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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 $100 \times 10^6\,m^3$ 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

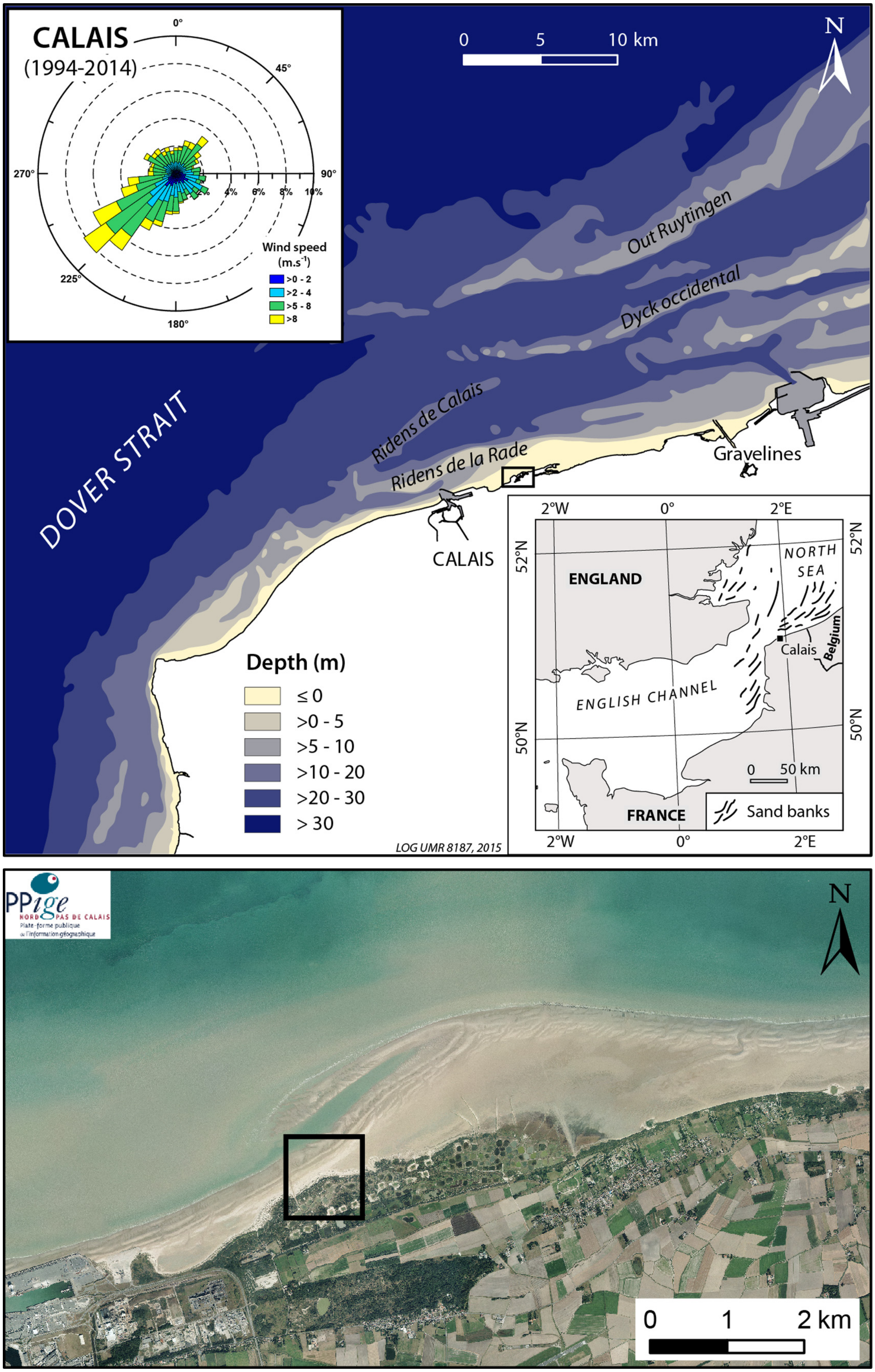

Fig. 1. Location map of the study area. The inset on the aerial photograph shows the location of the investigated coastal dunes. Wind rose diagram based on three-hourly mean wind speed and direction from the Météo-France station in Calais.

(years 1938, 1949, 1957, 1961, 1965, 1969, 1970, 1972, 1975, 1977, 1980, 1982, 1986, 1988, 1989, 1992, 1993, 1997, 2005 and 2009), which were used for carrying out detailed geomorphological evolution of coastal dunes from stereo-pairs of aerial photographs. The error range of the orthorectified aerial photographs is ±2 m.

High-resolution topographic data of the foreshore, upper beach and coastal dunes were obtained from airborne LiDAR surveys realised in 2011 (03/21/2011) and 2014 (01/18/2014). The data were obtained with a Leica ALS60 LiDAR system that acquired topographic data with a density of 1.2–1.4 points/m^2. The LiDAR operating system was combined with real time kinematic DGPS and inertial motion unit, ensuring a planimetric precision of less than 0.5 m. The position accuracy of the LiDAR data points ranged from ±0.10 to 0.17 m with a vertical accuracy less than ±0.10 m as verified with several ground control points using a very high resolution differential GPS (Leica TPS Syst1200). However, vertical error can easily increase to ±0.25 m or even more in areas covered by dense vegetation (Saye et al., 2005). The LiDAR topographic data were therefore filtered to remove vegetation and other objects above ground surface. Digital Terrain Models (DTM) were created from the filtered data using Golden Software Surfer™. The different DTMs were then used to calculate volume changes between each LiDAR survey. The DTMs were obtained using linear Delaunay triangulation interpolation, which resulted in a grid with a 1 m resolution. According to previous work on the spatial characterization and volume calculation of coastal dunes using LiDAR topographic data, a grid cell resolution of 1 m^2 provides reliable representation of topography and accurate volumetric measurements in coastal dunes (Woolard and Colby, 2002).

Observed and predicted hourly water levels at Calais were obtained from the SHOM (*Service Hydrographique et Océanographique de la Marine*). Water level data were analysed to determine the periods of time during which high water levels could reach the toe of the investigated coastal dunes. Tri-hourly and hourly wind data were obtained from Météo-France for the period 1994–1999 (tri-hourly data) and 2000–2014 (hourly data) to assess efficient winds for potential aeolian sand transport.

