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Using LiDAR Topographic Data for Identifying Coastal Areas of Northern France Vulnerable to Sea-Level Rise

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ABSTRACT

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A major portion of the coast of northern France consists of wide macrotidal beaches and coastal dunes protecting low-lying backshore areas (mostly reclaimed lands) from marine flooding. Although the shoreline was stable or even prograded seaward in places during the last decades, several coastal areas underwent severe erosion during the same period, while flooding sporadically occurred locally during major storms. A study of the potential impacts of sea-level rise on the coast of northern France was conducted based on airborne LiDAR topographic data collected from 2008 to 2014. Mapping of areas at risk of erosion and flooding during storm-induced events associated with high water level with a 100-year return period by 2050 was carried out using high water level statistics derived from tide gauge measurements, offshore wave climate statistics, and a sea-level rise projection based on RCP6.0 scenario (IPCC, 2013). Wave run-up was computed based on the Cariolet and Suanez (2013) equation developed for macrotidal beaches and using beach topographic profiles extracted from the LiDAR data. Results show that marine flooding would still be limited in 2050 even with a higher sea-level, but reveal that coastal dune erosion will most likely be widespread (Fig. 1). However, our study also shows that if coastal retreat proceeds during the next decades at the same or higher rates as today, several coastal dune systems will be entirely eroded in the near future, which would result in extensive storm-induced marine flooding in several coastal areas.

ADDITIONAL INDEX WORDS: *Coastal hazards, marine flooding, climate change.*

INTRODUCTION

Although demographic projections for the 21st century only show a slight increase of population living along European coasts, about 50 million people in Europe are living in low lying coastal areas exposed to coastal hazards (Neumann *et al*., 2015). This is particularly the case in the densely populated coastal areas bordering the North Sea, such as in Belgium, the Netherlands, and Denmark, where reclaimed lands below mean sea level are subject to marine flooding. The northern coast of France is part of this extensive set of low-elevated shorelines exposed to coastal risks that are likely to worsen in the next decades with predicted sea level rise associated with climate change (IPCC, 2013).

It is well established that global sea-level has been rising since the late 19th century and that the rate of sea-level rise increased during the last decades (Church and White, 2011). However, tide-gauge data as well as satellite altimetry clearly show that the rate of rise displays strong regional variations due to climate-related processes, such as steric effects and water mass redistribution, and/or to vertical land movement caused by natural or anthropogenic geological processes (Nichols and Cazenave, 2010). Recent observations of mean sea-level records from tide gauge sites along the North Sea and English Channel coastlines revealed that the rate of (local) sea-level rise was particularly high in the North Sea, exceeding 4.0 mm yr^{-1} between 1993 and 2009 (Wahl *et al*., 2013) which is significantly higher than mean rate of global sea-level rise of 3.2 mm yr^{-1} measured by altimeter satellites during the same period (Church and White, 2011).

In this paper, we present the results of a study carried out along the coast of northern France, using a series of LiDAR topographic data collected between 2008 and 2014 which were used for analyzing shoreline change and for mapping areas at risk of erosion and flooding. The possible impacts of future sea-level rise by 2050 are also assessed based on a moderate scenario of greenhouse gas emissions from the IPCC (2013) Fifth Assessment Report.

STUDY AREA

The coast of northern France is located in the eastern English Channel and southern North Sea (Figure 1). A major portion of this coast consists of wide dissipative barred beaches (300-600 m) and coastal dunes protecting low-lying backshore areas (mostly reclaimed lands) from marine flooding, despite a considerable expansion of urban and port areas during the 20th century (Figure 1). Although the shoreline was stable or even prograded seaward in places during the last decades, several coastal areas underwent severe erosion during the same period (Chaverot *et al*., 2008), while flooding sporadically occurred locally during major storms (Maspataud *et al*., 2012).

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The tidal regime in the region is semidiurnal and macrotidal, the tidal range increasing from the North Sea to the English Channel, with a mean spring tidal range of more than 5.4 m at Dunkirk to approximately 8.5 m at Berck-sur-Mer (Figure 1). Due to the large tidal amplitude, tidal currents are strong along the northern coast of France with a flood-dominated asymmetry responsible for a net regional sediment transport to the north in the coastal zone of the English Channel and to the east-northeast along the North Sea coast (Héquette *et al*., 2008).

