sediment surplus and sea-floor aggradation (Aernouts and Héquette, 2006; Anthony *et al.*, 2006). The mechanism of shore-attachment of banks, documented from ancient maps and from recent studies of shoreline migration and inner shoreface bathymetry (Garlan 1990; Aernouts, 2005), appears to be most important in coastal accretion in this area. Here it leads to significant seaward shoreline migration over a short period of time (years). Examples of sectors of coast where shoreface tidal sand banks have recently become shore-attached occur east of Calais where this has resulted in the development of an extensive sand flat and active dune formation (Anthony *et al.*,

2007a). Elsewhere, local dune accretion may occur within downdrift termini associated with updrift eroding sectors, as in Wissant Bay (Aernouts and Héquette, 2006; Sedrati and Anthony, 2008). Overall, however, present dune accretion is rather limited, and large stretches of the dune-bound shoreline show signs of stability, and even erosion in places, suggesting limited onshore sediment supply, notwithstanding the abundance of sand on the shoreface.

Observations of the polarity of actively migrating bed-forms (such as dunes or sand waves) on the shoreface banks of the region indicate clearly that residual sediment transport is essentially shore-parallel to shore-oblique rather than onshore-directed (Augris *et al.*, 1990; Vanwesenbeeck and Lanckneus, 2000). Furthermore, hydrodynamic measurements and sediment transport modelling carried out in 5 to 6 m water depths (Héquette *et al.*, 2008a) have shown that the hydraulic regime is dominated strongly by shore-parallel tidal flows that favour longshore sediment dispersal rather than shore-normal transport (fig. 7). Estimates of sediment flux using the SEDTRANS96 numerical model (Li and Amos, 2001) for combined flow conditions suggest that although sediment transport is strongly controlled by tidal processes, waves can significantly enhance bed shear stresses (fig. 7D), resulting in increased sediment remobilization, and hence higher sediment flux (fig. 7E). Although wave oscillatory currents result in enhanced onshore-directed shear velocity at the bed (fig. 7D), sediment appears to be essentially transported alongshore on the shoreface (fig. 7F), even during high energy events. Our results show that net onshore bed stress, which may lead to shoreward sediment transport, occurs on the shoreface during slack tide, but these conditions last for very short periods and represent very limited sediment transport, several orders of magnitude lower than longshore transport. More significant onshore transport may occur during low-frequency storm events, when onshore-directed orbital velocities associated with high amplitude waves are strong enough to overwhelm longshore tidal currents. The supply of nearshore sediments to beaches may be restricted to shallower water depths, however, with wave orbital currents becoming more efficient in driving sediment onshore as tidal flow velocity magnitude decreases and wave asymmetry increases shoreward.

Fig. 7 – Time series of hydrodynamic parameters recorded in 5 m water depth seaward of Dunkirk from 26/03/2004 to 09/04/2004. A: water depth; B: mean near-bottom current direction; C: significant wave height; and of D: computed shear velocity and E: modelled sediment transport based on SEDTRANS96 model. Directional distribution of mean currents and computed total sediment flux (qt) are also shown (F); see fig. 1 for location (modified from Héquette *et al.*, 2008a).

Fig. 7 – Données hydrodynamiques obtenues à 5 m de profondeur au large de Dunkerque entre le 26/03/2004 et le 09/04/2004. A : profondeur ; B : direction moyenne du courant près du fond ; C : hauteur significative des vagues ; estimations (D) des vitesses de cisaillement au niveau du fond et (E) des transports sédimentaires à partir du modèle SEDTRANS96 model. La fréquence directionnelle des courants moyens et des transports sédimentaires totaux (qt) est également indiquée (F) ; voir fig. 1 pour la localisation (d'après Héquette *et al.*, 2008a).