4. Results

4.1. Development of sandy islets and shoreline advance

On the 1938, 1949 and 1957 aerial photos, three sandy "islets", 190–360 m long and 150–210 m wide, detached from the main shore, are clearly visible on the upper beach platform (Fig. 2). In 1938, these islets were poorly vegetated and were separated from each other by channels, and from the main shoreline by a wet upper beach 110 m wide, indicating tidal incursion around and past them at high tide. The main shoreline consisted of low vegetated coastal dunes, with a hummocky topography, and to landwards, reclaimed salt marshes backed against a dike erected in 1773 (Taaf dike). In 1957, the sandy islets were still disconnected, but appeared more vegetated and partially covered by low coastal dunes (Fig. 2). According to Briquet (1930), coastal dunes in this area were not continuous, but formed an archipelago of small sandy islands separated by narrow channels and spaced one hundred metres or more apart (Briquet, 1930, p. 298). In his description of the shoreline in ca. 1920–1925, Briquet (1930) called these coastal dunes, developed at the uppermost tide level, "insular dunes" as they formed isolated features, detached from the main foredune and surrounded by the sea during spring tides. It is likely that the three islets visible on the 1938 aerial photographs correspond to these "insular dunes" described by Briquet. In 1938, only three large sandy islets and four small ones were present along this section of the coastline.

Between 1963 and 1993, these islets were progressively integrated to the main shore (Fig. 3). In 1963, they were separated by channels, but by 1972, the two eastern ones were clustered together, and only a pathway to the beach remained (Fig. 3). The density of vegetation cover, likely marram grass and shrubs, increased during this time period. Dune morphology was chaotic, but hemispheric mounds are discernible on the 1963 aerial photo, especially on the western islet. Behind, hunting ponds were dredged and connected to the sea by a channel which was artificially excavated in order to maintain seawater incursion in the ponds. By 1986, the connected sandy islets formed the new shoreline (Fig. 3), resulting in a shoreline advance of 320 m since 1938. Incipient coastal dunes progressively developed on the upper beach and the "older" dunes were covered by shrubs. This was followed by the development of an established foredune visible on the 1993 aerial photo. The 1993 aerial photographs also shows that a new incipient foredune, with a hummocky topography, developed seaward of the established foredune, resulting in continuing shoreline progradation.

4.2. Formation of large isolated nebkhas

By 1986, a few discrete, scattered, bare, circular sandy hummocks, developed on the upper beach, 45–50 m seaward of the incipient foredunes (Fig. 3). By 1993, most of them had disappeared, but in 1997, a dozen of roughly circular sand patches, 13–40 m long and 10–28 m wide were visible (Fig. 4). They were separated from the incipient foredune zone by a bare sand area 35–65 m wide. By 2000, a series of nascent nebkhas had developed. To the east, two lines of nebkhas developed. A first line of 5 nebkhas was close to the incipient foredune zone, while the seaward most nebkhas were located 30–50 m from the incipient foredune zone. In 2001 the nebkhas were partially vegetated and most of them were 1–1.5 m high, the highest ones reaching an elevation up to 2 m (Tékin, 2004). By 2005, they formed well developed isolated nebkhas, still disconnected from the incipient foredune zone (Fig. 4). On the aerial photo of 2005 (Fig. 4), the wet sand surface

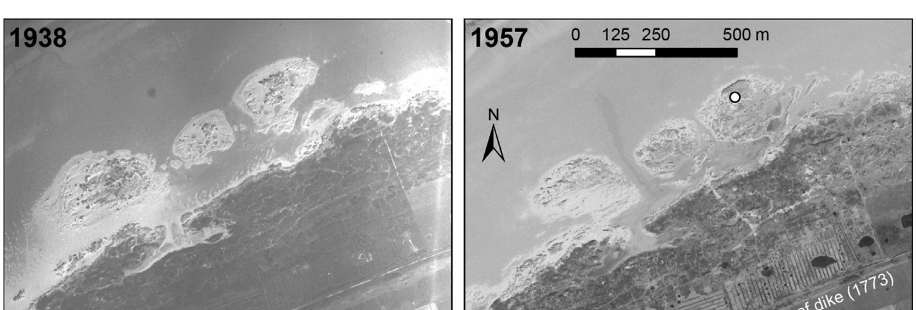

Fig. 2. 1938 and 1957 aerial photographs showing the evolution of sandy islets on the upper beach east of Calais. The white circle corresponds to the location of a Second World War blockhouse.

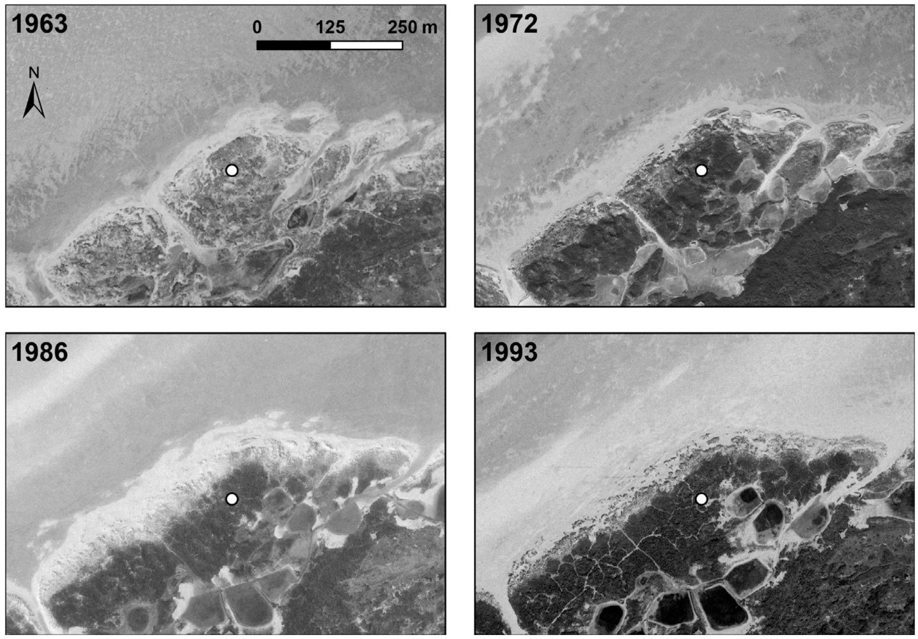

Fig. 3. Series of aerial photographs from 1963 to 1993 showing the progressive merging of the sandy islets that resulted in shoreline advance. The white circle corresponds to the location of the Second World War blockhouse shown on Fig. 2.

