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ORIGINAL PAPER

Potential impacts of extreme storm surges on a low-lying densely populated coastline: the case of Dunkirk area, Northern France

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Abstract Along the southern coast of the North Sea, a large proportion of the Flemish coastal plain consists of densely populated reclaimed land, much of which lying below mean high tide level. This is particularly the case along the northern coast of France, from Dunkirk to the Belgium border, where the shoreline consists of coastal dunes that protect low-lying reclaimed lands from marine flooding. This area is vulnerable and subject to several risks. Extreme weather conditions could induce strong surges that could cause (1) a shoreline retreat, (2) marine submersion and (3) land and/or urban flooding due to drainage problems of the polders. Highly energetic events such as the November 2007 storm could have had much more severe consequences especially if they occurred at high tide and/or during a spring tide. In the current context of global change and projected sea-level rise, it is then important for the local authorities to take into account the potential impacts and return periods of such events, in order to implement coastal risk policies prevention and management, to reinforce sea defense, increase pumping station efficiency and plan warning systems against marine submersion and polder flooding, which is not the case yet in Northern France.

Keywords Storm surges · Low-lying coastline · Vulnerability · Erosion · Submersion · Polder flooding

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1 Introduction

The study of the vulnerability of a specific system (human and/or natural) to a specific hazard (such as floods, storms) or range of hazards referred to as climate events, and of its ability to adapt to changes, for example in climate hazards, is a relatively new field of research that brings together experts from a wide range of fields, including climate science, geomorphology and management (Brooks 2003). Since the growing body of literature on vulnerability contains a sometimes-bewildering array of terms, as vulnerability, sensitivity, resilience, risk, hazard and so on (IPCC 2001; Brooks 2003), the relationships between these terms are often unclear with different meanings when used in different contexts and by different authors. As explained in Brooks (2003), researchers from the natural hazards field tend to focus on the concept of risk (the probability of occurrence of a particular event/product of hazard and vulnerability), while those from the social sciences and climate change field often use to talk in terms of vulnerability. Thus, climate scientists often view vulnerability in terms of the likelihood of occurrence and impacts of weather-marine and/or climate-related events (Nicholls et al. 1999).

In the perspective of sea-level rise and possible variations in storm regime in response to climate change (Zhang et al. 2004; IPCC 2007), low-lying coastal areas will be vulnerable to episodic marine submersion of coastal defenses, coastal plain flooding and coastal erosion risks and will have to face a number of economic, scientific and environmental concerns (Watson et al. 1997; Nicholls et al. 2007). Energetic events such as storms represent major factor controlling short- to medium-term morphological evolution of many sandy shorelines (Stone and Orford 2004). Therefore, the understanding of the potential effects of high-energy events on beaches and dunes and on coastal structures is of primary importance for rational coastal management.

In northern Europe, the North Sea region and particularly the low-lying coastlines of Denmark, northern Germany, the Netherlands, Great Britain, Belgium and Northern France are highly sensitive to storm surges (Tolman 1991; Jelgersma et al. 1995; Gonnert 1999; Langenberg et al. 1999; Woodworth et al. 2007; Weisse et al. 2011). Indeed, in the historical times but also more recently in the twentieth to twenty-first centuries, storm surges have severely impacted the North Sea basin and led to major disaster along its coasts (Lamb 1991), highlighting the existing potential for high impact damage, threatening human life as well as property (Safecoast 2008). The impacts of extreme storm surges are unfortunately well known in the North Sea since the storm of 1953 (Lamb 1991; McRobie et al. 2005).

Storm surges events result from the frictional stress of strong winds blowing toward the land, pushing water toward the coast and causing the water level to be raised (Pond and Pickard 1983; Gonnert et al. 2001). These strong winds usually result from low-pressure systems, which act to raise the sea level through the inverse barometer effect (1 hPa decrease in atmospheric pressure raises the sea level by $\sim$1 cm) (Parker and Foden 2009). This, coupled with strong onshore winds, can raise the sea level by several centimeters to meters, additional to normal tides. If a particular high surge comes together with a high tide and especially during spring tide, both effects combine and serious beach/dune erosion or even flooding can result, depending on the coastal topography and the structure of defenses against the sea (Woth et al. 2006). Given the configuration of the coastline and the bathymetry, the severity of the storm surge depends primarily on wind speed, wind direction and duration. It is a fortiori when extreme water levels are reached that can occur coastal erosion episodes, marine submersion and even flooding. This is particularly the case along the densely populated southern North Sea coast of France where macrotidal sandy beaches (Masselink and Anthony 2001; Reichmuth and Anthony 2002) are backed by coastal dunes that protect the low-lying backshore areas against marine flooding. It is worth pointing out that coastal flooding generally occurs, in the research area, when the sea overtops barrier beaches or coastal defense structures or when it breaches through dunes and water enters the hinterland low-lying areas (Pirazzoli et al. 2007). The studied coast is episodically exposed to storm surges that mainly induce coastal erosion and shoreline retreat (Maspataud et al. 2009; Ruz et al. 2009).

From a number of well-documented surge episodes recorded along this coast (Maspataud 2011), the aim of this paper is to highlight the potential occurrence of strong storm surges if extreme storm events happen during the next century on the low-lying and densely populated area of Dunkirk. In this area, the coastal risk management needs, now more than ever, to encompass three fronts: coastal erosion, marine submersion of sea defenses structures and coastal and polder flooding.

2 Study area

2.1 Physical setting and forcings

East of Dunkirk, the shoreline consists of a 300–400 m wide dissipative beach backed by coastal dunes that protect low-lying reclaimed lands from marine flooding (Fig. 1c). The foredune is 10–15 m high and 50–150 m wide. Since 60 years, coastal dunes have been massively transformed or destructed due to the urbanization and to the development of the port of Dunkirk.