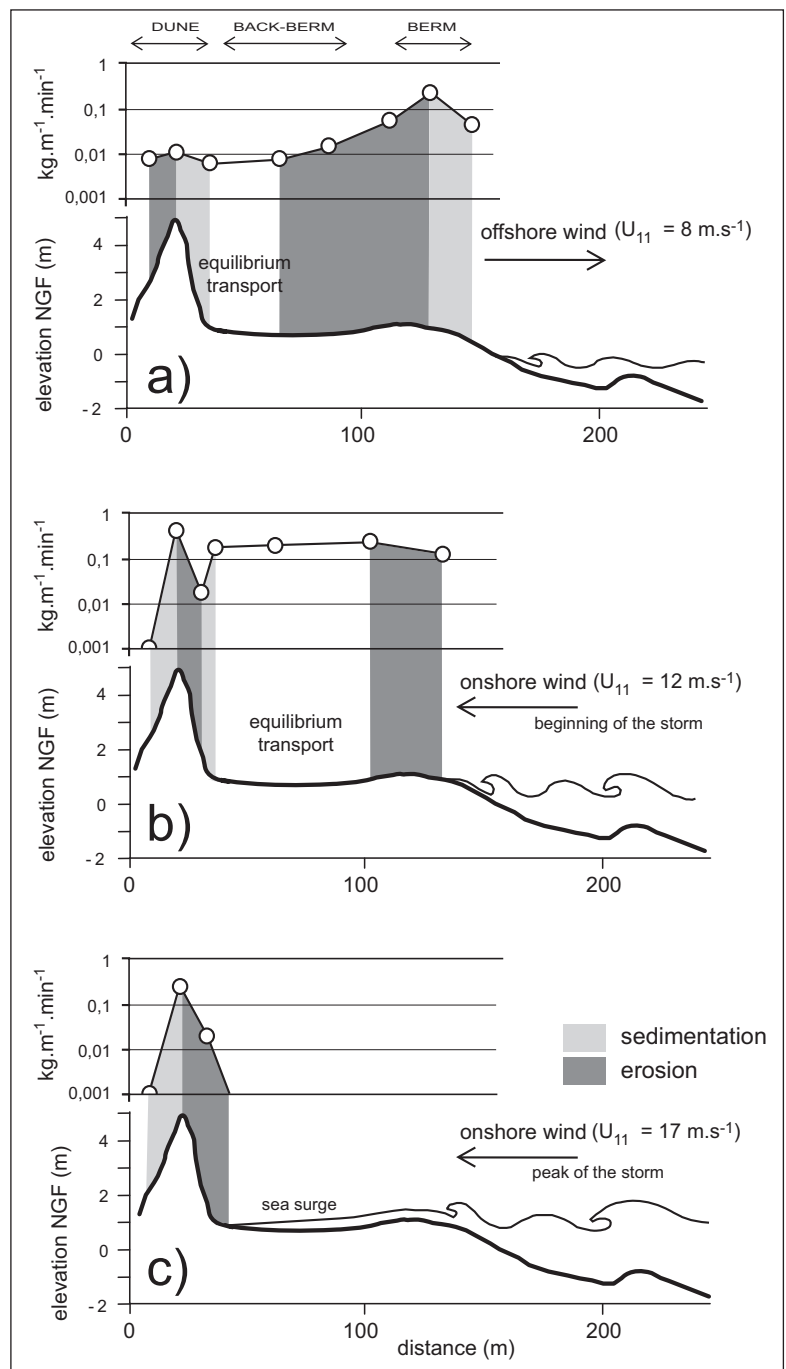
The exact mechanisms of onshore sand supply to the beaches are therefore still unknown, but sand may possibly enter from the shoreface to the shore through either wholesale welding of nearshore banks or ridges driven by storms, or as more diffuse storm-driven packets of sand. Wholesale welding of sand banks to the coast would seem to be a rare phenomenon, as driving a large coherent body of sand towards the coast would require repeated high-intensity storm waves. While storms tend to drive banks onshore, strong shore-parallel tidal currents tend to stretch them alongshore, a process that appears to counter shoreward bank migration induced by impinging storms. It is unlikely that the present pattern of large-scale coastal dune stability (and even localised erosion) is due to the exhaustion of fine sand supply, as the shoreface sand banks are rich in fine sand. Analyses of changes in storminess and shoreline evolution during the 20th century have shown that coastal dune erosion and shoreline retreat are not primarily controlled by storm frequency and intensity, because periods of higher storminess have not necessarily resulted in more rapid retreat or more generalised coastal erosion (Chaverot *et al.*, 2008). Our results suggest that at medium to long timescales, shoreline behaviour and coastal dune evolution are not simply controlled by the magnitude and frequency of hydro-meteorological forcing, but are also strongly dependent on the local sediment budget of the coastal zone. The latter can vary significantly through time due to a combination of several factors, including shape and orientation of the coastline, changes in nearshore bathymetry, and accommodation space. At a short timescale, however, the large tidal range and the complex topography of multiple intertidal bars and troughs are significant factors that restrict sand transfer from beaches to dunes, thus potentially limiting accretion of the latter.

