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Development of large nebkhas along an accreting macrotidal coastline, Northern France

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ABSTRACT

Very large isolated nebkhas, up to 4 m high and 14 m wide, have developed on the upper beach of a several hundred meters wide foreshore on the French coast of the Dover Strait. This macrotidal shoreline is characterized by abundant sediment supply from the shoreface related to the onshore welding of a nearshore sand bank. Continuing beach accretion provided the conditions for rapid seaward development of incipient foredunes. The nebkhas developed on the uppermost beach, slightly above the highest astronomical tide limit, forming hemispheric to oval-shaped mounds only reached by spring tides and/or storm surges. They do not form an incipient foredune zone, but mounds that grew vertically and remained in the form of isolated huge nebkhas disconnected from the incipient foredune zone by a swale. The nebkhas consist of scattered landforms that do not impede aeolian accretion landward in the incipient foredune zone where the maximum accretion rates were recorded. The distribution of such large coastal nebkhas is probably limited in beach environments since the descriptions of similar examples of aeolian coastal landforms are virtually absent in the scientific literature, suggesting that they are presumably restricted to low gradient macrotidal beaches associated with an excess of sand supply.

1. Introduction

Sandy beaches offer an exposed source of sediment and so most sandy beaches are fringed by some form of sand dune formed by sand transported by wind and deposited landward of the beach (Davidson-Arnott, 2010; Martinez and Psuty, 2004). Dunes of various size and morphology can be found depending on sediment supply, dominant wind velocity and direction, moisture and vegetation cover, but also on the geomorphology of the nearshore and intertidal beach (Houser and Ellis, 2013). Immediately landward of the active beach, incipient foredunes, which are also called embryo dunes by some authors (e.g., Davidson-Arnott, 2010), commonly develop, consisting of low dunes forming by aeolian sand accumulation in areas covered by pioneer plant communities (Hesp, 2002, 2012). Their formation is due to the presence of some roughness elements on the backshore that reduce wind flow velocity, resulting in sediment deposition. On beaches, the debris that accumulate at the drift line efficiently increase surface roughness, favouring the deposition of aeolian sand, but the formation of incipient dunes essentially takes place above the high tide limit where vegetation is the most common roughness element that initiates their formation. According to Hesp (1984, 1989), their morphological development depends on plant species, density, height and cover, as well as wind speed, rates of sand transport, and beach progradation rates. In their early stage of development, incipient foredunes may form nebkhas, often with attendant shadow dunes (Hesp, 1981). Nebkhas (also called nabkhas, coppice dunes, dune mounds) form isolated hummocks, and are common features in many aeolian settings (Melton, 1940; Hesp, 2011). They are sometimes considered as a distinct dune type (Pye and Tsoar, 1990; Nickling and Wolfe, 1994; Lancaster, 1995; Hesp and McLachlan, 2000). They usually develop as a result of the deposition of wind-driven sediments around shrubs in arid and semi-arid regions (Cooke et al., 1993). Nebkhas differ from shadow dunes that develop as a result of sediment deposition in the lee of an obstacle (Bagnold, 1941; Hesp, 1981). Nebkhas are also very common features along sandy coastlines (Hesp, 2011). They are found in arid and semi-arid coastal environments (Khalaf et al., 1995; Langford, 2000; El-Bana et al., 2007; Ardon et al., 2009; Khalaf and Al-Awadhi, 2012; Hernandez-Cordero et al., 2015) as well as in temperate (Hesp and Walker, 2013), cool temperate humid (Mountney and Russell, 2006) and cold environments (Ruz and Hesp, 2014). They can develop at various locations, from the upper beach to low backbarrier areas (Carter et al., 1992), although nebkhas can also form in interdune areas or in the slacks of active dunes (Hesp

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and McLachlan, 2000). However, they usually develop on the backshore on swash-aligned drift material or on storm debris lines, through alongshore growth of pioneer plant seedlings and/or by rhizome growth, forming a quasi-continuous line of low (50–100 cm high) vegetated mounds (Hesp, 1989).

The shape and size of coastal nebkhas is variable. Along the arid coastal plain of Kuwait for example, the nebkha height varies between 0.4 and 1.2 m on average (Khalaf and Al-Awadhi, 2012). Nebkhas developing in temperate environments are usually forming discrete hummocks that are typically 0.2–0.5 m to 1–2 m in *height* (Davidson-Arnott, 2010; Montreuil et al., 2013). In cool humid coastal environments, as along the southern coastline of Iceland, an extensive nebkha field developed, with individual nebkha up to 2 m high (Mountney and Russell, 2006). Small nebkhas, 0.5–1 m high are also found along arctic coastlines (Ruz and Hesp, 2014).

Incipient foredunes can be ephemeral features that can be partly or completely eroded during storm events, especially when they develop near the high tide limit. They may also withstand storms if they are high enough above high spring tide limit where they represent the initial stage of foredune development. Foredunes (incipient and established) are dependent aeolian landforms, linked to beach and nearshore processes and are sometimes considered as the only distinctive coastal dune forms (Bauer and Sherman, 1999), where real dune formation can begin (Arens, 1996). According to Hesp (2002), all other factors being equal, large foredunes are more frequent on dissipative beaches, which are characterized by wide foreshore and maximum potential sediment supply. Macrotidal sandy beaches, with a wide wind-exposed foreshore at low tide, are also thought to represent optimal conditions for the development of coastal dunes (King, 1972; Carter, 1988). Well-developed coastal foredunes are thus common along low-gradient macrotidal beaches (Battiau-Queney et al., 2001; Anthony et al., 2006, 2009; Pye and Blott, 2008; Montreuil et al., 2013). This is particularly the case on the northern coast of France where nebkha of substantial size have developed seaward of the foredune along a prograding macrotidal foreshore of the southern Dover Strait. In this paper, we report on the formation and evolution of isolated huge nebkhas that appear to be uncommon for seawardmost dunes and we try to determine the conditions leading to their development.