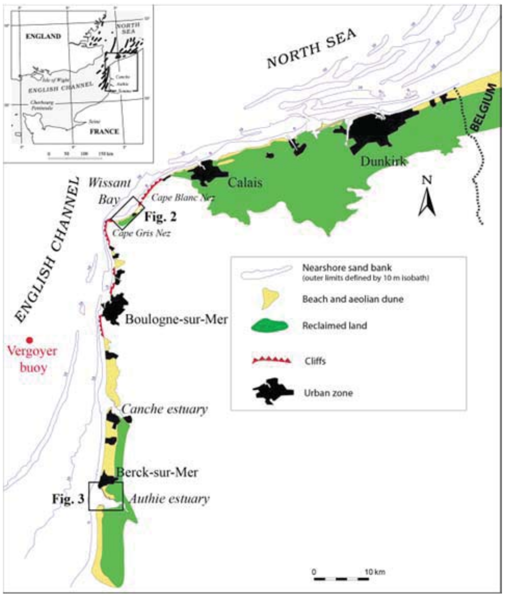

Figure 1. Location of the study area.

The dominant winds in the eastern English Channel and southern North Sea are from west-southwest and from north to northeast. In response to these winds, the offshore wave regime is characterized by short-fetch waves from southwest to west, originating from the English Channel, followed by waves from the northeast to north, generated in the North Sea. Most waves have periods and significant heights of less than 5 s and 1.5 m, respectively, but may episodically exceed heights of 4 m during major storms (Ruz *et al*., 2009). Wave heights are much lower at the coast, however, due to significant wave refraction and shoaling over the tidal sand banks of the eastern Channel and southern North Sea (Héquette *et al*., 2009).

METHODS

The potential impacts of sea-level rise on the coast of northern France were assessed based on high-resolution topographic data of the intertidal zones and coastal dunes, which were obtained from airborne LiDAR surveys carried out between 2008 and 2014. A complete topographic coverage of the coast of northern France from the Authie estuary to the Belgium border (Figure 1) was obtained in May 2008, March 2011 and December 2013/January 2014. Partial LiDAR surveys were also conducted in November 2012 in specific areas.

The 2008 survey was carried out with an Optech ALTM 1020 LiDAR having a planimetric position accuracy of ± 0.25 m and a vertical accuracy of ± 0.1 m over bare surface areas. The other surveys were conducted using a Leica ALS60 LiDAR system that acquired topographic data with a planimetric accuracy ranging from ± 0.1 to 0.17 m with a vertical accuracy < ± 0.10 m as verified by several ground control points using a very high resolution differential GPS (Leica TPS Syst1200). The vertical error range can easily increases to ± 0.25 m or more in areas covered by dense vegetation (Saye *et al*., 2005).

A density of data points of 1.2 to 1.4 points/m^2 was obtained during the different LiDAR survey. LiDAR topographic data were filtered to remove vegetation, buildings and other objects. Filtered data were then used to create contour Digital Terrain Models (DTM) using Golden Software Surfer™. The DTMs were obtained by linear interpolation using a Delaunay triangulation resulting in a grid with a 1 m resolution, a grid cell resolution of 1 m^2 appearing to provide reliable representation of topography and accurate volumetric measurements in coastal dunes using LiDAR data (Woolard and Colby, 2002).

Shoreline evolution between 2008 and 2014 was calculated based on different sets of LiDAR topographic data mentioned above. Shoreline position was determined from each DTM as the upper beach/coastal dune limit based on a change in slope gradient on the upper beach calculated as:

$$\|\vec{g}\| = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \qquad (1)$$

Where $\vec{g}$ is the slope gradient, *z* the elevation, *x* and *y* the coordinates of each point of the calculation of the grid. The value of the gradient is 0 for a horizontal surface and tends to infinity for a slope approaching the vertical. The transition between the upper beach and the coastal dunes corresponds to a sharp increase in the value of the slope gradient that is then selected for mapping shoreline position. To validate this semi-automatic shoreline extraction method, shoreline position detected from LiDAR data was compared at several sites with the position of the dune toe simultaneously determined in the field using a high-resolution differential GPS. The comparison of these two shoreline indicators usually showed small position differences, especially along erosive shoreline stretches, with a standard deviation of approximately 1.5 m. The margin of error associated with the delimitation of the shoreline was thus estimated at ± 1.5 m based on this comparison. Shoreline change measurements were carried out on cross-shore transects spaced every 50 m along the shore for each period between the different LiDAR surveys. When comparing shoreline position between two dates, the error margin can be considered to be ± 3 m.