Fig. 8 – **Conceptuel model of aeolian sediment transport over the Rousty beach profile.** A: during offshore wind; B: during onshore wind, at the beginning of a storm; C: during onshore wind, at the height of a storm. The morphology of the profile is representative of the zones under erosion of the Camargue as there is a fossil dune (2.400 years BP, Vella *et al.*, 2005), a trough-like back-berm and a berm. The wind measurements were realised at Saintes-Maries-de-la-Mer by Météo-France (located 3 kilometers to the west).

Fig. 8 – **Modèle conceptuel du transport sédimentaire éolien sur le profil de Rousty.** A : pendant un vent de terre ; B : pendant un vent de mer, en début de tempête ; C : pendant un vent de mer, au paroxysme d'une tempête. Ce profil est caractéristique des secteurs en érosion des plages de Camargue puisqu'il montre : une dune fossile (2 400 ans BP, Vella *et al.*, 2005) ; une bache et une berme. Le vent est mesuré à la station Météo-France des Saintes-Maries-de-la-Mer, située à 3 km à l'ouest du site.

The Rhône delta beach/dune system, Mediterranean Sea : offshore-onshore aeolian sediment transport

In order to describe the episodic nature of sediment exchange across the shore profile in the wave-dominated microtidal setting of the Rhône delta, a two-week investigation (ROUSTY0102 experiment) was conducted in the Rousty area on currents and waves, beach profiles and on sediment trapping (fig. 1D). The survey zone is an area undergoing erosion, devoid of coastal structures, and characteristic of unmanaged Camargue beaches. Variations in aeolian sediment transport measured by traps during the experiment were interpreted using a box model (Nordstrom



et al., 1996), which provides information on the sediment source and sink areas across the emerged profile (fig. 8). Under offshore and onshore wind conditions, the most important zones of sediment transport are found on the upper part of the profile (dune and berm zones) where winds are theoretically stronger. Lower sediment accumulation occurs where dunes physically block the winds (dune foot) or where topography and vegetation break down wind speeds, and thus sediment transport (backshore) (fig. 8).

Under offshore wind conditions, the rate of sand transport balances between the landward and seaward faces of the dune (fig. 8A). Sand transport is enhanced from the low back-berm to the top of the berm, whilst on the beachface the rate of sand transport decreases. An increase in sediment transport across the beach is controlled by the interaction of several factors: topographic obstacles facing the wind direction, which can accelerate flow (Hesp *et al.*, 2005), the aeolian cross-shore fetch distance (Nordstrom *et al.*, 1996; Jackson and Cooper, 1999) and the fact that on the berm the sand is dry and not subject to crust formation in contrast to the lower-lying back-berm. During offshore winds, the sediment budget of the beach/dune system is negative, with supply to the submerged part of the profile. Aeolian sediment transport on foredunes during offshore winds remains a subject of debate and has been poorly investigated. K.F. Nordstrom *et al.*, (1996) indicate an absence of sand transport around the dune toe while K. Lynch *et al.* (2008) highlight a change in flow direction and a possible reverseal. Nevertheless, both cases investigated involved high dunes (>10 m) which are not directly comparable with the low dune systems of the erosional shores of Camargue.