Nowadays, no more than 7 km of coastal dunes remain along the coastline between Dunkirk and the Belgium border (Ruz et al. 2005) (Fig. 1c). The area presents a high population density along coastal municipalities with 1980 inhab/km^2 in Dunkirk, which is the regional highest rate along this stretch of coast. Moreover, the population is mainly concentrated on a narrow coastal strip and most of administrative, touristic and leisure installations are located close to the beach and port activities (Fig. 2).

This macrotidal coastline is affected by semi-diurnal tides with a mean tidal range at Dunkirk of 5.6 m during mean spring tides and of 3.5 m during mean neap tides. This coastline is exposed to dominant shore-parallel moderate winds from a south to southwesterly window, but fetch and coastal orientation conditions restrict the incidence of southwesterly waves (Fig. 1b). Associated with this wind regime is a fetch-limited environment both influenced by tides and waves and exposed to relatively low-energy waves, with short-wave periods (5–6 s) and mean significant wave heights generally below 1.5 m in offshore modal conditions (less than 1 m at the coast) that are refracted by numerous offshore sand banks (Fig. 1a).

Northerly onshore winds are less frequent, but they occur in winter and, combined with low atmospheric pressure, they can frequently result in storm surges responsible for upper beach/dune erosion (Vasseur and Héquette 2000; Clabaut et al. 2000; Ruz et al. 2009) and polder drainage problems. Statistic studies carried on return periods of surges (the difference between the observed and predicted high water level), recorded by the Service Hydrographique et Océanographique de la Marine in this area, reported at Dunkirk an annual surge of 1.04 m, a decadal surge of 1.49 m and a centennial surge of 1.94 m (Clique and Lepetit 1986; Tomasin and Pirazzoli 2008).

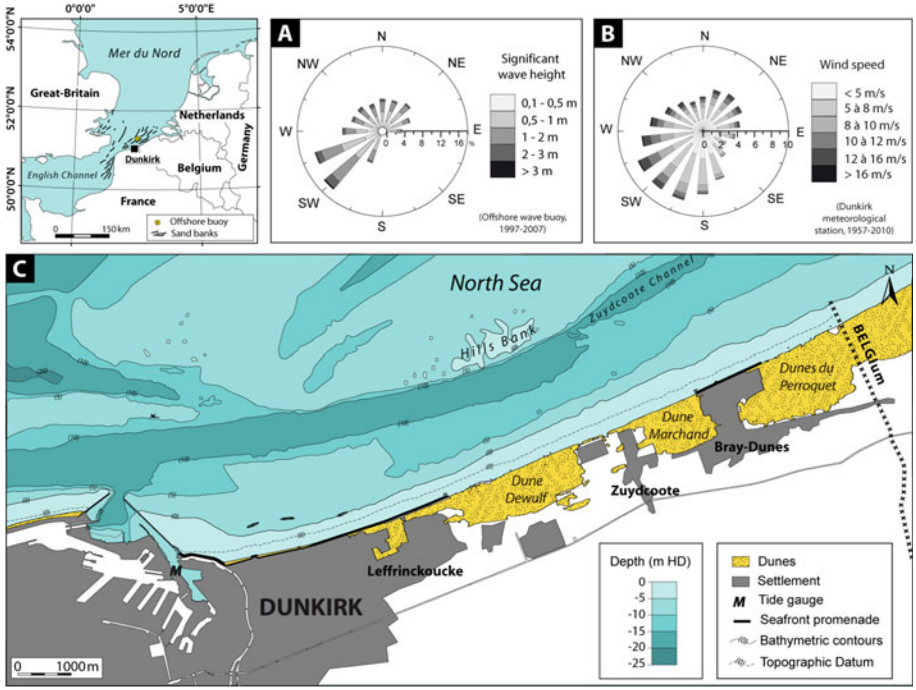

Fig. 1 Location map of the study area along the Southern North Sea coast of France. *Insets* show rose diagram of significant wave height, recorded at offshore wave buoy Westhinder (courtesy of the Belgium Agency for Maritime Services and Coast, 1997–2007) and *rose diagram* of hourly wind speed, recorded at Dunkirk Meteorological Station (1957–2010)

2.2 Polder area and drainage system

Along the southern coast of the North Sea, a large proportion of the Flemish coastal plain (Fig. 3a) consists of densely populated reclaimed land, much of which lying below high water level. In this region, over an area of 100,000 ha of polder, 85,000 ha of land are located below the highest high tide level and about 450,000 inhabitants are concerned. Some areas like "Les Moeres" (Fig. 3a), are located up to 2 m below mean sea level (MSL is 3.24 m above French Hydrographic Datum[1]), this village being the lowest locality in France.

The polder presents a particular water drainage system, the "Wateringues" (commonly named Watergangs), managed by the French Institution Interdépartementale des Wateringues, in addition to the common sewage systems in place in urbanized areas (Fig. 3b). In order to prevent the polder from being waterlogged, a dense system of draining canals (more than 1,000 km of watergangs) with natural and intermittent flow and pumps, drain excess water from the polder and discharge it directly into the sea through sluice gates opened at low tide. The entire system established and perfected over centuries is entirely devoted to the following objectives, evacuate the excess water to the sea, block the entry of

[1] The French hydrographic datum (HD) is chosen as the lowest astronomical tide level (LAT), a theoretical level exceptionally reached by the sea at low tide, and from which are referred the depths given on marine charts and the tide levels.