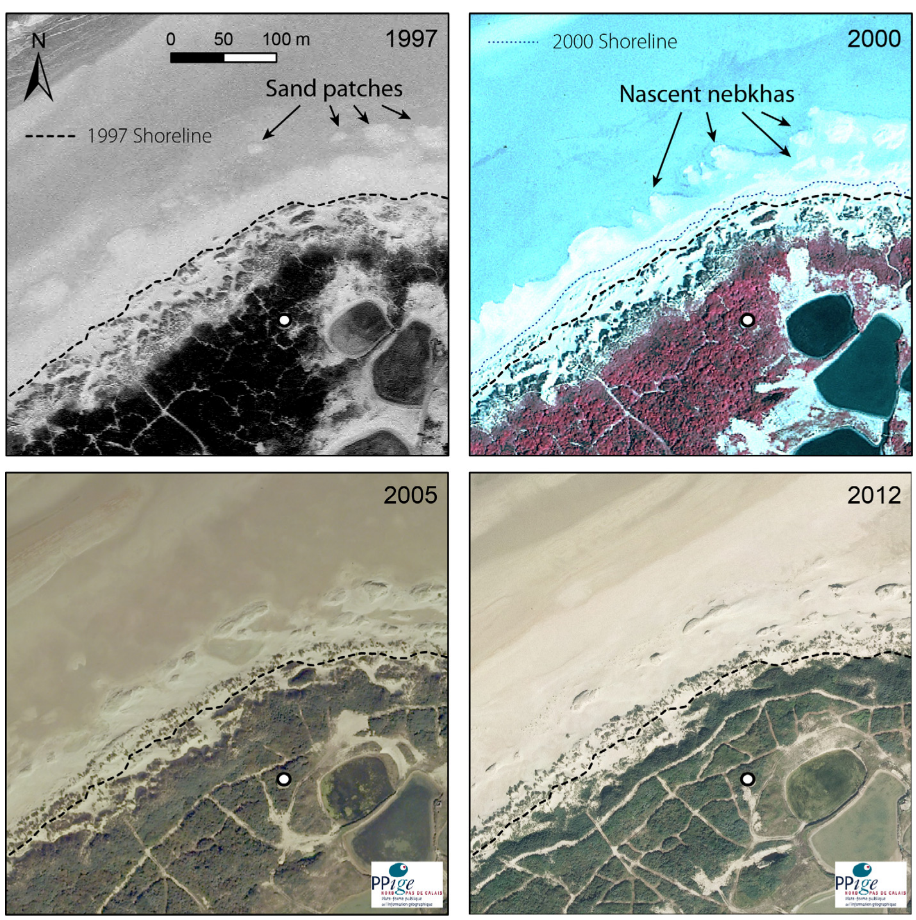

Fig. 4. Series of aerial photographs from 1997 to 2012 showing the development of large nebkhas on the upper beach and seaward expansion of the incipient foredune zone. Note the inland position of the Second World War blockhouse shown on Figs. 2 and 3 (white circle), evidencing significant seaward shoreline displacement since the 1950s.

between the nebkhas and the incipient foredune zone indicates they were episodically surrounded by water during high tides.

While the nebkhas formed, an incipient foredune zone developed at the toe of the established foredune (Fig. 4). In 1997, the incipient foredune was characterized by a hummocky topography, with scattered well vegetated hummocks. Between 1997 and 2000, the incipient foredune zone developed seaward, due to significant sand accumulation resulting in a shoreline advance of 20 m on average (Fig. 4). Incipient dunes grew in size and linked up and by 2005 they were forming a shore-parallel partially vegetated foredune zone. Only very few changes occurred between 2005 and 2012 and the shoreline remained fairly stable. During the whole period, between 1997 and 2012, the interdune area between the nebkhas and the incipient foredune zone remained devoid of vegetation. The analysis of aerial photographs revealed that the incipient foredune zone developed seaward at the expanse of the swale between the nebkhas and the advancing incipient foredunes (Fig. 4).

Presently, an established foredune, 10 to 15.5 m high, is anchored by shrubs (*Hippophae rhamnoides*, common sea-buckthorn) and is fronted by a hummocky incipient foredune zone up to 10 m above French topographic datum (IGN69), partially colonized by *Ammophila arenaria*. Both established and incipient foredunes are lower in the eastern part of the studied area. Eight very large nebkhas, parallel to the incipient foredune, are located 20–40 m seaward of the main shoreline (seaward limit of the incipient foredune zone). Their seaward toe is slightly above the highest astronomical tide elevation (Fig. 5).

Most of them have a height of 2–3 m (Table 1) and are located at the landward limit of a 20–30 m wide, low gradient, upper beach (slope of 1.0–1.3% between the MHWS and the HAT level). The largest nebkha is 4 m high, 52.5 m long and 10 m wide. This particularly long nebkha results from the coalescence of two individual nebkhas. The variation in the size and the shape of the nebkhas over a short distance may be related to the time of initiation of each individual nebkha, but also to their coalescence during their subsequent development. These scattered nebkhas, aligned along the uppermost tidal level on the very upper beach, form hemispheric to oval-shaped mounds only reached by spring tides and/or storm surges (Fig. 6). They do not form an incipient foredune zone, but mounds that grew vertically and have remained in the form of isolated huge nebkhas.

On the upper beach, some poorly developed nebkhas are still forming today, which are commonly observed in areas of extensive shell pavements (Fig. 7). Such shell pavements, covering the beach, limit sediment transport (Carter, 1976) and it is also difficult for plants to establish in dense shell lags (Davidson-Arnott and Law, 1990). Surface shell lags also likely limit the development of pioneer species all along the wrack line. Wind driven fine sand preferentially accumulates around clumps of vegetation (*Elymus farctus*),