During onshore wind conditions at the beginning of a storm (fig. 8B), the berm provides the sandy sediment for the back-berm (equilibrium transport) and for the dune foot where accretion occurs. As in the case of offshore winds, a reverse sedimentary situation is observed on the dune from the seaward to the landward face. As water level rises under increasing storm activity (increasing wind speeds and wave heights, and sea-level rise) (fig. 8C), the uprush tops the berm crest, floods the lower-elevation back-berm and, consequently, aeolian sand transport on the beach stops and is restricted to the dune. Water overwashing the berm and flooding the back-berm is only a few centimetres deep, sufficient to completely stop aeolian sediment transport. The particular morphology of the Camargue beaches therefore plays an important role in storm surge propagation and offshore-onshore sediment transport (Aujustinus *et al.*, 1990; Suanes and Provansal, 1993; Bruzzi, 1998).

In order to estimate the shoreface influence on the beach and dune sediment input we used a S4ADW current meter at 3 m water depth throughout the ROUSTY0102 campaign. The data were then computed in the SEDTRANS96 model to estimate hydrodynamic parameters and potential sediment transport (fig. 9). During offshore wind conditions (beginning of the campaign), the sediment transport was significantly reduced ($0.0006 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$) and seldom directed shoreward (obliquity of about 20° from the coastline). Based on these results and on the direct field observations,

we hypothesize that in the shoaling and nearshore zones, the offshore winds (opposed to the onshore wave propagation) reduce wave heights and, thus, the shear current velocity. Even if onshore (oblique) sediment transport from the shoreface seems possible during seaward winds, the measurements on the beach/dune system indicate an offshore movement unfavourable to beach supply. During storms, the sediment transport is effective (maximum: $0.06 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$) (fig. 9D) but is oriented offshore. The bottom of the profile, around 3 m deep, seems to be subject to significant sediment transport only when the waves are around 2 m in height. This value corresponds to the annual wave height return period in the offshore zone. Hypothesised onshore sediment transport due to oscillatory waves is probably concealed by undertow and/or downwelling at this water depth. Consequently, hydrodynamic conditions are not favourable to onshore sediment transport from the shoreface to the beach during storms. Moreover, in the long term (centennial timescale), this process is confirmed by the negative sediment budget of the Rhône delta shoreface suggesting offshore sediment loss (Sabatier *et al.*, 2006).

In order to quantify annual potential sand input or output between the beach/dune systems, the conceptual model of episodic aeolian sediment transport (fig. 8) was extended to obtain a medium-term theoretical sediment transport calculation (Sabatier *et al.*, 2007). This calculation is based on calibrated (Sabatier *et al.*, 2002) equations from Bagnold (1941) into which the phases of beach flooding (no aeolian transport) are integrated. If the storm surges are not considered, the offshore ($34.6 \text{ m}^3\cdot\text{m}^{-1}\cdot\text{yr}^{-1}$) and onshore ($30.3 \text{ m}^3\cdot\text{m}^{-1}\cdot\text{yr}^{-1}$) aeolian sediment transport are balanced. Nevertheless, if the sea surge is integrated, the net offshore balance is twice as important ($10.6 \text{ m}^3\cdot\text{m}^{-1}\cdot\text{yr}^{-1}$), and the sediment budget becomes negative because of a significant reduction in onshore transport ($24.0 \text{ m}^3\cdot\text{m}^{-1}\cdot\text{yr}^{-1}$). This change in sand budget is caused by episodic events, a mere 8% of the time. Sea surges are rare but play an important role in potential onshore sand transport because they occur when the wind is strongest. Rainfall is not integrated because of the lack of data, but the net seaward directed sediment budget is probably higher. We note that these calculated volumes merely indicate an order of magnitude, and are aimed at presenting an overview of the potential aeolian transport feeding the dune systems. However, this approach provides insight into the consequences of beach flooding in a microtidal wave-dominated environment.