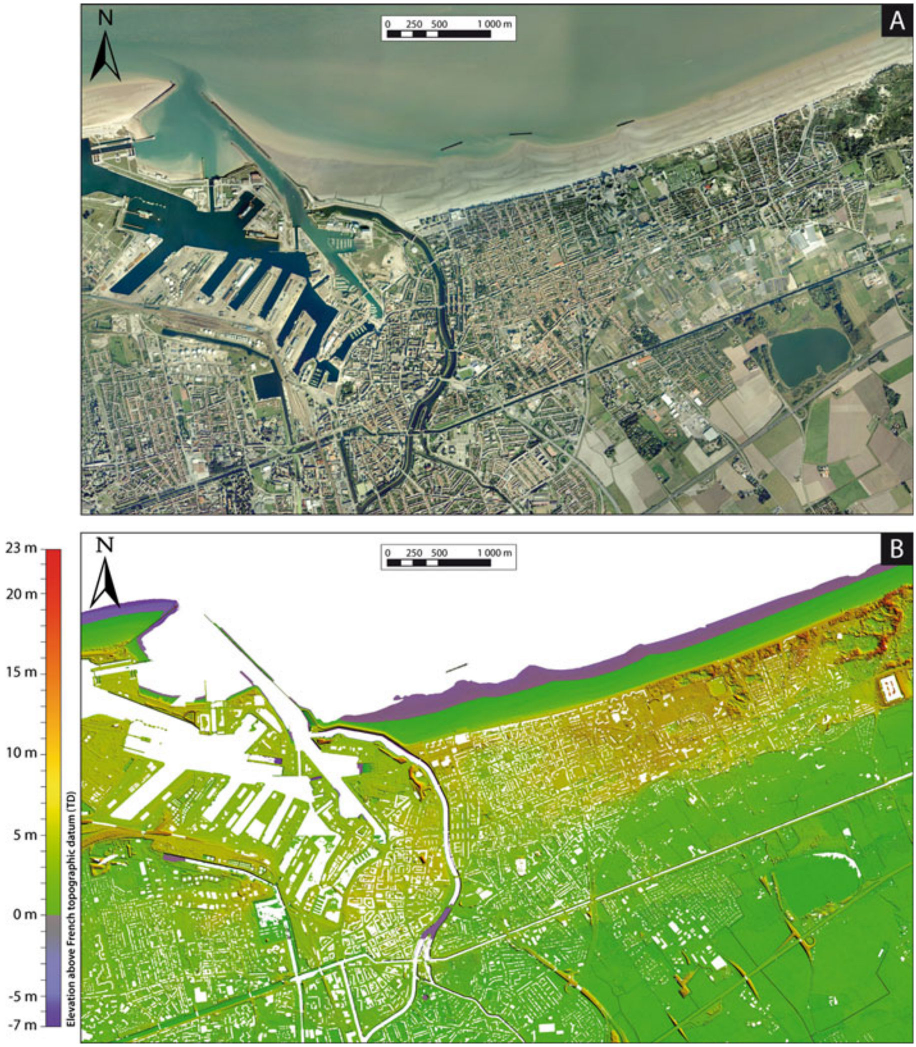

Fig. 2 A low-lying and densely populated reclaimed land: **a** orthorectified aerial photographs (year 2005, provided by the PPIGE, NPDC) and **b** high-resolution digital elevation map derived from airborne regional LIDAR data (year 2008, provided by the Institution Interdépartementale des Wateringues) of Dunkirk city

sea water at high tide, regulate the flows to the sea throughout the year and maintain the water elevation at a constant level in the polder during the wet periods and retain fresh water during dry periods.

The drainage of excess water during low tide can be inhibited when the water level is not low enough to permit sluice gate opening and water drainage at low tide. It is particularly the case when significant surges occur (induced by wind and/or atmospheric and tidal-specific conditions). The problem may get worse when these disadvantageous conditions persist, preventing discharge of fresh water into the sea for several days. In case of a meteorological extreme event combined to a pump or sluice gate breakdown or a dyke

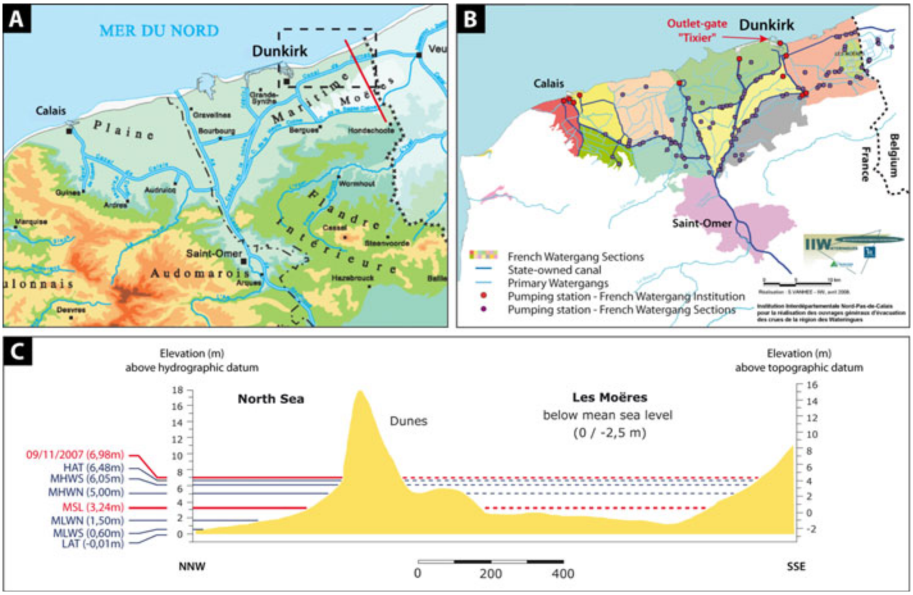

Fig. 3 Maps of **a** the Flemish coastal plain (provided by the *Atelier de Cartographie du Conseil Régional du Nord—Pas de Calais*) and **b** the French watergang system of draining canals and pumps (provided by the French *Institution Interdépartementale des Wateringues*). Topographic transect **c** from the beach to the polder where are superimposed the main water levels relative to HD. HAT represents the highest astronomical tide level, and LAT the lowest astronomical tide level also corresponding to the HD

failure, the resulting risk could be the flooding of extended low-lying urbanized and cultivated areas.