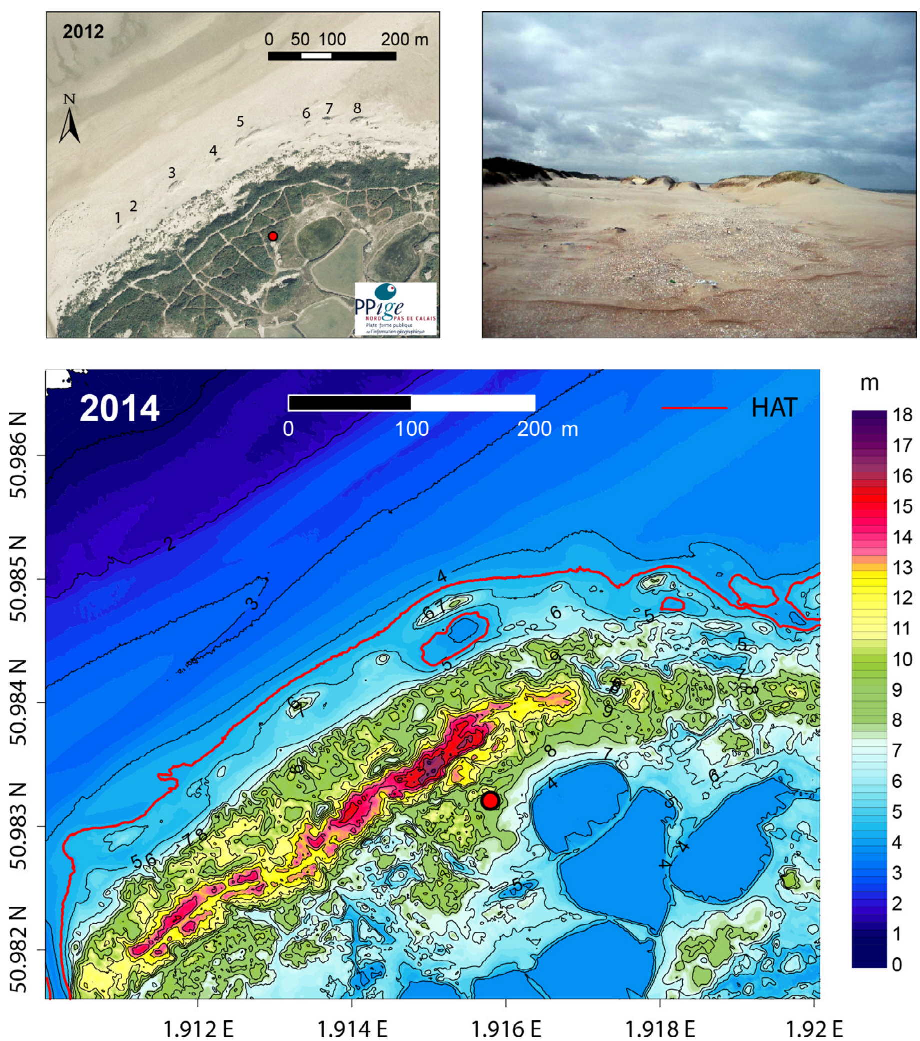

Fig. 5. Vertical aerial photograph (upper left), ground photograph (upper right), and Digital Terrain Model of the study area based on airborne LiDAR topographic data (bottom map) showing large nebkhas on the upper beach. The red circle corresponds to the location of the Second World War blockhouse shown on Figs. 2–4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Morphological parameters of the nebkhas. The location of each nebkha is shown on Fig. 5. The main shoreline corresponds to the seaward limit of the incipient foredune zone.

Nebkha No.	Length (m)	Width (m)	Height (m)	Distance from main shoreline (m)
1	14	8	1.9	19.5
2	9.7	8.7	1.8	19.4
3	32.2	12	3.5	24
4	13.8	11	2.6	28
5	52.5	10	4	40
6	15.3	9.5	1.8	36
7	17.5	9	3.2	32
8	31.5	14.5	3.6	22

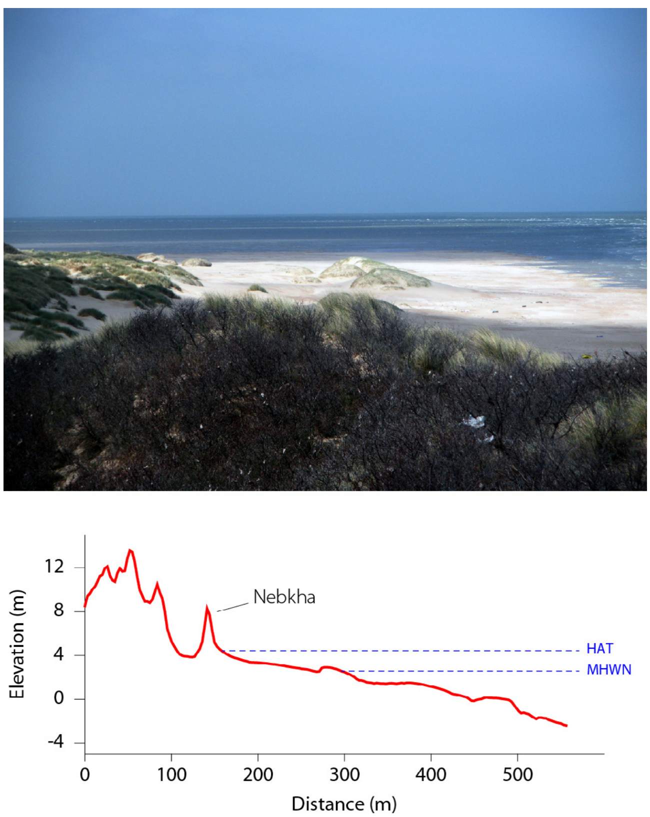

Fig. 6. Photograph showing the presence of large nebkhas on the upper beach and typical cross-shore profile of the beach and coastal dunes east of Calais (based on LiDAR topographic data acquired in January 2014).

Fig. 7. Low nebkha surrounded by shell pavements on the upper beach east of Calais.

resulting in the formation of circular low-elevated incipient nebkhas (Fig. 7). *Elymus farctus* (sand couch-grass) is a perennial pioneer, salt-tolerant, strand species. It is a rhizomatous plant spreading outwards by means of long and wiry underground stems. By putting up vertical sympodial branches as a result of repeated tillering, *Elymus farctus* can keep pace with rapid though modest accumulation of sand (Nicholson, 1952). Once the plant starts catching sand, its root system begins to develop a network of deep roots with side branches. To prevent being buried by the sand, the plant is continually growing. This plant, with culms 20–60 cm, can germinate (either by seedling or from rhizome fragments) in accumulations of organic tidal litter or directly on the beach and can survive seawater inundation. When *Elymus farctus* germinates, windblown sand preferentially accumulates around clumps of vegetation. A discrete, semi-circular, convex dome is typically formed (Fig. 7). Then, they progressively grow up and enlarge, forming nebkhas. Although most of the nebkhas are exclusively colonised by *Elymus farctus*, some well-developed ones have clumps of *Ammophila arenaria* on their crest.

Located near the highest water level limit, they are episodically surrounded by seawater during wind-induced and/or barometric surges. When developing, the seaward most ones can be episodically eroded during storm events. Nebkhas are mainly parallel to southwesterly dominant winds and most of them have an elongated shape. However, depending on wind direction, nebkha morphology can change (Fig. 8). Under strong dominant winds from the southwest, parallel to the beach, they have a tail parallel to the prevailing wind direction (240°) (Fig. 8A). Under direct onshore winds, their stoss side can be eroded and sand preferentially accumulates on their landward side (Fig. 8B). Most of the nebkhas have steep flanks, inclined up to 50° and can be steepened on their seaward side in response to episodic wave scarping.

4.3. The influence of hydro-meteorological conditions on the evolution of nebkhas and incipient foredune zone

The analysis of hourly uppermost water levels recorded in Calais harbour (Fig. 9) reveals that between 1993 and 2012, uppermost water levels reaching the nebkhas occurred only 15 times, less than once a year on average. The very low occurrence of extreme water levels between 1996 and 2000 may have also favored nebkhas and incipient foredune zone development. In 2013, however, 9 very high water levels were recorded, during two major storm events. A first storm, the Godehart storm, from 3 to 6 November 2013, was characterized by strong southwest winds, with instantaneous wind speed exceeding 21 m/s. A surge of 0.63 m at high tide resulted in water levels up to 8.08 m above HD (4.54 m IGN 69) on November 3, 2013.

