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Sedimentary records of coastal storm surges: Evidence of the 1953 North Sea event

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ABSTRACT

The expression of storm events in the geological record is poorly understood; therefore, stratigraphic investigations of known events are needed. The 1953 North Sea storm surge was the largest natural disaster for countries bordering the southern North Sea during the twentieth century. We characterize the spatial distribution of a sand deposit from the 1953 storm surge in a salt marsh at Holkham, Norfolk (UK). Radionuclide measurements, core scanning X-ray fluorescence (Itrax), and particle size analyses, were used to date and characterise the deposit. The deposit occurs at the onset of detectable ^{137}Cs - coeval with the first testing of nuclear weapons in the early 1950s. The sand layer is derived from material eroded from beach and dunes on the seaward side of the salt marsh. After the depositional event, accumulation of finer-grained silt and clay materials resumed. This work has important implications for understanding the responses of salt marshes to powerful storms and provides a near-modern analogue of storm surge events for calibration of extreme wave events in the geological record.

1. Introduction

Sea-level rise will be a significant future environmental hazard, with the Intergovernmental Panel on Climate Change projecting that global mean sea level will rise 0.26–0.98 m above present by 2100 (Church et al., 2013). However, the greatest social and economic impacts are when moderate and extreme storms result in coastal flooding, which will increase in frequency with higher sea-levels (Nicholls et al., 2007; Church et al., 2013; Haigh et al., 2016). With the potential for the frequency of storm events to also increase (Seneviratne et al., 2012; Goodwin et al., 2017), it is important to understand how such events may affect emergency response, adaptation and infrastructure planning. There have been recent efforts to increase our understanding of the spatial and temporal clustering of extreme sea-level events, which has implications for the management and repair of flood-defence systems (Haigh et al., 2016). This endeavour requires a comprehensive dataset of extreme events in which to investigate spatial and temporal trends and provide information on coastal resilience and geomorphic response. In the United Kingdom, Haigh et al. (2015, 2017) have developed a database of 329 coastal flood events from 1915 to 2016 (SurgeWatch) based upon a variety of sources. Of these, eight events are ranked as severe and one as disastrous, the latter being the storm surge of 1953.

To be able to better understand these high-impact low-probability events, it is important to have a much larger dataset (greater than the current nine documented events), from which to construct detailed analysis which requires turning to historical (e.g., RMS, 2007) and geological records of extreme sea levels and storm events. Coastal geological archives have provided evidence of hurricane landfall (e.g., van de Plassche et al., 2006; Brandon et al., 2014), as well as European

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storm surges (e.g., Tsompanoglou et al., 2010; Croudace et al., 2012; Bateman et al., 2018). However, use of the geological archive in geohazard assessment requires understanding of how such events are preserved in coastal environments. Identification of sedimentary deposits associated with extreme wave events (e.g., tsunamis and storm surges) in the geological record is often difficult (Sedgwick and Davis, 2003; Kortekaas and Dawson, 2007). Even within more recent times there are a paucity of studies and data (e.g., Dawson et al., 1995; Kortekaas and Dawson, 2007). Such geological evidence can aid in detecting past changes in storm surge activity, by extending reconstructions of storm surges from tide gauge records and of storm indices further back in time.

In this paper, we conduct a geological investigation into the preservation of the well-documented 1953 storm in a salt marsh environment, > 60 years after the original event. The 1953 storm was the most severe rapid event to occur in the North Sea during the 20th Century. The event occurred when a storm surge from the North Sea swept across the northwest European shelf and flooded low-lying coastal areas of countries around the North Sea. The resulting disaster in terms of loss of life and damage to infrastructure was enormous. The Netherlands was worst affected with 1836 people killed; in the UK and Belgium, death tolls were 307 and 22, respectively (Gerritsen, 2005). The storm surge led to breaches of coastal flood defences and produced the highest still-water levels on record at several tide gauges on the UK east coast. Several features were observed in the coastal zone at the time, including notches in soft rock cliffs, cliff retreat, and erosion of coastal dunes and reactivation of wash-over deposits (Spencer et al., 2015). However, the expression of the 1953 storm surge in the stratigraphic record around the North Sea remains unclear. Many previous studies of extreme wave events in the stratigraphic record have relied on detailed sedimentological descriptions and micropaleontology (e.g., Kortekaas and Dawson, 2007; Morton et al., 2007). Here we combine sedimentology with elemental geochemistry to identify a known event in a salt marsh. In addition, an understanding of the effects of past storm surges (e.g. the December 13th 1981 event in the Severn Estuary; Croudace et al., 2012) is much needed in the UK as future such events may pose a significant threat to existing coastal industrial and urban infrastructure, and planned nuclear reactors on the coast (e.g., Hinkley, Somerset; Sizewell, Suffolk; and Bradwell, Essex).