3 Storm surge hazards and local impacts

3.1 The Big Flood of 1953

In northern Europe, everyone remembers the well-known North Sea flood of 1953 (“The Big Flood”; McRobie et al. 2005), which affected the coastlines of the Netherlands, England, Belgium, Denmark, and so on.

In France, Dunkirk area was also affected by this storm (Fig. 4). During this event, on the January 31 to February 1, 1953, strong onshore winds (from a N-NW window) blowing at 55–65 knots were combined with a spring tidal range and resulted in a residual tidal height maxima of 2.40 m at high tide with a maximum water level of 7.90 m above HD recorded at Dunkirk, while the predicted water level was about 5.50 m HD.

The local impacts produced by high water levels and highly energetic waves were significant. Two breaches of 200 and 120 m long were opened in the Eastern dike of the outlet canal (Fig. 4a, b), in addition to dike submersion (Fig. 4b) and marine flooding of low-lying quarters of the city (Fig. 4c). This event also resulted in shoreline retreat, but fortunately no victims were deplored like in England or Holland.

This strong surge event is not an isolated case along this coastline (review in Maspataud 2011). The dike of the outlet canal was already breached by a storm in 1949 (partially

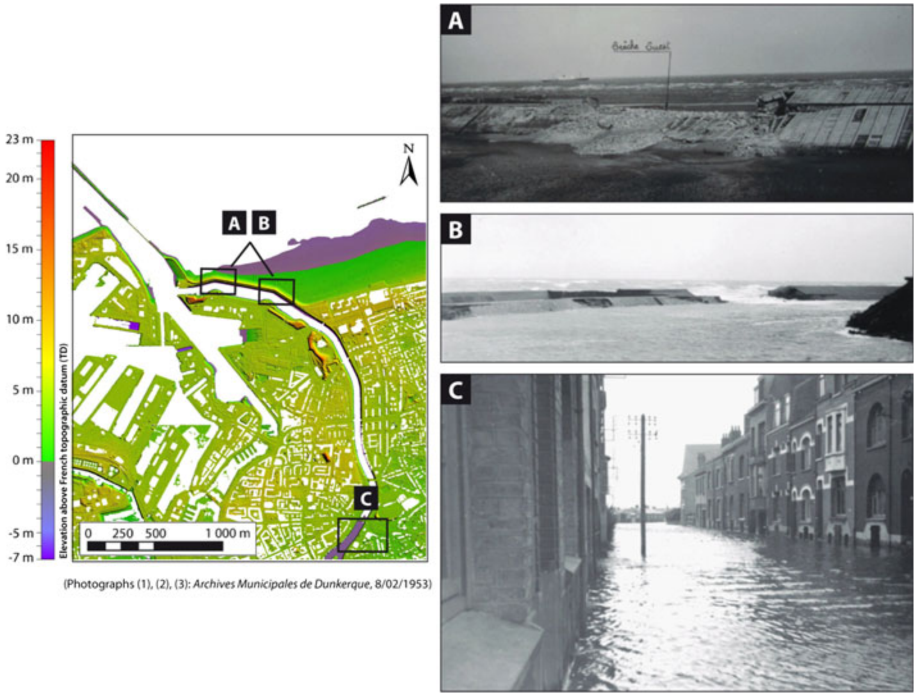

Fig. 4 Local impacts of the well-known North Sea flood of 1953 in Dunkirk: **a** two dike breaching along the outlet canal, **b** dike submersion, **c** marine flooding (poststorm photographs from the *Archives Municipales de Dunkerque*)

strengthened after this event), with Northerly winds resulting in a residual tidal height maxima of 1.55 m at Dunkirk (predicted high water level: 5.60 m HD; recorded water level: 7.15 m HD). Episodically, storm events induced coastal erosion or marine submersion during the last 50 years. In January 1978 for example, strong North Sea winds, combined with a spring tidal range induced a submersion of the sea front promenade during two consecutive high tides as a result of high water levels and strong waves.

3.2 The November 2007 North Sea storm surge

Fifty-four years after the Big Flood of 1953, starting in the night of the November 8 to November 9, 2007, a new strong storm surge, affecting the coastlines of the North Sea, occurred (Lamb 1991; Parker and Foden 2009). In Northern France, this storm surge was one of the largest surge affecting the Dunkirk coastline since the devastating flood of 1953.

Strong direct onshore winds (N-NW, higher than 10 m/s), blowing persistently during 48 h (Fig. 5a), were combined with an atmospheric pressure decrease of 23 hPa (Fig. 5b). Despite moderate tidal range conditions (4.67 m), these onshore winds resulted in a surge of 1.20 m during two consecutive high tides (Fig. 5c). The recorded surge magnitude due to the combined effects of the tide and the storm surge was 2.16 m at low tide. It should be noticed that this recorded surge magnitude of 2.16 m (hourly sampling; instantaneous surge of 2.38 m with data per 5 min) is probably underestimated because the tide gauge is located in Dunkirk harbor (Fig. 1c).