A second storm, Xaver storm, struck northern Europe in December 2013 (Masselink et al., 2016). Strong northwest winds, low atmospheric pressure, combined with a spring tide, generated a significant storm surge that has been responsible for erosion all along the coastline of the region. At Calais, on December 5th and

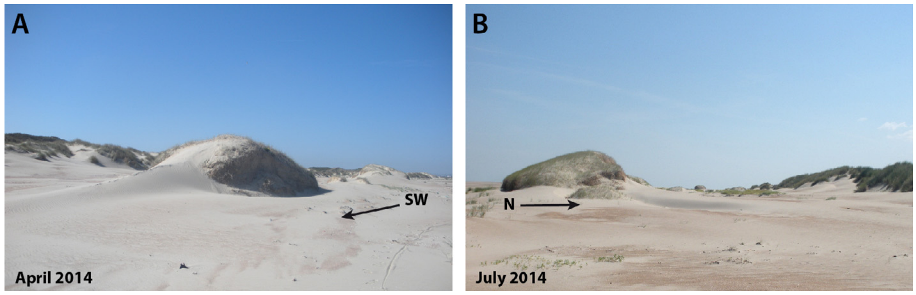

Fig. 8. Sand accumulation behind nebkhas under (A) longshore and (B) onshore winds.

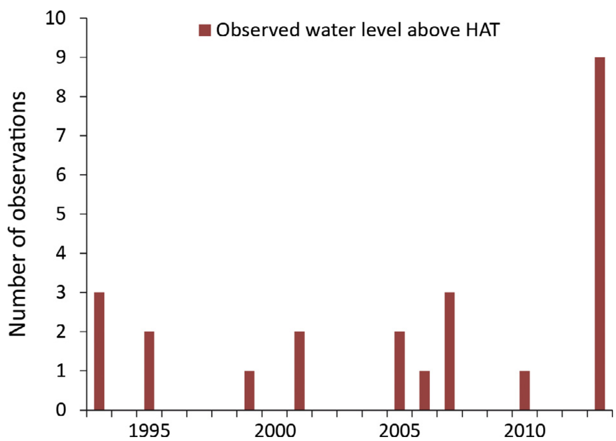

Fig. 9. 1993–2013 annual frequency of water levels above highest astronomical tide (HAT) measured at Calais tide gauge (data: *Service Hydrographique et Océanographique de la Marine*).

6th, southwestern to northwestern mean hourly winds above 8 m/s blew during more than 24 consecutive hours. The maximum instantaneous recorded wind speed was 24.4 m/s, while the maximum mean hourly recorded wind speed was 16 m/s. In this area, where wind speed rarely exceeds this value (Chaverot et al., 2008), it has been shown that wind duration is a major factor inducing storm surges. Moderate winds, 8–10 m/s, blowing more than 24 h and combined with a high tide, can induce significant erosion along this coastline (Ruz et al., 2009). In Calais harbour, on December 6th 2013, the maximum recorded water level reached about 8.68 m above hydrographic datum (Daubord, 2014) or 5.22 m relative to topographic datum (IGN69). This observed water level is greater than the numerical value of extreme high water levels calculated for a 100-year return period which is 5.04 m (IGN69).

The recent morphological evolution of the nebkhas was strongly influenced by this latter storm event. The LiDAR topographic data collected on January 18th 2014 show that most of the nebkhas underwent erosion during the December 2013 storm event (Fig. 10). During the storm surge, the maximum water levels reached the swale, isolating some nebkhas and eroding their landward slope. This happened only in areas where the swale depth was well under the storm surge level (Profile 4 and 5, Fig. 10). The width of the seaward most nebkhas was reduced; however their height remained stable or increased due to vertical accretion. Two nebkhas were severely or completely eroded during this event (see Profile 1, Fig. 10). The swale that formed between the nebkhas and the incipient foredune zone underwent both erosion and accumulation between 2011 and 2014 (Fig. 11). Erosion mainly affected slightly lower areas located landward of the nebkhas (Fig. 10), which were reached by the storm surge of December 2013. The incipient foredune zone was not reached by this storm surge and accumulation prevailed, with sand accretion resulting in up to 1.2 m of accumulation between 2011 and 2014 (Fig. 10). Meanwhile, the established foredune remained fairly stable.

A sediment budget calculation from a comparison of LiDAR data obtained in 2011 and 2014 along this portion of the coastline (Fig. 11) was negative for the foreshore, with a mean erosion of $-0.19\ m^3/m^2$. This negative budget can be related to the Xaver storm event, the 2014 LiDAR survey having been carried out only a few weeks later. However, on the upper beach, including the nebkhas, the sediment budget was positive, with a gain of $+0.20\ m^3/m^2$. The maximum accumulation was recorded in the incipient foredune zone with a mean accumulation of $0.61\ m^3/m^2$. Even if huge nebkhas were present on the upper beach, they did not impede sediment transfer from the foreshore to the incipient foredune zone as well as in the swale where sediment accumulation locally occurred (Fig. 11).

Despite two major storm events in 2013, accumulation prevailed between 2011 and 2014, especially on the backshore, out of reach of uppermost water levels. During this period (from March 2011 to January 2014), efficient winds for potential aeolian sand transport (mean wind speed $\geqslant$5 m/s and wind direction 240–60°) blew 28% of the time, with winds above 8 m/s blowing 10.3% of the time. Strongest ($\geqslant$12 m/s) efficient winds occurred only 1.4%, mainly from the southwest sector (the highest mean hourly recorded wind speed during this period of time was 18.5 m/s). Twelve significant wind events (efficient winds $\geqslant$12 m/s blowing during more than 6 consecutive hours) were recorded during this period (Table 2). Seven of them occurred during neap tide or moderate tidal range, potentially favoring aeolian sand transport on the upper beach. During these events, the exposed upper beach was a hundred metres wide, ranging from 89 m to 264 m (based on tide gauge measurements), depending on the location of each nebkha. During such conditions, the maximum wind fetch at high tide, under parallel winds (SW) could exceed 2000 m, while under onshore winds (NNW) the fetch is restricted to less than 160 m. As stressed by Anthony et al. (2009), along macrotidal beaches, strong oblique onshore winds blowing on the dry upper beach during neap tides likely represent favourable conditions for incipient foredune accretion. Isolated nebkhas were not an obstacle for aeolian sand transport as they are scattered over the upper beach zone. Furthermore the bare sandy swale between them and the incipient foredune zone can also be a sand source for the incipient foredune.

