

Extracting storm-surge data from coastal dunes for improved assessment of flood risk

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ABSTRACT

Future changes in climate and sea level are likely to increase the threat from storm surges in many coastal regions. Mitigation of this threat requires an understanding of storm surge magnitude and frequency, and the relationship of these variables to climate parameters. This understanding is currently limited by the brevity of instrumental records, which rarely predate the twentieth century. However, evidence of former storm surges can be recorded in coastal dunes, because the dune topography may trap high-magnitude deposits at elevated locations. Here we combine a range of techniques to extract storm-surge data from coastal dune sediment. The sediment is tracked in the subsurface with ground-penetrating radar to assess its height and extent, and its age is determined with good precision through optically stimulated luminescence dating. The probable age of the sediment (A.D. 1775 or 1776) is within a period of increased storminess in northwest Europe, and the local magnitude of the event is likely to be greater than any on instrumental record. By utilizing coastal dunes for storm surge analysis, our approach provides a valuable new source of information for understanding storm surge risk, which is vital for the protection of coastal regions.

INTRODUCTION

Instrumental records of sea level provide the basic return-frequency data for flood events, but reliance on these records presents two major problems for flood-risk predictions. First, the records are shorter than the return frequency of extreme events, leading to imprecision in the time-magnitude estimates of major storm surges (Van den Brink et al., 2005). Second, the climate of the future is unlikely to remain the same as it was during the period covered by instrumental records. Future changes in climate are likely to affect storm tracks, altering the storm-surge response compared to that during the monitoring period (Lowe and Gregory, 2005).

In northwest Europe, storm tracks are linked to the phase and strength of the North Atlantic Oscillation (NAO) (Ulbrich and Christoph, 1999; Pinto et al., 2009), which defines the pressure gradient between the Icelandic low and the Azores high. The relationship is not straightforward (Lozano et al., 2004), and the response of extreme events to changes in the NAO may be different from that of moderate events (Pinto et al., 2009; Ulbrich et al., 2009). This relationship would be better understood if storm-surge data existed for periods when the NAO mode was different from today, particularly for the centuries preceding the instrumental record. This period of interest corresponds to

the episode of recent climate history referred to as the Little Ice Age, lasting from ca. A.D. 1400 to 1850, when Northern Hemisphere temperature was as much as 0.6 °C cooler than during the late twentieth century (Mann, 2002). During the Little Ice Age, there was an increase in wind strength in the North Atlantic and Europe (Meeker and Mayewski, 2002; Matulla et al., 2008), and a corresponding increase in sand mobility in coastal dunes fringing European seas (Clarke and Rendell, 2009).

The analysis of sediment in coastal dune environments offers great potential for increased understanding of storm-surge risk. The elevated topography of the dune environment traps sediment indicative of the magnitude of former storm surges. The ability to tap this data source would open a new avenue of research on former storm-surge magnitude, and would complement the raw frequency data available from back-barrier overwash sediment. However, the extraction of this information is challenging, and necessitates a multidisciplinary methodology, which we present in this paper. Starting from an extensive bluff-face exposure on the western coast of the Netherlands, we describe the form of the sedimentological evidence in relation to the predepositional environment, aided by subsurface radar tracking. The sediment is dated to the late eighteenth century using optically stimulated luminescence (OSL) methods, combined with Monte Carlo simulations of radia-

tion deposition. Finally, the interpretation of the deposit is validated against eighteenth century documentary sources.

