Geomorphology 199 (2013) 8–21

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Storms, shoreface morphodynamics, sand supply, and the accretion and erosion of coastal dune barriers in the southern North Sea

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ARTICLE INFO

Article history:
Received 9 November 2011
Received in revised form 17 May 2012
Accepted 6 June 2012
Available online 16 June 2012

Keywords:
Storms
Shoreface
Tidal banks
Sand supply
Coastal dunes
North Sea

ABSTRACT

The coast of the southern North Sea is bound by dune barriers that have developed adjacent to a shallow storm- and tide-dominated shoreface comprising numerous shore-parallel to sub-shore-parallel tidal sand banks. The banks evolve under the joint control of tide-, wave- and wind-induced shore-parallel currents, which tend to 'stretch' them, eventually leading to bank division, and to shoaling and breaking storm waves, which tend to drive them ashore. The banks, thus, modulate the delivery of storm wave energy to the coast, redirect currents alongshore and are the sand sources for the accretion of coastal dunes. Foredune accretion occurs where major sand banks have migrated shoreward over the last centuries to be finally driven ashore and weld under the impact of storm waves. Morphological changes in the bank field can impact on shoreline stability through dissipation or enhanced shoreward transmission of storm wave energy and effects on radiation stress, particularly when waves are breaking over the banks. Where banks are close to the shore, mitigation of offshore sediment transport, especially during storms, can occur because of gradients in radiation stress generated by the complex 3D bank structure. These macro-scale mechanisms involve embedded meso-scale interactions that revolve around the mobility of sand waves, mobility of beach bars and troughs and foredune mobility, and micro-scale processes of bedform mobility in the subaqueous and intertidal domains, and of swash and aeolian beach–dune sand transport. These embedded interactions and the morphodynamic feedback loops illustrate the importance of synchroneity of sand transport from shoreface to dune on this coast.

Large stretches of the foredunes show either signs of stability, or mild but chronic erosion. Furthermore, a demonstrated lack of a clear relationship occurs between storminess and coastal response over the second half of the 20th century. The present situation may be indicative of conditions of rather limited sand supply from offshore, notwithstanding the abundance of sand on the nearby shallow shoreface, except in areas where a nearshore storm-driven tidal sand bank has become shore-attached. Apart from the important influence of shoreface sand banks and of wave–bank interactions, foredune accretion and erosion also depend on various context controls that include individual storm characteristics, wind speed and incidence relative to the shore, tidal stage during storms, and direct human intervention on the shore through foredune and beach management. The bewildering variability inherent in these intricately related parameters may also explain the poor relationship between storminess and barrier shoreline change and will still continue to render unpredictable the response of shores to individual storms.

1. Introduction

Storm effects on coastal sand barriers have received wide attention, in part because of increasing human occupation of storm-exposed coasts. Much of the literature has focussed on hurricane impacts on the North American coast (e.g., Morton, 2002; Stone et al., 2004; Zhang et al., 2005; Sallenger et al., 2006; Wang et al., 2006; Claudino-Sales et al., 2008; Houser et al., 2008), especially on the low-lying Atlantic seaboard where the transgressive history of much of the coast renders storm impacts pervasive (Forbes et al., 2004). In Europe, efforts have focussed on the various modes of coastal response to storms in a context of marked morphological variability, and have included work by Cooper et al. (2004), Regnauld et al. (2004), Ferreira (2006), Mendoza and Jiménez (2006), Ciavola et al. (2007), Chaverot et al. (2008), Sabatier et al. (2009), Gervais et al. (2012), Haerens et al. (2012), and Suanez et al. (2012). These efforts clearly show that the conceptual framework and capacity for accurate prediction of storm-induced coastal change remain incomplete (Forbes et al., 2004). The precise response of a coastal stretch to each storm event depends on numerous inter-related parameters. Whereas coastal erosion is a common but not exclusive result of storms, interactions between storms and the shoreline are complex. This complexity is inherent to the functional

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doi:10.1016/j.geomorph.2012.06.007

mechanism of storms, which includes various parameters such as air pressure, mean water level, wind speed, wind direction relative to the coast, and waves (e.g., Betts et al., 2004; Backstrom et al., 2008, 2009; Haerens et al., 2012). Coastal response to storms is also complex, because it is controlled by multiple factors related to incident storm characteristics and to coastal and shoreface morphology and sediment supply. These latter factors integrate a longer-term perspective on storm impacts on the coast.

Of course, a commonly strong link exists between the beach and the shoreface in terms of sediment exchanges induced by storms, although Houser (2009) has recently pointed out the insufficiencies in recognizing this synchroneity. Although coastal erosion is a common outcome of storms, storms may also rework sediment onto the beach, thus, generating accretion. For example, on the Atlantic coast of the US, northeast storms produce downwelling that results in offshore-directed sediment transport, whereas upwelling created by southwest storms results in onshore-directed sediment transport (Wright et al., 1994; Hill et al., 2004). Stone et al. (2004) also showed that barrier islands can conserve mass during catastrophic cyclones, and that less severe cyclones and tropical storms can promote rapid dune aggradation and can contribute sediment to the entire barrier system.