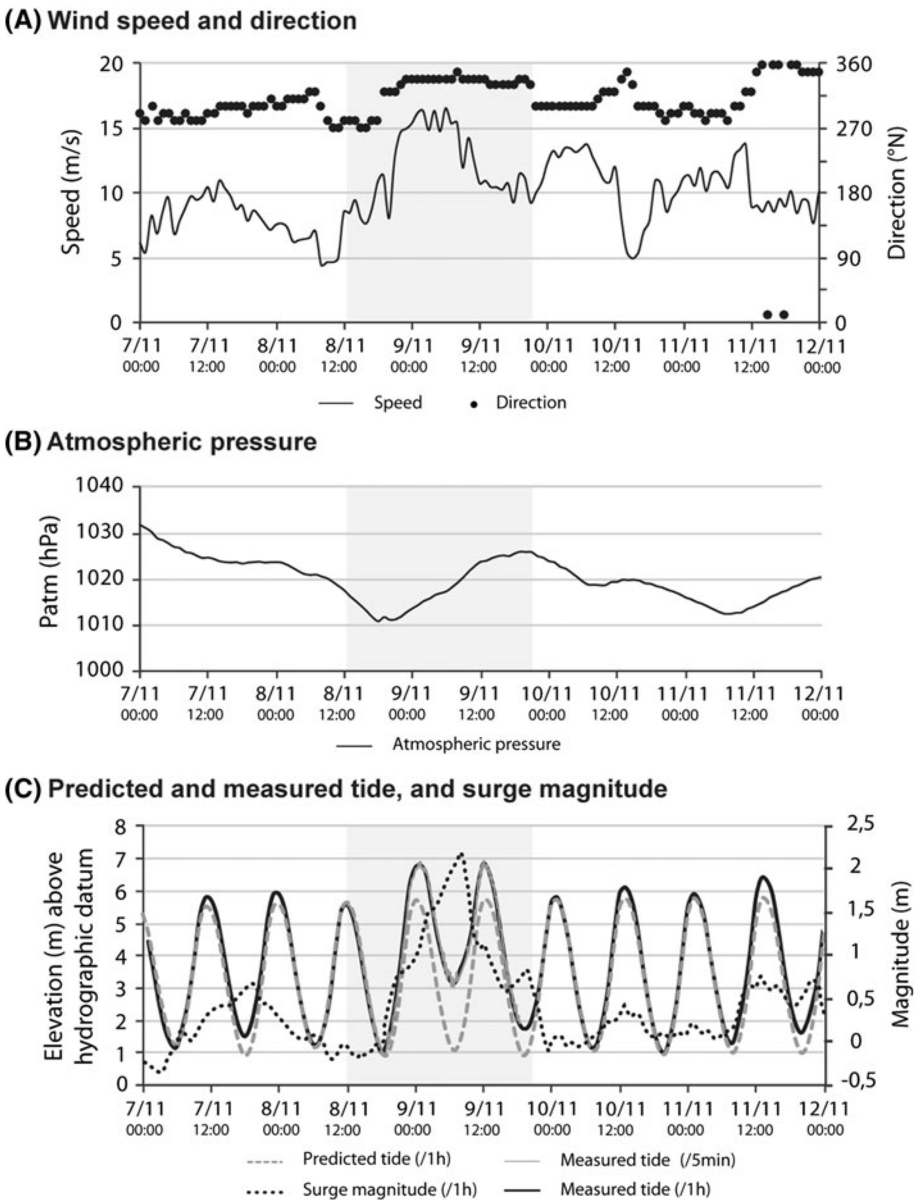

Fig. 5 Time series of **a** wind, **b** atmospheric pressure, **c** predicted and measured tide, and surge magnitude recorded at Dunkirk station during the November 8–9, 2007 storm event. Water elevation is relative to the Hydrographic Datum (HD)

Although at high tide the surge was less than 1.20 m, and occurred during moderate tidal range conditions, the highest water levels recorded on the November 9, 2007 were about 6.8 m HD (01:00 UTC) and 6.9 m HD (12:00 UTC) (without waves). It nevertheless induced beach erosion, dune scarping (Fig. 6b1–b2) and seafront promenade submersion (Fig. 6c). Strictly based on the recorded water levels at the Dunkirk tide gauge, without

Fig. 6 Local impacts of the November 8–9, 2007 storm event: (**b1**, **b2**) beach/dune erosion and shoreline retreat along the coastline East of Dunkirk, **c** seafront promenade submersion and **d** polder drainage could not occur during 24 h (semi-aerial and ground photographs from A. Maspataud, 2007–2010 and G. Delaine, 1994)

considering waves and onshore wind-induced stresses, the dune foot would have really been reached only once a time, and the sea front promenade would never have been overtaken by breaking waves during this storm event. However, persistent onshore winds and wave breaking induced wave-related processes that had a significant impact on the storm surge at the coast. Several studies show that wind-wave stress processes frequently produce a wave setup, a mean sea-level elevation due to the wave action (Komar 1998), that can contribute significantly to the whole storm surge insofar as this wave-induced setup can represent several tens of centimeters in the total surge (Wolf 2009).

Processes that control the swash zone are also involved in the sea level rise to the shore, as the sum of the water-related setup and the wave uprush induce wave run-up processes (Komar 1998; Ruggiero et al. 2001; Stockdon et al. 2006). Conditions during which wave run-up maxima reached or exceeded the elevation of the dune foot (6.80 m) or the beach-dike junction are taken to be a reasonable proxy for respectively potential erosion of the dune front or dike submersion. Using the Ruggiero et al.'s formula (2001), well suited to dissipative macrotidal beaches, the estimated values of run-up (theoretical but consistent with field observations) exceeded 0.50 m during the peak of the storm and rose extreme water levels up to 7.31 and 7.40 m above HD, at high tides on the November 9, 2007 (Maspataud 2011).

It should also be noticed that, as this surge of 2.16 m occurred at low tide, the maximum water level over which gravity drainage cannot be performed was then constantly exceeded. Consequently, during this storm event, the drainage of the polder (by gravity drainage and sluice gate operation) could not be operated during 24 h (Fig. 6c). Hydraulic data recorded at the outlet gate (*Station de Tixier*) reveal that before and after the peak of the storm, the sluice gate opening occurred at low tide normally (Fig. 7 bottom plot). On the contrary, gravity drainage was impossible on 9 November because of the significant residual tidal height of 2.16 m.