SEDIMENTOLOGY

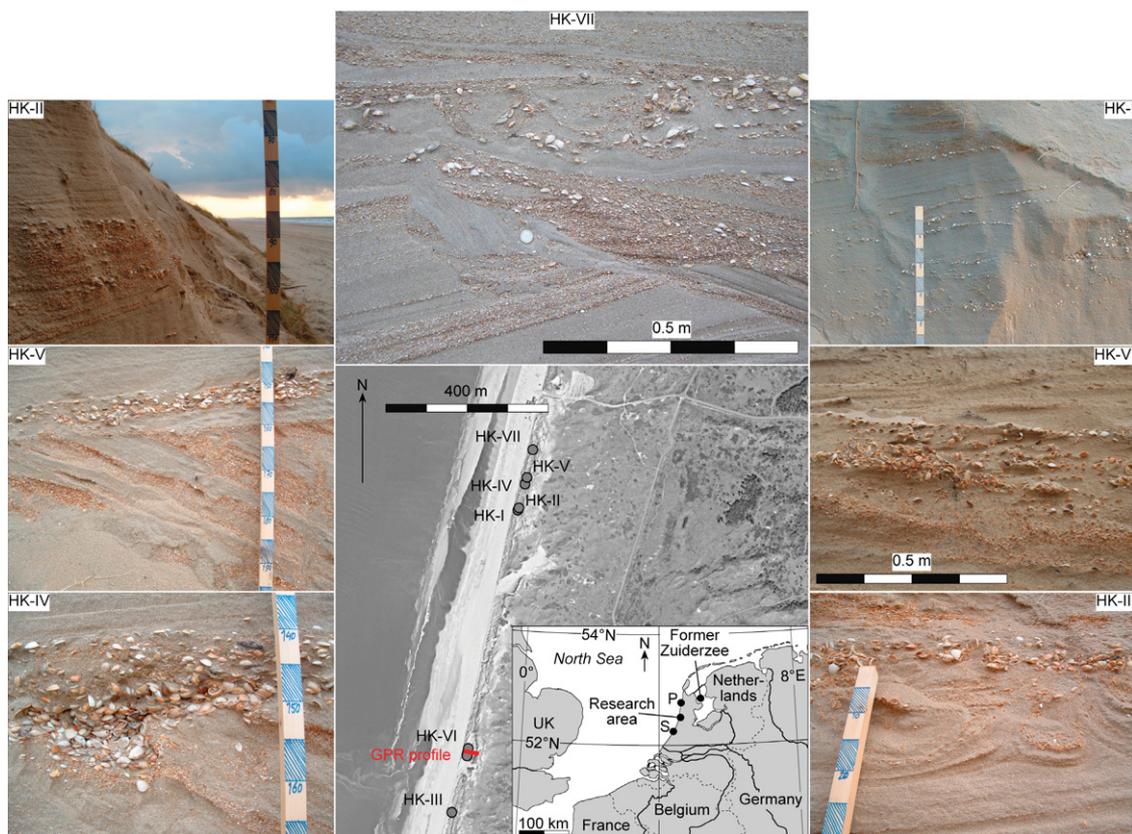
For this research we described and analyzed storm-surge sediment temporarily exposed within a 1-km-long stretch of coastal dunes near Heemskerk, Netherlands (Fig. 1). This dramatic exposure was created during a significant storm surge in November 2007, which eroded the foredune back by 10–15 m at the field location. The striking feature of this exposure was a discontinuous, convolute bed of shell-bearing sand, 10–15 cm thick. The shell unit undulated in height along the exposure, commonly exceeding 4 m +NAP (NAP, the national vertical datum in the Netherlands, is roughly mean sea level), and in some places dipping below the dune foot (~2.5 m +NAP). The exposed shell unit reached the highest point of 6.5 m +NAP at section HK-1, where it was observed as a series of convex-side-up shell layers separated by sand beds. Locally, the unit was observed to truncate the underlying dune sand (HK-V, HK-VII; see Fig. 1).

The mass of the shells, found with scattered pieces of brick and intact bivalves, rules out eolian transport. Moreover, the convolute beds and other deformation structures of the shell unit are indicative of near-surface saturation by water during formation: air, trapped by a water-saturated upper zone and compressed by pressure from the water column, deforms the surrounding sediment (De Boer, 1979). As the maximum elevation of the shell unit far exceeds normal water levels (mean high water is ~0.9 m +NAP), the extensive shell layers could only have been deposited during storm-surge conditions.