2. Study site

Our study site is a small salt marsh at Holkham on the north-facing coastline in North Norfolk, UK (52.974532°N, 0.759193°E; Fig. 1). The salt marsh is located east of the River Burn and behind an extensive coastal dune system. This coastline is low-lying and characterised by a moderate to low wave regime from the North Sea, westerly longshore drift and macro-*meso* tidal ranges (Andrews et al., 2000; Bateman et al., 2015). The coast at Holkham prograded during the Holocene and there is active accumulation of beach dunes at present (Andrews et al., 2000; Bateman et al., 2018). We targeted Holkham marsh to identify and describe the geological deposit resulting from the North Sea flood of 1953 because the event caused flooding with water reaching up to 6.31 m OD nearby at Wells-Next-The-Sea in Norfolk (Supplementary material 1), erosion of dunes, and deposition of shingle and sand on salt marshes at this location (Steers, 1953; Steers et al., 1979; Spencer et al., 2015).

3. Materials and methods

Seventy-six cores were taken across Holkham marsh using gouge and Dutch augers to determine the general stratigraphy of the site (Figs. 1 and 2). A master core (where the thickest 1953 storm deposit was found) was then collected using a Russian corer following De Vleeschouwer et al. (2010) for further laboratory analyses. Cores were logged in the field following Tröels-Smith (1955) and a subset of cores were surveyed into a local benchmark. The age-depth relationship of the core is based on ^{210}Pb and ^{137}Cs determinations using high-resolution Gamma spectrometry at the GAU-Radioanalytical Unit (National Oceanography Centre in Southampton – NOCS). Samples were prepared and analysed following standard procedures to determine ^{210}Pb and ^{137}Cs activities. Calculation of the sediment accretion rate (SAR) (cm yr^{-1}) assumes that no radionuclide migration occurs within the sediment profile following deposition. However, the post-depositional mobility of the radionuclides and sedimentation phases should be considered during interpretation. The application of ^{210}Pb and ^{137}Cs dating in coarse-grained sediments could also be hindered by the lower sorption capacity of siliceous particles (Tsompanoglou et al., 2010).

XRF geochemical scanning is a time and cost-efficient means to obtain high-resolution geochemical information and laser diffraction particle size analysis can provide detailed information on grain size populations in a sedimentary succession; hence, both methods were used. Itrax X-ray fluorescence core scanning was undertaken at NOCS, using Mo and Cr X-ray tubes. The peak area intervals are "nominally proportional to concentrations of major and minor elements within the sediment" (Croudace et al., 2006). Particle size analysis was carried out using a Coulter LS230 Laser Diffraction Particle Size Analyser following removal of organics using hot H_2O_2. End-member modelling analysis (EMMA) was performed on each grain-size dataset following Dietze et al. (2012). Bulk density and loss-on-ignition were undertaken using standard methods (Chambers et al., 2010). Magnetic susceptibility of the cores was determined using a Bartington loop sensor (MS2C) and MS2 instrument.

4. Results and discussion

The locations of the seventy-six cores in the Holkham marsh are shown in Fig. 2. The stratigraphy of the Holkham salt marsh is characterised by clays and silts with organics and occasional sand which is typical of salt marsh environments (Fig. 3). A sand horizon was present at ~40–60 cm below the surface in most cores, possibly representing an earlier event than the 1953 storm. At the landward (southern) side of the marsh the uppermost sediment is a peaty soil, reflecting development of high-marsh. Dune sands, sometimes covered with peaty soils, are present in the northern portion of the salt marsh (Fig. 3).

In the south-east portion of the marsh (in 16 of the 76 cores) a thin sand layer of between 0.5 and 3.0 cm thick (μ = 1.26 cm) was found between 23 and 28 cm (μ = 25.4 cm) in the cores (Figs. 2–4). The altitude of the base of the sand layer varies between 2.5 and 2.7 m above Ordnance Datum (UK) (μ = 2.6 m) (Fig. 4). The maximum thickness of the deposit is greatest in the southern landward edge of the marsh which is slightly higher in elevation (Fig. 4). There is a significant correlation between elevation of the thin sand deposit where it is present and latitude ($r = 0.74$; $p < 0.001$) suggesting that the topography of the marsh was similar in the past to today (higher in the southern edge). There is no significant relationship between longitude and elevation of the thin sand unit. There is a significant relationship between thickness of the thin sand unit and elevation ($r = 0.55$, $p < 0.05$), illustrating that the thicker units are in the higher southern parts of the marsh.

In the core analysed in detail, profiles of ^{137}Cs and ^{210}Pb show trends associated with changing radionuclide inputs and sediment composition (Fig. 5) and produce consistent chronologies. ^{137}Cs variations provide evidence for two main rates of sediment accumulation that are largely corroborated by the ^{210}Pb record (determined by gamma spectrometry). Key markers in the ^{137}Cs record were used to build the age model, including: (1) the first appearance of ^{137}Cs, coincident with the onset of atmospheric nuclear weapons testing ~1954 (range = 1950–1955); (2) the ^{137}Cs bomb peak (1963, albeit rather subtle); and (3) changing inputs from marine discharges from the Sellafield reprocessing plant as revealed by distinct inflections (Gray et al., 1995; Tsompanoglou et al., 2010). McCubbin et al. (2002)