This surge, the largest event measured since the 1953 storm surge, fortunately occurred at low tide, during moderate tidal range conditions. The highest water level recorded during the November event was approximately 0.90 m lower than the level reached during the 1953 flood or storm surge. Moreover, the peak of the storm surge occurred nearly 5 h

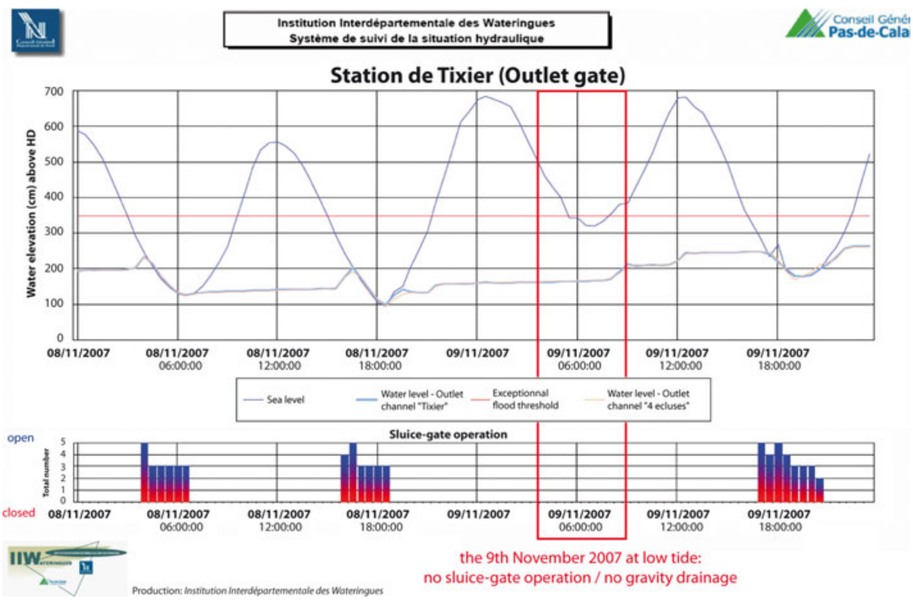

Fig. 7 Data recorded at the outlet gate (*Station de Tixier*) during the November 9, 2007 storm. Water elevation (cm) above HD (*top plot*) and sluice gate operation gravity drainage (*bottom plot*) (data extracted between the November 8, 2007 00:00 and November 10, 2007 00:00, and courtesy provided by the *Institution Interdépartementale des Wateringues*)

before high tide. The November 2007 storm surge did not therefore induce widespread flooding, only a slight submersion of the seafront promenade due to high water level and wave action (driven by strong winds). If the storm surge happened only few hours later, at high tide, maximum water levels would have been higher than in 1953, and the consequences could have been disastrous. It is largely a matter of chance that this was not the case. However, damages can also occur during moderate surges, when they are combined with a spring tide, as what happened, when a 1.10 m surge arised in March 2007 (Ruz et al. 2009).

4 Perspectives on potential impacts of extreme surge events

If the peak of the surge occurred 1–2 h before high tide or at high tide, with moderate tidal range conditions (4.66 m) and a predicted high tide level of 5.76 m above Hydrographic Datum, the observed water level could have reached 7.92 m HD. In this case, the event would overtake a magnitude exceeding by several centimeters the highest level of 1953 (7.90 m HD). In case of a storm surge induced by direct onshore winds (N-NW), several areas could be flooded, especially if some strong waves overtop the sea front, some streets could be flooded as what happened in January 1978 (Fig. 8). In this sector, new residential areas could be affected by such high water levels (Fig. 9b, c). The area enclosed by a red

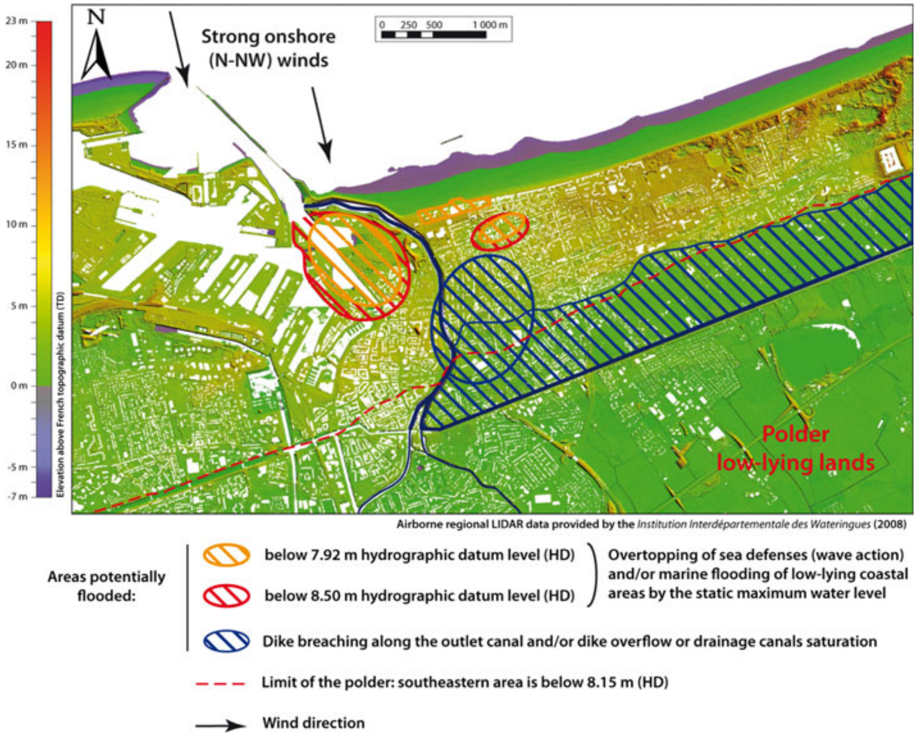

Fig. 8 Potential risks in case of occurrence of the November storm surge of 2.16 m (1) at high tide under the same tidal range conditions and (2) at high tide under spring tide conditions

dotted line also represents the limit of the polder, where land elevation is lower than the estimated water level of 7.92 m HD.