The shell layers consist mainly of fossil molluscs reworked from Holocene shoreface and tidal-channel deposits. Mollusc composition differs little from that of present-day Dutch beaches, with the presence of mollusc species typical of water shallower than ~15 m –NAP (e.g., *Cerastoderma edule*, *Macoma balthica*, *Angulus fabulus*, *A. tenuis*), as well as species

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Figure 1. Location of study site, and images of seven foredune exposures (HK-I–HK-VII) showing various storm surge-related sedimentary structures. Scale bar visible in five exposures has 5 cm sections. Seven exposures were situated along 1-km-long stretch of scarped foredune in western Netherlands, as shown on aerial photograph. Ground-penetrating radar (GPR) profile associated with HK-VI is shown as red line. S—Scheveningen, P—Petten. HK-II: 20-cm-thick unit of shells and shell hash without deformation structures. HK-V: Air-escape structure (to right of scale bar) in unit that consists of intercalated sand and shell hash. HK-IV: Pocket of shells in sand. Some shells are articulated *Cerastoderma edule*. They are empty, indicating that they died shortly after being displaced by storm surge. HK-VII: Convolute beds highlighted by distribution of whole shells, and underlying slump structure. HK-I: Multiple subparallel horizons of single shells that are mostly oriented convex-side up. HK-VI: Flame structures in shell hash underlying shell-rich unit. HK-III: Convolute beds highlighted by distribution and orientation of shell hash, covered by shell layer.



typical of deeper water (e.g., *Spisula subtruncata*, *Maetra corallina*, *Donax vittatus*, and the gastropod *Euspira pulchella*). The only double-valved specimens found in the storm surge deposit were *Cerastoderma edule*; ~50 of these were clustered at section HK-IV. As there was no sand inside any of these specimens, it is likely that they were alive when they were uprooted from the seabed and washed onto shore at the time of the storm surge.

Information on the inland extent of the shell-rich unit was obtained through ground-penetrating radar (GPR). The exposed bluff face at section HK-VI provided an ideal starting point for GPR profiling, allowing immediate ground-truthing of the GPR signatures (Fig. 2). The shell unit is identifiable as a planar, high-amplitude reflection that shows a gentle overall dip in a landward direction. The continuous reflection extends to 1 km inland, where it appears to be linked to former interdune lows. At these inland locations, wind-blown pits, boreholes, and hand-dug trenches provided further verification of the GPR signature.

The distribution of the storm surge unit reflects a contemporary frontal dune configuration that differs from the artificially maintained sand dike marking the modern coastline. In historical times, vulnerable lows in the dune ridge

were not uncommon, as testified by numerous paintings and drawings. Several dune gaps were present near Heemskerk during the eighteenth century (Kops, 1798). The presence of these gaps explains the nature and lateral distribution of the observed storm surge unit. Water entered the inner dunes through gaps, scouring wide channels, overtopping low dunes, and depositing extensive perched fans (cf. Morton and Sallenger, 2003) and sheets. Sand and shells were transported landward and deposited mainly behind the frontal dunes and other large obstacles, where current velocities and wave energy diminished. The fact that the exposed shell layers were overlain by thick units of eolian sand is the result of steady coastal erosion since their deposition, and an associated landward shift of the frontal dune. Annual coastal profiles from the research area show that the dune crest and dune foot have shifted landward by 30–40 m since A.D. 1965. Before that time, the frontal dune was located even farther seaward, placing the initial storm-surge unit behind the ridge and therefore not buried, or only slightly buried, for part of its existence.

DATING

OSL dating was conducted on three sections of the frontal dune (HK-I, HK-III, and HK-VII),

plus one section 600 m inland (ZN-I) that had previously been studied in a former exposure, but had not been reliably dated (Jelgersma et al., 1995). The OSL signal of quartz grains is reset by daylight exposure during transport of the grains, and builds up after burial through absorption of naturally occurring ionizing radiation. By using grains of quartz embedded in the sediment, OSL provides a direct means of dating an event, often when no other dating method is suitable. However, the OSL dating of flood deposits provides two significant challenges. (1) The exposure of quartz grains to sunlight during the event may be insufficient to completely reset the OSL signal, leading to an overestimate of the age. However, using recent developments in signal processing (Cunningham and Wallinga, 2010), this effect was found to be insignificant for all but one sample (for methods, see the GSA Data Repository¹; also see Figs. DR1–DR3 and Tables DR1–DR2 therein). (2) A more serious challenge is the heterogeneous nature of