5. Discussion

The nebkhas described in the present study are the largest we are aware of developed in the foreshore/intertidal region of a beach. The development of huge, spatially isolated nebkhas disconnected from the main foredune and situated this far out on the foreshore/intertidal region is probably uncommon as, to our knowledge, it has not been specifically reported in the scientific literature. Very large nebkhas have been described in desert

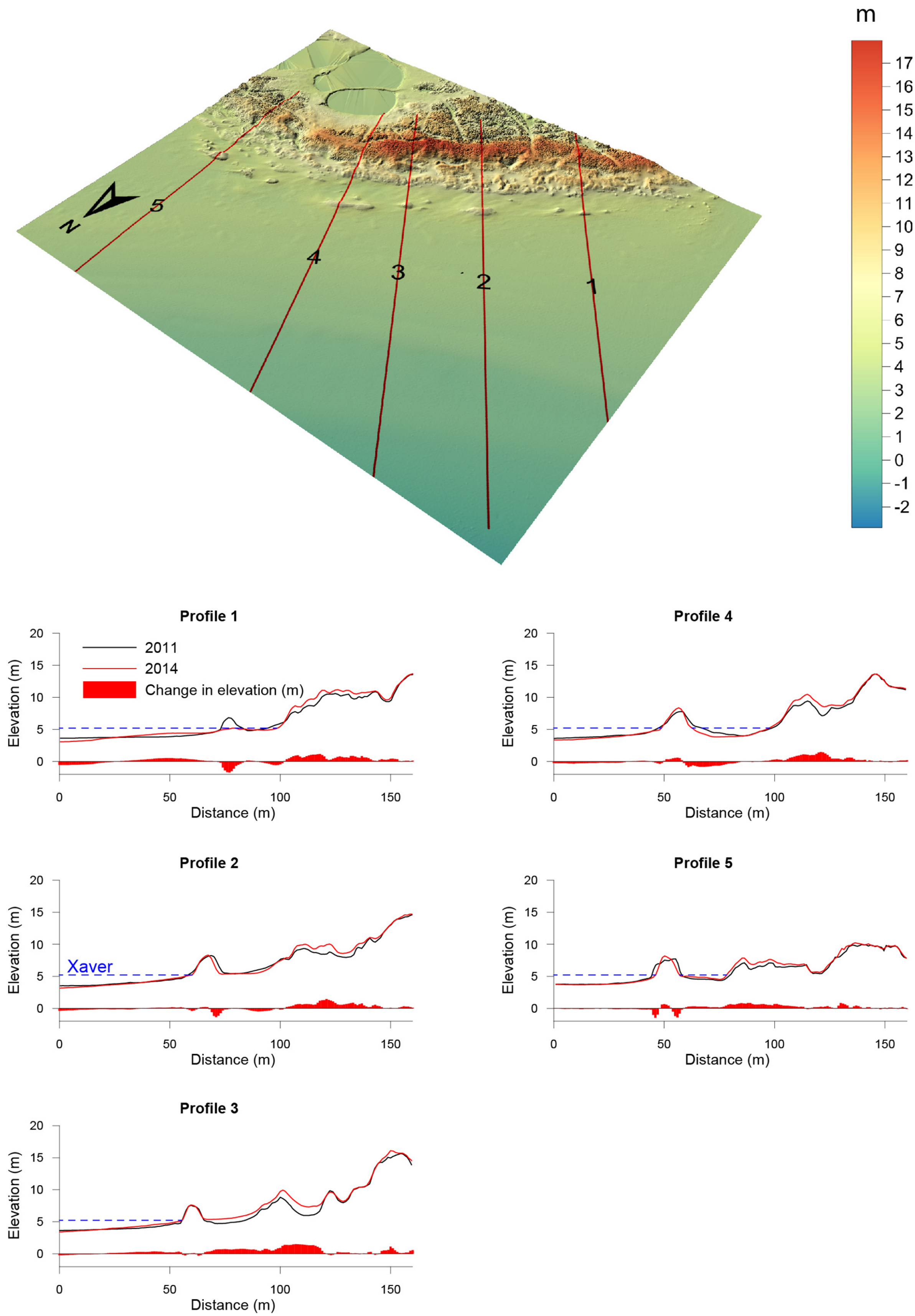

Fig. 10. LiDAR-derived Digital Terrain Model showing the morphology of the study area in March 2011 and the location of topographic profiles showing changes in elevation on the upper beach and incipient foredune zone between March 2011 and January 2014.

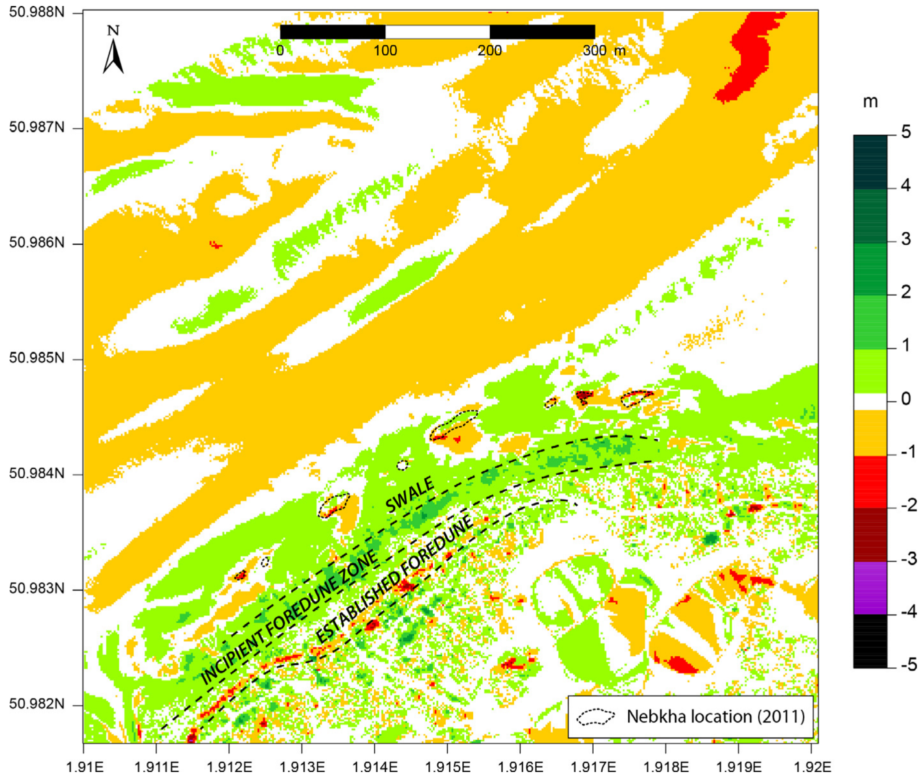

Fig. 11. Net changes in surface elevation over the study area between March 2011 and January 2014 based on LiDAR topographic data. The location of the nebkhas in 2011 is also indicated.