The second scenario is the occurrence of such an extreme event combined with a high tide during a spring tide. Considering a spring tidal range of 5.67 m (recorded 15 days before the 9 November storm), with a predicted high tide level of 6.34 m HD and a surge of 2.16 m, the water level (in the harbor) could reach 8.50 m HD. In this configuration, potentially flooded areas might be larger (Fig. 8), and several low-lying and new residential areas, built at low elevations (7.49–7.79 m HD) at the harbor entrance, could be particularly affected (Fig. 9). Furthermore, in case of watergangs overloading, or dike breaching, parts of the city could also be flooded, as what happened in 1953.

In a context of global change and projected sea-level rise, such events could induce major damages in the next future, especially if an extreme surge occurs at high tide during a spring tide. In the future, water level setups due to storm surges might increase, such as expected, for example, in Woth et al. (2006), or when strongly increasing rates of mean sea-level rise will outperform the growth of beaches and will induce more exposed coastal protection structures and dunes, as higher waves will be able to propagate toward the coast (Niemeyer et al. 2011). Then, stronger storms and higher risks may be expected as a consequence of a combination of sea-level rise and increased storm surge setup, and a consequence of a possible increase in extreme wind speeds in the

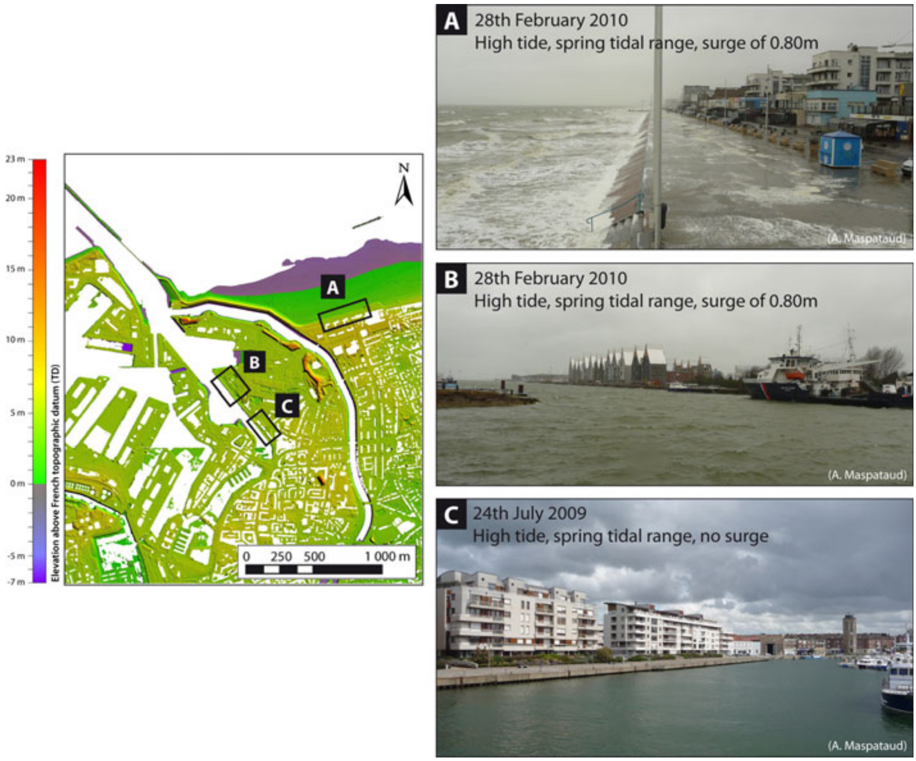

Fig. 9 Low-lying and new residential areas that could potentially be affected if extreme high water levels occur: **a** western part of the Dunkirk seafront promenade, **b**, **c** new built-up areas along the Dunkirk East-harbor

future (Rockel and Woth 2007). Extended areas near the seafront and the Dunkirk harbor entrance could be submerged and/or flooded. Furthermore, coastal dunes, which act as natural ramparts against marine flooding, could dramatically retreat, and the polder could be inundated. Although the sea defenses system in place in Northern France is now much better than it was in 1953, if the above scenario happened, it could result in the submersion of large proportion of the seafront breaching of dykes, polder flooding and dramatic coastal retreat.

Tidal analysis, carried out to assess the return period of the chosen scenarios, show that during the last decades, damages from flooding were, in most cases, limited mainly by chance because no major surge coincided with a high spring tide. Indeed, these events correspond either to moderate surges coinciding with high tide or to significant surges with the peak being reached some hours before or after the high tide (Pirazzoli et al. 2007). Tide–surge interactions seem to increase eastward along the English Channel, but no significant long-term changes in the distribution of tide–surge interaction are evident (Haigh et al. 2010). Checking in what extent extreme surges might actually coincide with high spring tides in Dunkirk, Pirazzoli (2006) estimates the possibilities of coincidence of about 41.29 % in this station (French average of 37 %), considering the monthly distribution of astronomical tides ($\geq$6.31 m) and surges at or above the 99.9th percentile ($\geq$1.08 m).

Estimating the return periods (T_{return}) for instantaneous surges of 1.80 m (10 years), 2.15 m (50 years) and 2.25 m (100 years), Pirazzoli (2006) provided a reasonable estimate of the return period, for example, for the maximum recorded surge of 2.18 m (T_{return} about 72 years) on the January 3, 1976 (Maspataud 2011), and the exceptional surge of 2.40 m on the February 1, 1953 with a return period exceeding 100 years. In order to assess the likelihood of extreme water levels associated with storm surges in Dunkirk area, Simon (2008) calculated the return period of extreme water levels (above HD) at high tide for 10-years (7.113 m), 20-years (7.193 m), 50-years (7.323 m) and 100-years (7.433 m) storm tide levels. The above-estimated extreme water levels of 7.92 m HD (scenario 1: surge of 2.16 m, at high tide) and 8.5 m HD (scenario 2: surge of 2.16 m, at high tide, during a spring tide) appear to be well above the before-mentioned 100-year level. It is worth pointing out that Pirazzoli (2006) also presented ranges for estimated extreme water levels above HD in Dunkirk: in 2050 for a 50-year [mean value of 8.02 m (7.91–8.13 m)] and a 100-year return period [$\approx$8.15 m (7.95–8.35 m)], and in 2100 for a 50-year [$\approx$8.60 m (8.11–9.09 m)] and a 100-year return [$\approx$8.73 m (8.45–9.01 m)]. As shown by Lowe and Gregory (2005), these results thus suggest that, in the future, return periods of large events, for the same extreme water levels, could decrease in the next decades/century: for example, for scenario 1, a maximum water level of 7.92 m HD for estimated $T_{\text{return}} > 100$ years, while $T_{\text{return}(2050)} \approx 50$ years and $T_{\text{return}(2100)} < 50$ years and, for scenario 2, a maximum water level of 8.50 m HD for $T_{\text{return}(2050)} > 100$ years and $T_{\text{return}(2100)} \approx 50$ years.