2. Study area

The French North Sea coastline is a 55 km long almost continuous sand beach barrier extending from the Cap Blanc Nez chalk cliff to the Belgium border, facing the eastern English Channel and the southern North Sea (Fig. 1). The coast essentially consists of wide and gently sloping sandy beaches with multiple intertidal bars (Anthony et al., 2005; Reichmüth and Anthony, 2007) backed by coastal dunes that commonly exceed 10 m high and reach up to 25 m in places (Battiau-Queney et al., 2001; Ruz et al., 2005). The dunes merge with the French coastal plain that extends 10–20 km landward. The coastal plain is a low-lying reclaimed land with mean elevation of 2 m above mean sea level. Based on historical records (old topographic and hydrographic maps), this area experienced shoreline progradation since at least the 14th century (Briquet, 1930). As the shoreline prograded seaward, dikes were erected in order to gain new farm lands. Nowadays, coastal dunes and dikes are the only protection against marine flooding.

The study area consists of a 350–500 m wide beach at low tide, east of Calais (Fig. 1), comprising a series of intertidal bars and an upper beach platform bounded landward by coastal dunes. The coastal dunes bound a salt marsh that has been largely modified by humans, with the excavation of numerous hunting ponds (Fig. 1). Eastward, the intertidal zone forms a protruding and extensive sandflat. The beach and sandflat exhibit large variability in surface sediment size, depending on morphology, elevation and exposure to waves. The intertidal bars and troughs are composed of well-sorted fine to medium sand (mean grain size: 0.2–0.33 mm), while the upper beach sandflat mainly consists of fine sand (mean grain size: 0.23 mm). The coastal dunes in the backshore are composed of fine to medium sand (mean grain size: 0.17–0.31 mm).

Offshore, tidal sand banks are widespread across the nearshore zone and the inner shelf where they form extensive linear sand bodies sub-parallel to the shoreline (Augris et al., 1990; Beck et al., 1991). Nearshore tidal sand banks have been migrating alongshore and/or onshore for centuries. Immediately east of Calais, a sand bank called "banc Braseux", parallel to the shoreline, merged to the shore during the 16th century (Briquet, 1930), which resulted in the formation of a convex-shaped sand platform protruding seaward (Fig. 1). During the 19th and 20th centuries, the Ridens de la Rade, a shallow 13 km long and 1.4 km wide sand bank (Fig. 1), migrated alongshore and onshore and became eventually attached to the shore (Augris and Clabaut, 2001). Comparison of bathymetric charts revealed that this shore-attached sand bank grew up to about 100×10^6 m^3 during the 20th century (Héquette and Aernouts, 2010), forming an extensive sub-tidal sand source for the development of the intertidal sandflat and coastal dunes in the backshore (Anthony, 2013; Anthony et al., 2006), therefore favouring shoreline progradation.

Except for episodic storm events, the coast is exposed to low-energy waves. The dominant winds are from west to southwest, with a secondary wind direction from north to northeast (Fig. 1). Winds are usually moderate, with more than 45% of winds having a mean velocity of less than 5 m/s; strongest winds ($\geqslant$16 m/s) occur only 0.06% of the time. Associated with this wind regime, waves predominantly come from the English Channel with a direction from southwest to west, followed by waves generated in the North Sea from the north to northeast. Modal significant wave height is less than 1 m with wave periods typically ranging from 4 to 8 s, but maximum wave height may episodically exceed 5 m with periods of 9 to 10 s during major storms (http://candhis.cetmef.developpement-durable.gouv.fr/campagne/). Wave heights are significantly lower at the coast, due to significant shoaling and energy dissipation over the offshore sand banks, resulting in wave heights that hardly exceed 1 m in the intertidal zone even during storms (Sedrati and Anthony, 2007; Héquette and Cartier, 2016).

The tidal regime in the region is semi-diurnal and is characterized by a large tidal range that increases from the North Sea to the English Channel, the tidal amplitude reaching 6.5 m at Calais during spring tides. Due to this large tidal range and current funnelling through the Dover Strait, tidal currents are powerful along the northern coast of France, reaching near-surface velocities of 1.5 m s^{-1} during flood and 1.35 m s^{-1} during ebb in the narrow channels of the nearshore sand banks (Augris et al., 1990). Tidal currents flow almost parallel to the shoreline, with flood currents directed to the east-northeast and ebb currents to the west–southwest. Because the dominant waves come from the southwest and the tidal currents asymmetry is flood-dominated, net sediment transport on the shoreface and on the foreshore is directed to the east-northeast (Héquette et al., 2008; Cartier and Héquette, 2015).

3. Methodology

The evolution of coastal dunes was based on the comparison of orthorectified vertical aerial photographs (years 1963, 1983, 2000 and 2012) and georeferenced and rectified aerial photographs