The present well-developed dunes on the accretional shores of Camargue also yield insight into the conditions necessary for natural dune formation. The dune fields of Beauduc and Espiguette spits (around 10 m high and 50-200 m wide) are subject to ideal dune forming processes. Firstly, they display a positive sediment budget for both the beach and the shoreface (Sabatier *et al.*, 2006) in relation to the organisation of the littoral drift cells (Sabatier and Suanes, 2003; Sabatier *et al.*, in press). Secondly, because the shoreline is moving seawards, aeolian fetch on the beach is sufficient to supply the dune. Thirdly, due to the general curved shoreline (from west-east to north-south), the wind

angle relative to the beach/dune system is variable and induces aeolian fetch that favours important sand transport (Bauer and Davidson-Arnott, 2002). The dune between Piémanson and the mouth of the Grand Rhône (around 3 m high and 50 m wide) displays a similar scenario because of the positive sediment budget in this area, linked to the littoral drift cell organisation and river sediment input, which assure stability or seaward movement of the shoreline (Suanez and Provansal, 1998; Sabatier and Suanez, 2003). Furthermore, the present positive-budget dunes are located on spits and sand ridges close to a river mouth. Fossil dunes in areas presently undergoing erosion were built under similar conditions (L'Homer *et al.*, 1981; Vella *et al.*, 2005). To conclude, the aeolian fetch and the sediment budget (Psuty, 1992; Hesp, 2002) control dune formation along the Camargue coast. Nevertheless these two crucial parameters are not well established in areas undergoing erosion. A combination of unfavourable wind conditions, a berm and lower-elevation back-berm morphology propitious to beach flooding during onshore winds, and a net offshore sediment transport from the shoreface, signify that the erosional shores of Camargue are not conducive to the formation of large dune systems.

Discussion and Conclusions

The investigated sites have a number of points in common, notably the fact that dunes have resulted from long-term formational processes. For example, this spans the mid- to late Holocene in the case of the North Sea, the Vougot site and Camargue, or merely the 19th century due to human activities as at the St-Trojan site. However, the erosional processes connected to the storms are rapid. Due to the high vulnerability of these coastal features and their socio-economic importance, coastal managers require scientific data to improve dune management strategies. For example, on the north coast of France, the efficiency and impact of sand defence on the beach/dune sediment budget has been demonstrated (Ruz and Meur-Ferrec, 2004; Anthony *et al.*, 2007b; Ruz and Anthony, 2008). On the Camargue coast, new data on the unfavourable climate to dune formation has helped coastal managers. If the future policy is to replace dikes with dunes, coastal managers should provide artificial nourishment for dune formation.

Another common point between the studied sites is the importance of water levels and the submergence of the beach. Water level plays a key role in dune toe erosion and also