Whereas the general link between storms and the response of sand barrier shorelines has been recognised in the literature, the role of shoreface modulation of storm impacts on the shore has received much less attention. Among the few studies having shown that the morphology of the shoreface can strongly influence coastal response to storms and sediment dispersal on the shoreface are those of Field and Roy (1984), Hequette et al. (2001), and Backstrom et al. (2008, 2009). In this paper, the morphological response of a dune barrier coast in a storm-dominated macrotidal setting on the southern coast of the North Sea is examined with reference to storm impacts at long (order of decades) to short (order of years) timescales. The morphodynamic connections between storms and barrier shoreline response and the embedded macro-, meso- and micro-scale levels of interaction are reviewed. The essential role of storms in patterns of shoreline change comes out as being strongly influenced by the conditions prevailing on the inner shoreface.

2. The southern North Sea barrier and shoreface system

2.1. Barrier and shoreface morphology

The North Sea coast of France from Cape Gris Nez to Belgium (Fig. 1) comprises two sand barriers, respectively, in Wissant Bay between Capes Gris Nez and Blanc Nez, and from Cape Blanc Nez along the southern North Sea as far as the Netherlands (Fig. 1). Each barrier consists of two to three generations of sub-shore-parallel dunes 100 to 600 m wide and with a maximum inland height of 25 m, impounding former tidal embayments. The barrier foredune is associated with beaches exhibiting multiple bar-trough (ridge-and-runnel) couplets that are widely exposed at low tide. The Wissant Bay barrier comprises variably eroding or accreting foredune sectors. The barrier stretching from Cape Blanc Nez to the Netherlands bounds the empoldered North Sea coastal plain, large parts of which lie below sea level, and face risks of flooding from storms. Large stretches of this latter barrier have been massively transformed or obliterated by urban and port development. The foredunes in both barrier sectors exhibit blowouts and deflation corridors.

The gently sloping shallow shoreface, extending seaward of the beach bars and troughs, is characterised by an important field of prominent tidal sand banks and ridges (Fig. 1). The bank field off the coasts of France and Belgium, which forms the Flemish Banks complex, is particularly well developed as the narrow Dover Strait opens up on the epicontinental southern North Sea. These banks are several kilometres long and have heights of up to 10 m. The crests of sand banks closest to the shoreline lie at depths of less than 5 m below the mean low water line (Fig. 1). They practically impinge on the beach in places. These elongated sand bodies are commonly oriented WSW–ENE, roughly parallel to sub-parallel to the coastline. Sediment distribution in the bank field is strongly related to the bathymetry, with fine to coarse sand in the interbank troughs, whereas

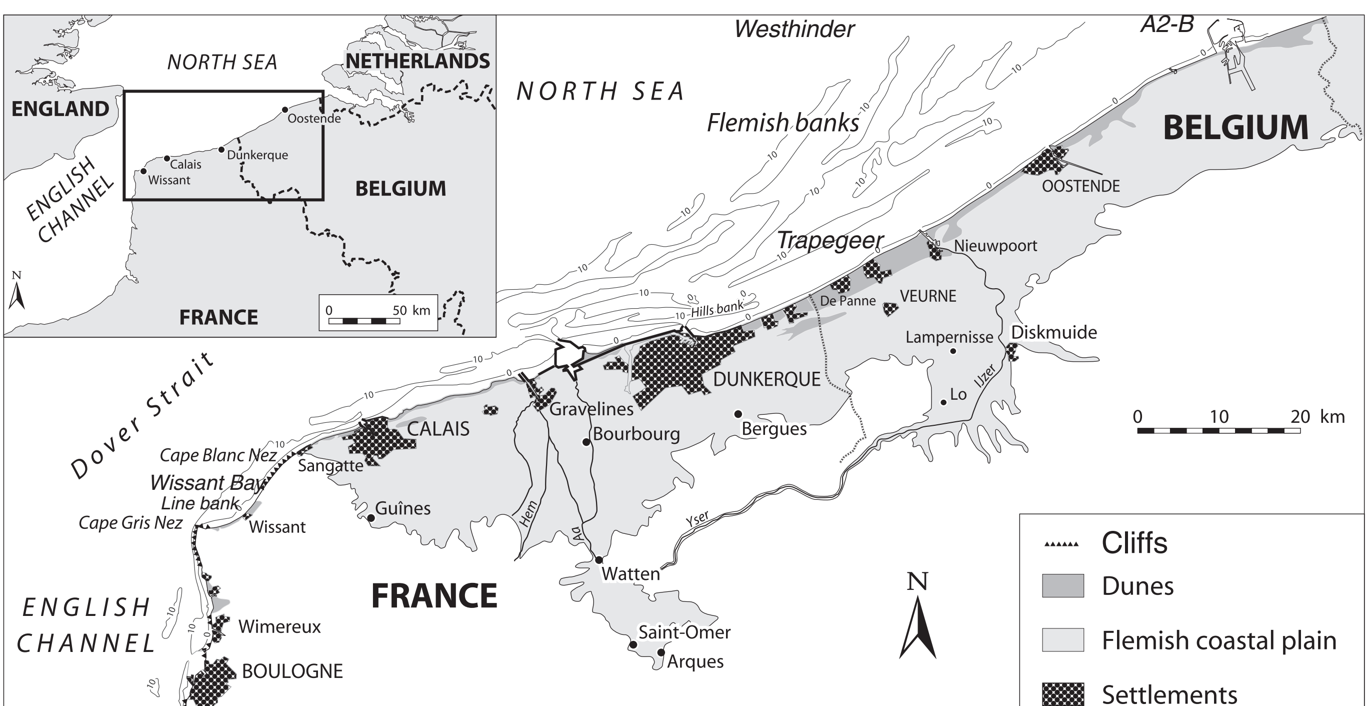

Fig. 1. The dune barriers and shallow shoreface of the southern North Sea. Bathymetric contours are from Augris et al. (1995).