To assess the risk of coastal erosion and marine flooding, critical high water levels were determined based on storm surge observations from Boulogne-sur-Mer, Calais and Dunkirk tide gauge stations (Figure 1) and tidal predictions computed by the French Hydrographic Service (SHOM). A joint probability method was used for determining the 100-year return period high water level for each tide gauge station based on the probability distributions of extreme water levels (observed positive surges and predicted high tide levels) (SHOM, 2012).

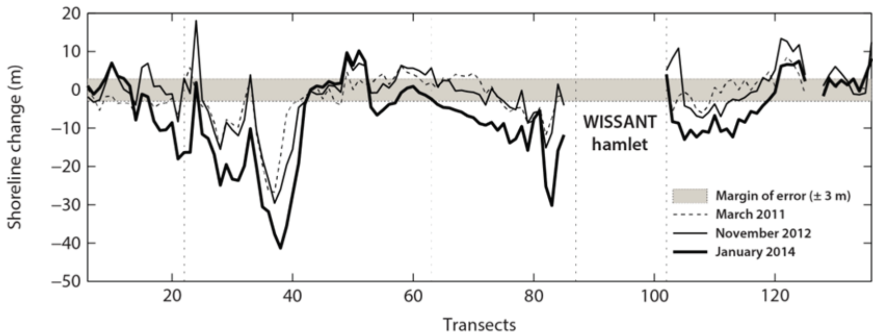

Figure 2. Shoreline changes along the coast of Wissant Bay between May 2008 and January 2014. The shoreline positions are extracted from LiDAR Digital Terrain Models (see text for explanation) and are relative to the May 2008 shoreline.

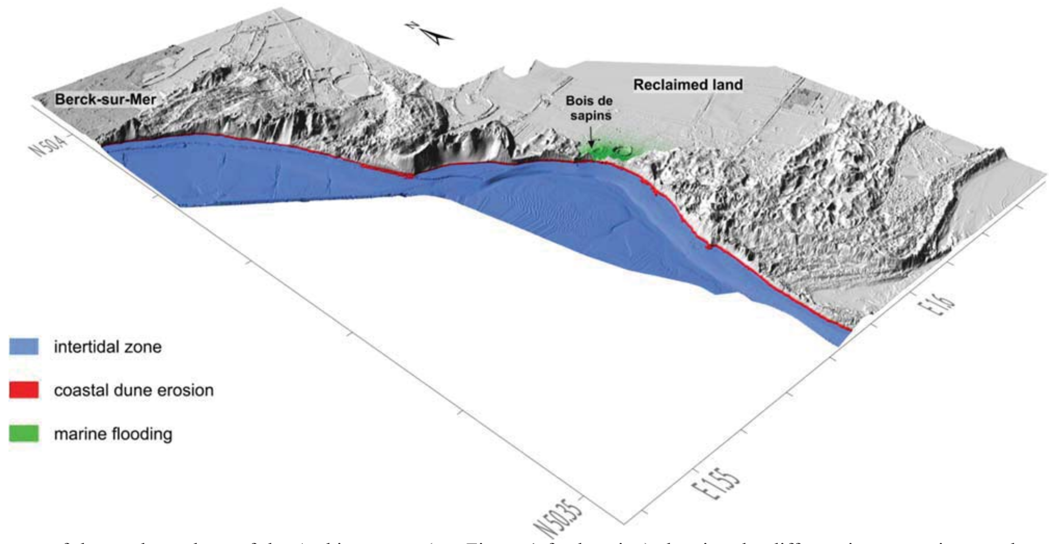

Figure 3. 3D map of the northern shore of the Authie estuary (see Figure 1 for location) showing the different impact regimes under conditions of extreme storm waves (H_o = 6 m, T = 10 s) associated with a 100-year return period water level that would result in a maximum wave run-up elevation of 6.95 m above French vertical datum (IGN69).