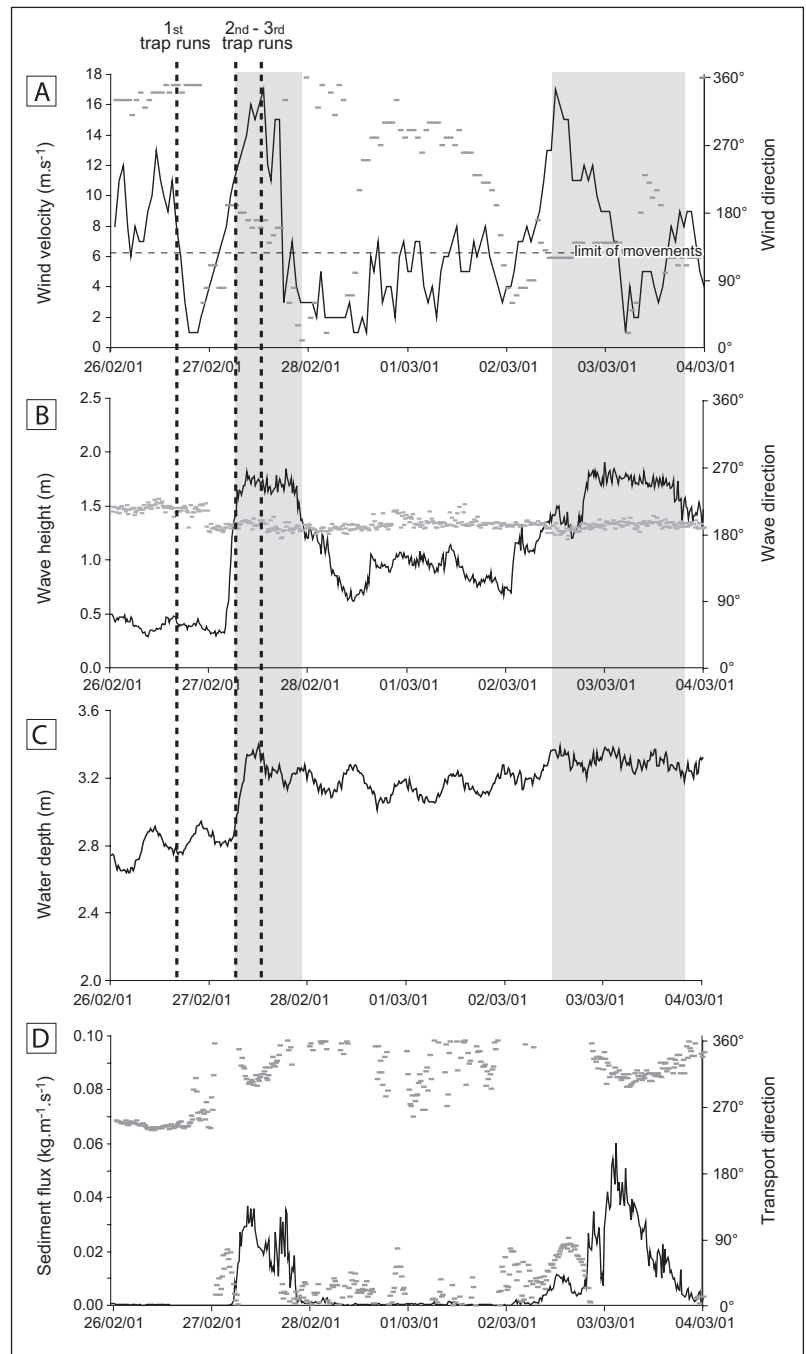


Fig. 9 – Time series of wind and hydrodynamic parameters recorded in 3 m water depth from 26/02/2001 to 04/03/2001. A: wind velocity and direction; B: significant wave height and direction; C: water depth; D: modelled sediment transport and direction based on SEDTRANS96 model. The grey area indicates phases of swash overtopping of the berm crest.

Fig. 9 – Données anémométriques et hydrodynamiques obtenues à 3 m de profondeur entre le 26/02/2001 et le 04/03/2001. A : vitesse et direction du vent ; B : hauteur significative des vagues ; C : profondeur ; D : flux et direction du transport sédimentaire calculé à partir du modèle SEDTRANS96. Les zones grisées représentent les périodes où le jet de rive franchit la berme et inonde la plage.

limits aeolian sand transport on the beach. During storms, the Camargue beaches (berm/back-berm/dune) presents similarities with the beaches of northern France (bar/trough morphology) in terms of aeolian dynamics, with the upper part of the beach being more sensitive to aeolian transport

whilst transport can be absent on the low-lying parts of the beach due to high moisture contents. The major difference is that onshore winds are strongly connected with storms impinging on Camargue's microtidal beaches, whereas these winds are more frequent on the macrotidal beaches of northern France, and are not always linked to storm activity.