¹GSA Data Repository item 2011311, methods, Figures DR1–DR6, and Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

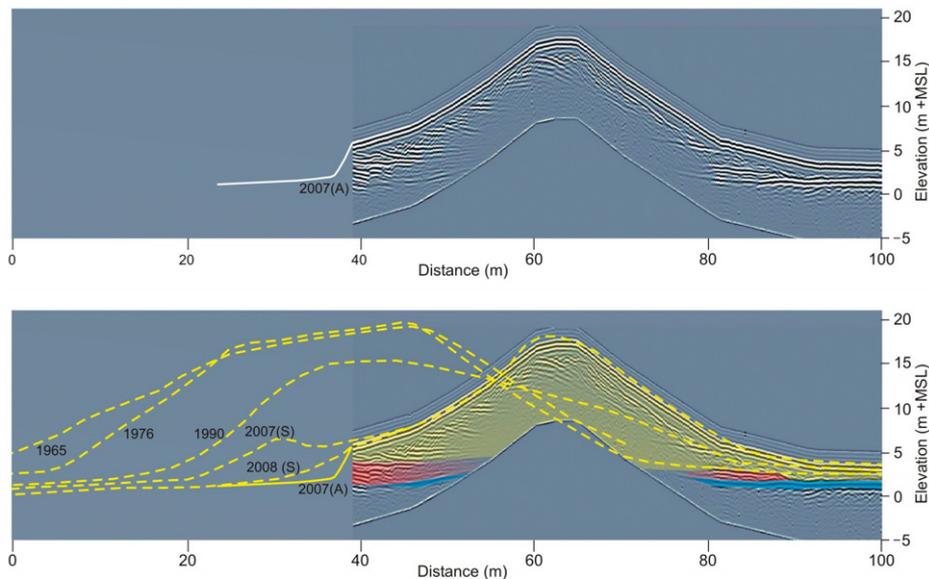


Figure 2. Ground-penetrating radar (GPR) profile across foredune at study site, and coastal profiles from selected years. Upper panel: GPR profile (200 MHz, unshielded), starting at exposure site HK-VI (left side of image) and tracking 60 m inland. MSL—mean sea level. Lower panel: Interpretation of GPR image. Storm surge beds (in red) are identified as planar, high-amplitude reflections, bracketed by curved facies representing eolian strata (in yellow). Groundwater table is shown in bright blue. Overlain are cross-shore profiles from the Dutch government monitoring database Jarkus, measured annually since A.D. 1965, showing steady erosion of dune foot and landward migration of dune crest. Profiles marked S (dashed lines) were recorded in spring; profile marked A (solid line) was recorded with RTK GPS (real time kinematic global positioning system) shortly after storm surge of November 2007.

flood sediments. For several of the storm surge samples, a high proportion of marine shells (~30% by weight) prohibits the usual approach to estimating the ambient radiation dose rate, as the shells have a significantly different radionuclide concentration from that of the surrounding sediment. To overcome this difficulty, we constructed a model of the deposition of beta electrons in the sediment, using a Monte Carlo transport code (Briesmeister, 2000; Schaart et al., 2002; Nathan et al., 2003), and determined the correction that should be made to the dose-rate calculations. With these techniques (detailed in the DR methods and Figs. DR4–DR6 in the Data Repository) we found consistent ages for the storm surge samples, validated by high-precision OSL ages on the overlying and underlying eolian sediment.

The OSL ages (Fig. 3; Table DR3) obtained for the three frontal dune sections indicate similar patterns of deposition across the three sites, categorized as follows: (1) eolian deposition prior to the storm surge event, A.D. 1600–1750; (2) deposition and deformation of sediment associated with the storm surge, A.D. 1760–1785; (3) eolian deposition following the storm surge event, A.D. 1775–1900. All three sections show an age gap between phases 1 and 2, most likely caused by erosion of material during the storm surge (apparent from the sedimentology). The inland section shows a similarly phased chronology, except that the underlying dune

sand (A.D. 1100) was deposited during an earlier period of eolian activity when the coastline was much farther seaward than today (Hallewas, 1981). For this site, the apparent age gap between phases 1 and 2 is more likely due to a hiatus in deposition.