In order to evaluate the maximum elevation reached by waves during extreme high water events, wave run-up was estimated according to Cariolet and Suanez (2013) equation based on run-up measurements on a macrotidal beach:

$$R_{max} = 0.67\ \xi_o\ H_o \qquad (2)$$

Where R_{max} is the maximum wave run-up elevation, H_o is the significant offshore wave height and ξ_o is the Iribarren parameter ($tan\beta/(H_o/L_o)^{1/2}$), L_o is the deep water wavelength and $tan\beta$ is the beach slope. The beach slope was measured between the dune toe and the mean high water level, which closely corresponds to the active section of the beach defined by Cariolet and Suanez (2013) to be used in Equation (2). Run-up was computed for two storm wave conditions based on wave statistics from the Vergoyer wave buoy off Boulogne-sur-Mer (Figure 1), using H_o = 3.5 m and T = 9 s for moderate storm conditions and H_o = 6 m and T = 10 for extreme storm conditions.

Sea level rise by 2050 was estimated based on the RCP6.0 scenario from the last IPCC report (IPCC, 2013). Under this scenario, the increase will be 7.3 mm yr^{-1} by 2050, or about + 29 cm (relative to 2010). This value was added to the high water levels and run-up elevations previously calculated as explained above for estimating water levels in 2050.

Coastal hazard mapping was conducted using the latest LiDAR topography data set (December 2013 and January 2014), based on the method of Sallenger (2000) which allows to distinguish coastal dune erosion (*collision regime*) when the maximum run-up elevation reaches an altitude between the dune toe and the dune crest and marine flooding (*overwash* and *inundation regimes*) when run-up reaches or exceeds the elevation of the dune crest. Overwash and inundation were not discriminated from one another because both processes can be responsible for marine flooding since overwash may lead to dune breaching and eventually to flooding. Foreshore erosion (i.e., Sallenger's *swash regime*) was not considered in the present study, because the beaches of the region do not necessarily undergo erosion during storms as intertidal bars prove to be remarkably stable even during high wave-energy events (Anthony *et al*., 2004).

RESULTS

Mapping of high water levels over the LiDAR-generated DTMs showed that most of the region's coastline is subject to erosion under present sea level conditions, even during moderate storm events. Coastal erosion is already significant at several sites along the coast of northern France such as in Wissant Bay where the shoreline locally retreated by more than 250 m during the second half of the 20th century (Chaverot *et al*., 2008). Our LiDAR surveys revealed that the coast of Wissant Bay continued to erode during recent years, the shoreline having retreated landward by more than 20 m in several places between May 2008 and January 2014, with a maximum retreat of about 40 m in the western part of the bay (Figure 2), corresponding to annual retreat rates on the order of 3.5 to 7.0 m yr^{-1}. The shoreline was stable or slightly prograded seaward in some areas however, notably east of the village of Wissant, which is likely due to the redistribution of eroded material along the coast.

Most of the coastline retreat took place between November 2012 and January 2014 with shoreline retreat in excess of 7 m along extensive stretches of the coast and up to nearly 20 m at several locations (Figure 2). These high values of coastal retreat can be explained by the occurrence of extreme water levels (return period > 100 years) associated with a series of severe storms during the fall and early winter of 2013 (Daubord, 2014). These storms were responsible for significant coastal erosion at several other sites along the coast of northern France like along the northern shore of the Authie estuary where shoreline retreat ranged from approximately 15 to 30 m between March 2011 and December 2013, reaching about 70 m along a low-elevated stretch of coastal dunes named "Bois de sapins" (Figure 3).