During storms, the links between the intensity of the forcing agents (wave energy, run-up) and the morphological response (dune erosion) are not straightforward at all sites. It seems that at the Vougot site, dune erosion phases are well correlated with maximum water level and storm intensity, whilst at Vert-Bois, the analysis indicates that the antecedent beach morphology controls dune erosion more than storm intensity. These two scenarios also exist on some erosive beaches of the North Sea coast of France (Ruz and Meur-Ferec, 2004). This different behaviour between the forcing agent and the morphological response is probably due to the beach/dune morphology of Vougot, which is fairly stable through time; the accretional processes do not significantly modify the shape of the beach (fig. 2), whilst the inter-storm morphology of Vert-Bois is constantly changing (fig. 5) due to aeolian processes and onshore transport of sediments during storm events and calm conditions. These results show that the erosion induced by storms cannot be correctly predicted or modelled if factors such as storm surge, wave set up and others are not accounted for. We also wanted to highlight the role of other parameters, not directly linked with the forcing of each dynamic event. These factors, at the junction between 'high waves – high tide – shoreward winds' and the relationship between storm duration and frequency, with resilience of coastal features, are more difficult to quantify analytically. We suggest that they be summarised as a set of seasonal indicators.

Onshore-offshore sediment transport from the shoreface to the surf zone and the beach were investigated at two sites, in macro- and microtidal environments. Because they are both open and not embayed environments, and associated with relatively mobile sea floor deposits, the hydrodynamic measurements provide a good opportunity for highlighting the influence of tidal currents in onshore-offshore sediment transport. Unexpectedly, net offshore sediment transport dominates at both sites; however, we suggest that the water depths from which sediment may be transported shorewards is more limited on a macrotidal shoreface, such as that bordering the northern coast of France, than in micro- and mesotidal contexts, where weaker tidal currents do not significantly limit cross-shore sediment movements. Short-term hydrodynamic conditions in northern France do not reflect long-term onshore sand movements, presumably because the development of prominent sand banks on the shoreface during the late Holocene progressively modified nearshore hydrodynamics (Anthony, 2002; Anthony and Héquette, 2007). Meanwhile, we found a good relationship between hydrodynamic measurements and long-term shoreface erosion of Camargue. The wave climate presents some similarities between the two sites, because both are fetch-limited. We suggest therefore that the tidal currents should have a large influence on these different behaviours.

Sediment supply to the dunes generally occurs during spring and summer at all sites. Along the eroded shores of Camargue, the pattern is different because onshore winds occur during autumn and winter, whereas offshore winds are dominant in summer. Our collective research therefore demonstrates that the traditional conceptual model of 'dune erosion during winter and dune recovery during summer' (Komar, 1976) cannot be universally applied to all beaches. In the same way, it is possible to classify the studied sites in the conceptual models of Psuty (1992) and/or Hesp (2002). However, these models do not take into account the role of the antecedent beach morphology, and the cross-shore variability of this morphology on beach/dune morphodynamics. This is not to say that these conceptual models are devoid of interest but rather that the site comparison presented in this paper highlights the importance of micro-scale processes on the beach/dune sediment budget. Furthermore, these conceptual models assume that several process-response parameters remain constant through time, which is obviously not the case in nature (Sherman, 1995). Finally, at each site, the ongoing research into beach/dune behaviour proposed by French coastal geomorphologists underlines the need for carrying out investigations at different timescales. The objective is to study the beach/dune system using several methods (profiles, aerial photographs, sedimentology, in situ wind and current measurements, sand traps etc.) and at various temporal scales. This approach is still being developed in the literature and remains the only way to improve knowledge of the coastal processes and interactions (Stive *et al.*, 2002). Even if these theoretical links are difficult to substantiate (Sherman, 1995; Lynch *et al.*, 2008), they should be an important focus of future research by coastal geomorphologists.

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