Table 2
Analysis of strong wind events (⩾12 m/s during more than 6 consecutive hours) between March 2011 and January 2014 based on hourly wind data recorded at Calais meteorological station. Tidal range and uppermost water level reached during each event recorded at Calais harbour tide gauge do not include wave-induced set-up. The upper beach widths were extracted from LiDAR topographic profiles (Fig. 10) and correspond to the distance between the uppermost water levels during the windy events and the toe of the nebkhas (4.5–5 m IGN 69). Mean spring tidal range: 6.5 m; mean neap tidal range: 4 m. The grey lines correspond to potential favourable conditions for aeolian sand transport.

Date of event	Duration (hours)	Mean wind speed (m/s)	Wind direction (°)	Uppermost water level (m IGN69)	Tidal range (m)	Upper beach width (m)
18/06/2011	6	12.9	SW 240/250	3.81	6.03	8 to 28
10/10/2011	8	13.3	SW 240/250	3.36	5.57	61 to 163
07/12/2011	11	12.8	WNW 270	2.84	4.48	95 to 209
04-05/01/2012	24	14.8	WNW 240/300	2.43	3.48	131 to 251
05/03/2012	25	14.4	NW 300-310	2.91	4.55	89 to 198
25/11/2012	7	14.6	SW 250	2.87	4.62	92 to 200
22/12/2012	10	12.5	SW 240	2.41	3.74	129 to 250
11-12/03/2013	23	14.1	E 60-70	3.85	6.39	7 to 24
18/04/2013	10	13.6	SW 240-250	2.25	3.35	138 to 264
10/10/2013	19	13.5	NNW 330-340	3.47	5.49	56 to 159
28/10/2013	7	15	SW 240	2.44	3.0	131 to 261
05/12/2013	7	14.8	WSW 250-260	4.10 m	6.67	0 to 10

environments where they can reach greater heights (Cooke et al., 1993; Langford, 2000; Lang et al., 2013). In China for example, nebkha-like features (*Tamarix* cones) up to 15 m high have been reported in the Taklimakan Desert (Qong et al., 2002). Large sand mounds that accumulate around clumps of trees are called mega-nebkhas (Khalaf et al., 1995). Such mega-nebkhas, reaching 10 m high and up to 1 km long, have notably been reported by Cooper (1958) on the edges of Oregon coastal dunes.

The large nebkhas described in this study, developed at the seaward edge of an upper beach platform close to the highest astronomical tide limit, are scattered and grew up *in situ*, reaching an elevation up to 4 m. According to Ranwell (1972), an irregular zone of scattered nebkhas and shadow dunes can develop if only a few seeds are transported to the backshore by swash or wind, or if only a few plants survive. In the study area, the development of scattered nebkhas is likely linked to the presence of shell lags that are commonly observed on the upper foreshore and backshore. In the presence of such shell lags, restricting sediment supply from the foreshore and the backshore, the wind is unsaturated, which reduces the sediment trapping capacity of the vegetation (Houser et al., 2008; Hesp and Walker, 2013). In this case, the establishment of pioneer plants is restricted (Davidson-Arnott and Law, 1990) and, in the study area, *Elymus farctus* is the only pioneer species colonising scattered nebkhas. In addition, because the observed nebkhas are isolated from the incipient foredune zone and are surrounded by bare sandy areas, they are exposed to winds from various directions that may supply or remove sediment from one part of the nebkha (Fig. 8) as exposure and shelter vary depending on wind direction as underlined by Hesp (2002).

It is well known that beach width and sediment supply, which are closely tied to surfzone-beach type, are important parameters controlling foredune development, particularly where sediment supply is not an important limiting factor (e.g., Short and Hesp, 1982; Psuty, 1988; Davidson-Arnott and Law, 1996). The development of nebkhas on the backshore east of Calais seems to be associated with a wide foreshore and upper beach in a context of abundant sediment supply along a macrotidal coastline. The formation of large nebkhas just above the uppermost tide level is probably favoured by the macrotidal regime characterizing this coastal area. Not only can the wide foreshore exposed at low tide serve as a sediment source for onshore aeolian transport, but the frequency of potentially erosive high water levels is extremely low.

Another key factor in foredune development is the supply of sediment from the shoreface to the beach (e.g., Anthony, 2013; Houser and Ellis, 2013), which is commonly controlled by the onshore migration of nearshore and/or intertidal bars (e.g., Aagaard et al., 2004; Houser, 2009). In this area, the welding of nearshore sand banks, which started since at least the 16th century resulted in the development of a broad sandflat (1500 m at low tide) in the early 20th century (Briquet, 1930). The local increase in sand supply to the beach resulted in beach progradation, which created space in the backshore for coastal dune development. As stressed by Anthony (2013), in this area, the seaward advance of the shoreline was related to the development of this extensive sandflat, followed by the development of coastal dunes with a time lag on the order of years.

Historical evidence reveals that beach progradation resulted in successive episodes of dune formation. By the mid-19th to the beginning of the 20th century, sandy islets 150–210 m wide, covered by small coastal dunes, formed on the upper beach, disconnected from the main shoreline (Briquet, 1930). These sandy islets were likely related to the presence of the extensive sandflat over which aeolian sand transport was active. Such large and low-elevated sandy islets disconnected from the main foredune have been reported in north Lincolnshire along the eastern coast of UK on a dissipative macrotidal beach (Montreuil, 2012; Montreuil et al., 2013). Even after 10 years of development, they were still expanding but had not merged with the established foredunes (Montreuil et al., 2013). East of Calais, however, the sandy islets observed on the aerial photography of 1938 (Fig. 2) progressively merged to the main shoreline, resulting in a shoreline advance up to 320 m seaward.

Following this phase of sandy islets coalescence and significant shoreline advance, continuing beach accretion resulted in the development of incipient foredunes, and nebkhas formed at the uppermost tide level, disconnected from the incipient foredune zone by a swale. Whereas, according to Briquet (1930), the formation of foredunes all along this coastline during the 19th century and the early 20th century resulted from the coalescence of large "insular dunes", only isolated nebkhas developed during the late 20th century. This is presumably linked to the progressive eastward migration of the extensive sandflat (Héquette and Aernouts, 2010) that resulted in the reduction in beach width along this stretch of the coastline.