DISCUSSION AND CONCLUSION

The existence of a significant storm surge in the late eighteenth century is confirmed by contemporary documentary sources. While reliable observations of surge height were not recorded at the time, written accounts attest to two major events taking place within the period determined by the OSL dating. These events occurred in consecutive years, 1775 and 1776 (Hering, 1776, 1778). Although there are no records concerning the field site, there are fragmentary records of the impact these storm surges had on more populated areas of the western Netherlands; these mostly concern the 1775 event. At the coastal town of Scheveningen, ~45 km south of the exposure site, half the town was flooded. Eyewitness accounts from Petten (20 km north of the site) recount the cutting of incipient channels into the frontal dune (Anonymous, 1776).

The extraction of sedimentary storm-surge records has hitherto exploited back-barrier sediment, notably hurricane overwash deposits in the western Atlantic (Donnelly et al., 2004; Boldt et al., 2010). Such records can determine storm surge frequency during the late Holocene, and

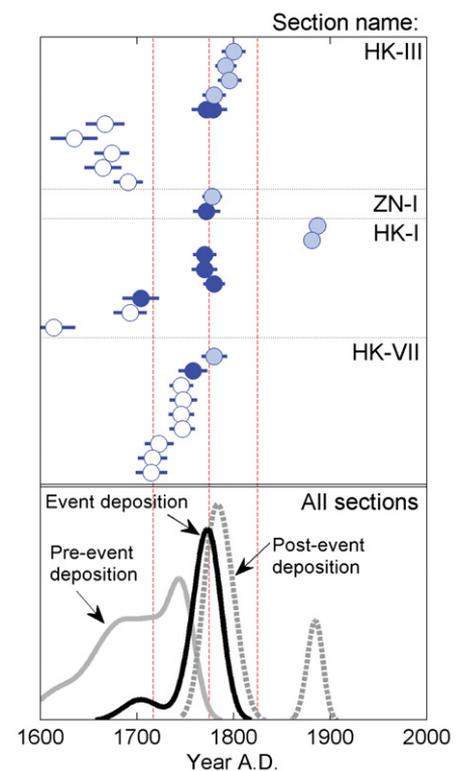


Figure 3. Optically stimulated luminescence (OSL) dating results. Upper panel: Each OSL age is plotted with its associated 1σ error term. Within each stratigraphic section (e.g., HK-III, ZN-I), samples are plotted in stratigraphic order. Open symbols—samples from below storm-surge unit; solid symbols—samples from within storm-surge unit; shaded symbols—samples from above storm surge unit. Lower panel: same OSL ages plotted as summed probability densities for pre-event, event, and post-event deposition. Dashed vertical lines indicate documented storm surges in A.D. 1717, 1775 and 1776, and 1825.

are particularly useful when they can be linked to climate parameters (Donnelly and Woodruff, 2007; Mann et al., 2009). The nonuniform topography of barrier systems makes analysis of their sedimentary record more challenging; nevertheless, an understanding of the subsurface can be gained through GPR profiling. The erosional signatures of storm surges have previously been identified in radar profiles (Bristow et al., 2000; Buynevich et al., 2004; Switzer et al., 2006). Furthermore, Buynevich et al. (2007) were able to use buried erosional scarps in a prograding barrier as a record of storm-surge frequency, with age constraints provided by OSL dating of the overlying sediment. Our methodology offers a new dimension in flood risk analysis. First, the elevation of the deposits within the dunes can be used to infer magnitude of storm surges, information that is not recorded in back-barrier sediment or erosional features. Second, the dune environment enables the use of OSL to date the sediment with a high degree of precision. The

importance of the dating should not be underestimated, as precise dating in the Little Ice Age time period is particularly difficult by other methods. This study further extends the use of OSL to shell-rich sediments, or other sediments with heterogeneity on the millimeter scale. Given the ubiquity of coastal dune systems, and the potential information on Little Ice Age storm surges contained within, this methodology could prove a vital tool in flood risk prediction under a changing climate.

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