The determination of coastal areas subject to marine flooding based on LiDAR-generated DTMs and storm-induced high water levels (including maximum run-up elevation) showed that only localized and spatially restricted, low-elevated, coastal areas would be at risk of inundation along the coast of northern France during a 100-year return period event. One of these areas is the "Bois de sapins" mentioned above, on the northern shore of the Authie estuary, where a breach has formed through the dune crest that hardly exceeds 7 m above French vertical datum (IGN69) (Figure 4). Even under present sea level, our data show that marine flooding could occur in this area under high-energy storm wave conditions associated with a 100-year return period water level, which would result in partial inundation of the low-lying reclaimed land located behind the coastal dunes (Figure 3).

With a 29 cm higher sea level in 2050, as projected with the RCP6.0 scenario (IPCC, 2013), this area would obviously be more easily and more completely flooded as an inundation regime would last a longer period of time at or near high tide (Figure 4A) and would affect a longer stretch of coast. Similar storm impact regimes would prevail in the western part of Wissant Bay where overwash and limited inundation could occur locally under present sea level conditions during an extreme storm event associated with a 100-year return period, while more extensive inundation would take place in 2050 with a higher sea level (Figure 4B). However, our results suggest that although a higher proportion of coastal dunes would undergo erosion with a higher sea level in 2050, marine flooding would still be essentially restricted to the shores of the Authie estuary and Wissant Bay.

DISCUSSION AND CONCLUSION

This study shows that the dune coast of northern France is subject to widespread shoreline erosion during high-energy wave events associated with a 100-year return period water level, even under present sea level. Severe coastal dune erosion is already taking place at a number of sites along the northern coast of France, notably in Wissant Bay and the Authie estuary where the shoreline retreated by tens of meters in places in response to the storms that hit western Europe during the fall and winter of 2013-2014 (Castelle *et al*., 2015). With a higher sea level in 2050, coastal dune erosion would not only be more widespread, but also more severe since the dune front should generally experience a collision regime up to a greater height.

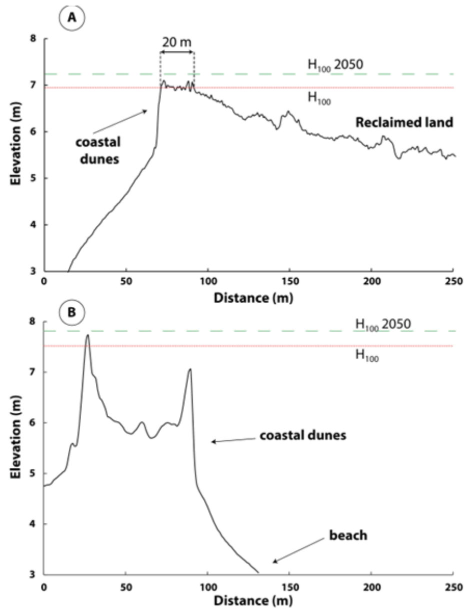

Figure 4. Cross-shore topographic profiles of the littoral zone showing maximum run-up elevation during extreme storm wave conditions (H_o = 6 m, T = 10 s) associated with a 100-year return period water level with present sea level (H_{100}) and with predicted sea level rise in 2050 (H_{100}2050); (A) "Bois de sapin" on the northern shore of the Authie estuary, (B) western shore of Wisant Bay.

Moreover, a rising sea-level will also result in a higher frequency of extreme water levels (Haigh *et al.*, 2011), which will also result in intensified coastal erosion.

Our results show that the risk of marine flooding is currently limited to a few sites. This work also suggests that although an increase of 29 cm in mean sea level by 2050 would induce more extensive flooding at sites already vulnerable to this hazard, flooding would still be essentially limited to the same sites. Such interpretation only based on the mapping of storm-generated high water levels over LiDAR-generated DTMs could be misleading, however, because coastal dunes are already eroding at high rates in places and coastal erosion will likely increase during the next decades with rising sea level (Nicholls and Cazenave, 2010). On the northern shore of the Authie estuary, for example, the low-elevated polders are only protected from marine flooding by a narrow (20 m) dune barrier that is affected by considerable erosion. If coastal erosion continues to proceed at the same or higher rates, coastal flooding will certainly take place well before 2050 at this location. The same situation occurs at a number of sites along the northern coast of France where coastal flooding is not an immediate threat, but where coastal dunes protecting low-elevated coastal lowlands are presently undergoing erosion, which could lead to flooding hazards in the near future.

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