Nebkhas started to develop by the mid 90's and progressively grew up, reaching 1–2 m high in 2001 (Tékin, 2004) and up to 3.5–4 m in 2011. Since 2011, very little change in their elevation was recorded (Fig. 11). While the nebkhas formed, a shore-parallel partially vegetated foredune zone developed at the toe of the established foredune (Fig. 4). In a situation with shore-parallel incipient and established foredune ridges, there are usually two sedimentation peaks, one in the incipient zone and the other one in the established foredune, with lower sedimentation in the bare zone separating the two (Arens, 1996; Keijsers et al., 2015). In the study area, maximum accumulation was recorded in the incipient foredune zone, with vertical accretion up to 1.2 m between 2011 and 2014, while no major changes were observed in the established foredune (Fig. 10). Although large nebkhas were present on the upper beach, they only trapped a small amount of wind-blown sand that was transferred from the foreshore to the incipient foredune zone. The swale between the nebkhas and the incipient foredune zone underwent both slight erosion and accumulation. Swales are generally low to limited aeolian deposition zones and become deeper as seaward incipient foredunes become higher (Olson, 1958; Hesp, 1983, 2002), but here, the swale remained fairly stable.

The analysis of aerial photographs and LiDAR topographic data revealed that the incipient foredune zone developed seaward at the expanse of the swale (Figs. 4 and 11). This evolution suggests that the nebkhas may progressively merge with the prograding incipient foredunes, being eventually included in a new incipient foredune zone. The merging of the nebkhas would therefore occur due to maximum sand accumulation in the incipient foredune zone and not as a result of sediment accumulation in the nebkha zone. This would contrast with what is generally observed along foredunes that develop seaward through the development of the seawardmost embryo dunes (Pye and Tsoar, 1990; Hesp, 2011). Here the scattered nebkhas would not interrupt sand transfer from the foreshore to the incipient foredune zone located landward.

Our observations suggest that the most developed nebkhas have reached an equilibrium stage as their height, length and width remained fairly stable since 2011, although some of them were eroded by the major storm surge of December 2013. According to Mountney and Russell (2006), nebkhas have a characteristic shape and tend to adopt a similar morphology in any bioclimatic setting, suggesting they reach equilibrium once they have developed beyond their embryonic state. According to Hesp and Walker (2013), as nebkhas build they usually evolve through an evolutionary cycle of development from small to large forms. Cycles of nebkha build-up and erosion, processes controlling their size and density, and vegetation behaviour were described by several authors (Suslov, 1961; Gile, 1966; Mahmoudi, 1977; Gibbens et al., 1983; Hesp, 1988, 1989; Khalaf et al., 1995). Three stages of development were proposed by Tengberg and Chen (1998): (1) sand deposition and nebkha development, (2) steady state, and (3) nebkha erosion due to the disappearance of the vegetation and of the mound of sand.

In the study area, three stages of nebkha development are observed. Initially, nascent nebkhas develop on a shell lag close to the highest astronomical tide level (Fig. 12A). The surface area and height of the nebkha increase with time as wind-blown sand is supplied from the foreshore. The largest ones, reaching a height

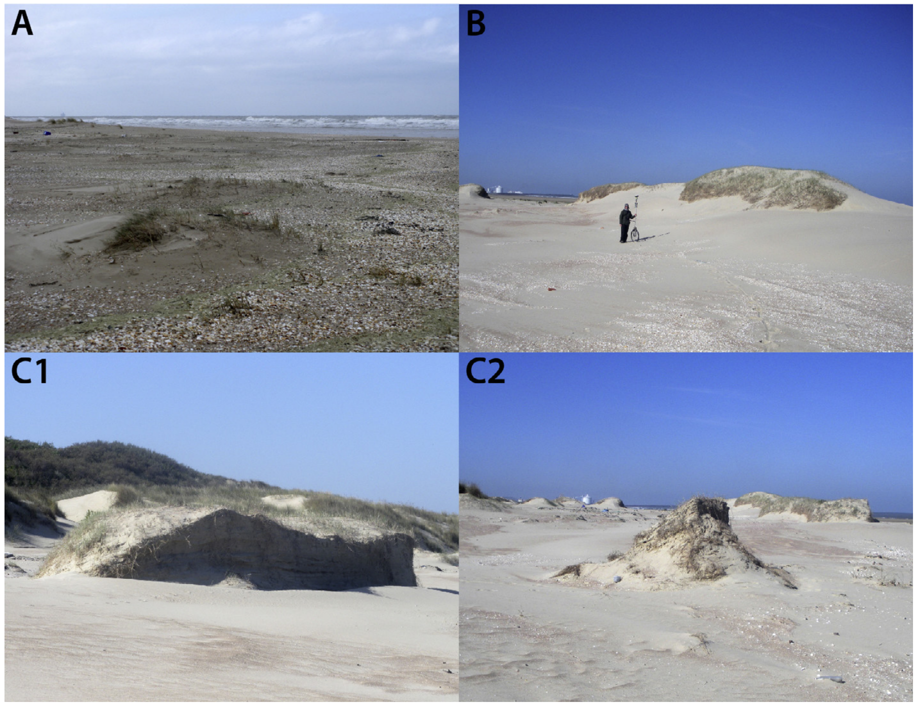

Fig. 12. Examples of stages of nebkha development east of Calais: (A) initial development of scattered low dunes developing on shell lag close to highest astronomical tide level; (B) fully-developed nebkha having reached equilibrium state; (C) partially-eroded nebkhas.

up to 4 m, seem to have reached an equilibrium state (Fig. 12B) as only minor change in their morphology can be observed. Nebkhas can develop and eventually attain equilibrium on the upper beach were they are only very episodically reached by storm surges. A major storm event associated with an extreme water level, such as the one of December 2013, can nevertheless partially or strongly erode some of the fully-developed nebkhas (Fig. 12C1 and C2) or even completely wash away smaller nebkhas (Fig. 10, profile 1). However, in this context of high sediment supply, nebkhas may eventually merge with the incipient foredune zone depending on the magnitude and frequency of future storm events.

6. Conclusions

(i) Large nebkhas, up to 4 m high and 14 m wide, have developed on the upper beach east of Calais, forming aeolian landforms parallel to the dominant southwest winds near the uppermost tide level and disconnected from the main foredune.
(ii) These large nebkhas formed in a coastal area characterized by abundant sediment supply from the shoreface due to the onshore migration of a nearshore sand bank that resulted in the formation of a wide sandy foreshore which favoured active incipient foredune development and significant seaward shoreline progradation.
(iii) 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.
(iv) The nebkhas consist of scattered landforms that did not prevent aeolian accretion landward in the incipient foredune zone where the maximum accretion rates were recorded.
(v) Due to the seaward expansion of the incipient foredune zone, the nebkhas could be progressively amalgamated in the prograding foredune zone if they are not eroded during storms associated with high water levels.
(vi) The distribution of such large coastal nebkhas is probably very limited since the descriptions of similar examples of aeolian coastal landforms are virtually absent in the scientific literature.
(vii) Such uncommon nebkhas developed on an upper beach are presumably restricted to low gradient macrotidal beaches associated with an excess of sand supply.

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