5 Discussions and conclusions

In this area, the extreme events consequences, like beach-dune erosion, marine submersion, urban and polder flooding strongly depend on the occurrence of three factors: a strong storm event with moderate to strong ($\geq$8 m/s) direct onshore winds (N-NW) blowing persistently during 24 h and more (Ruz et al. 2009) and low atmospheric pressures, inducing a storm surge, at high tide, and with a mean or spring tidal range. Such conditions could be worse, especially in case of dike breaching or submersion at high tide, impossibility of discharging excess water into the sea at low tide, pumps saturation or failure and worsen climatic factor like precipitation surplus. How long could the safety of the lowland areas in this region be maintained at present standards?

According to the previous results, there is a real risk of this coastal area facing extreme surge events (proven in the past and today persistent), such as marine submersion, low-lying urban and agricultural land flooding. There is also a concern about the capacity for the drainage system to evacuate excess water. During the last centuries, water levels in the southern North Sea increased due to mean sea-level rise (Weisse et al. 2011). More recently, MSL rose about +1.8 mm/year in Dunkirk during the last 50 years and about +3.2 mm/year in the neighboring belgian harbor of Nieuwport since 1966, with an accelerated rate of +4.3 mm/year since the 1990s. So, how long gravitating discharge of polder water will still be possible with the existing system? Among the different sections of the Watergang French system, the Dunkirk area is the most sensitive to hydro-meteorological events like storms insofar as this area possesses the largest sector of low-lying territories and because its coastline is often submitted to strong northern winds blowing over the North Sea.

Hazard mapping of hinterlands flooding, dike submersion and/or dune erosion represents a critical issue in coastal low-lying areas due to their sensitivity to extreme storm (Weisse et al. 2011). Furthermore, such energetic events are difficult to predict in advance, mostly when a combination of worsen factors (tide conditions, failure of coastal defenses, etc.) increase the potential risks, already present, as what happened along the western coast of France during the storm Xynthia that occurred in February 2010. This event, the most dramatic along the French Atlantic coast, may be to some extent compared with the North Sea storm surge of 1953: dikes submersion, polder flooded, deaths, etc. Following this storm Xynthia, the French government and scientific community as the local authorities agreed to emphasize that the inadequate consideration of all the phenomena, and their conjunction has led to considerable uncertainty about the event, and the real need to consider and interpret all historical events. All the more than today, the increasing availability of data and development of tools for several years allow the development of new methods. A quite recent awareness in France, unlike what had been done in North Sea neighboring countries.

In the most densely populated and low-lying areas of the North Sea coastal region, several national institutions are involved in storm surge forecasting and warning systems, depending upon the cooperation of different scientific disciplines and user communities. Keeping in mind the dramatic events of 1953, the Delta Plan, in the Netherlands, included for example heightening of dikes and construction of several new dams and barriers, especially in the 306 surcotes southwestern part of the country (Verlaan et al. 2005). In addition to better defense against flooding by the sea, warning systems were also improved, taking into account the magnitude of surges directly related to the strength of onshore winds, the local geometry of the coastline, the topography of the area (Von Storch and Woth 2008). Such systems make use of in situ data in order to develop and maintain operational ocean models used to forecast storm surges for coastal flood warning systems on the coasts of England, Wales and Belgium. Locally, in the case of severe storms, dikes and barriers can be staffed in time to prevent them from breaching or overtopping (e.g., Thames Barrier, Eastern Scheldt Storm Surge Barrier). Along the French coast of the English Channel, some regional institutions have already established operational systems to forecast events potentially at risk from weather-marine archives (events that have already resulted in a flood), in order to alert local authorities and warn and/or displace concerned populations. Knowing the extreme water levels that can be reached for given conditions (wind direction, speed and duration, and surge magnitude), weather-marine data should also be taken into account on the extreme northern coast of France.

Considering that such events have already occurred in the past and might probably occur again, in a forthcoming future, perhaps with shorter return periods, there remains a real need to implement coastal risk policies prevention and management in a European context (Weisse et al. 2011). Haigh et al. (2010) show that there is evidence for a small (0.3 mm/year) increase in annual mean high water (relative to mean sea level) at certain sites and also for an increase (primarily due to the direct rise in mean sea level) in extreme sea levels during the twentieth century in the Channel. Lowe and Gregory (2005) also confirm that changes in storminess will increase the height of storm surges at most coastal locations around the Channel and that increases in time-average sea level will also tend to increase the height of extreme water levels. Insofar as stronger storms and higher risks might be expected along such low-lying coast, as a combination of sea-level rise, enhanced storm surge setup and maybe increases in extreme wind speeds, stakeholders will have to consider estimated storm surges maxima for pessimistic but conceivable scenarios. They will thereby have to face increasing challenges in warning and protecting coastal communities against marine submersion, hinterlands flooding and coastal erosion. It is then important for the local authorities to take into account the potential impacts of such events, with policy implications in order to allocate sufficient funding for monitoring and reinforce sea defenses (according to potential extreme water levels), increase pumping stations efficiency, draw up regional urban and rural scenario's and, first of all, planning warning systems like in neighboring countries which is not the case yet in Northern France.

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