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Can sand dunes be used to study historic storm events?

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ABSTRACT: Knowing the long-term frequency of high magnitude storm events that cause coastal inundation is critical for present coastal management, especially in the context of rising sea levels and potentially increasing frequency and severity of storm events. Coastal sand dunes may provide a sedimentary archive of past storm events from which long-term frequencies of large storms can be reconstructed. This study uses novel portable optically stimulated luminescence (POSL) profiles from coastal dunes to reconstruct the sedimentary archive of storm and surge activity for Norfolk, UK. Application of POSL profiling with supporting luminescence ages and particle size analysis to coastal dunes provides not only information of dunefield evolution but also on past coastal storms. In this study, seven storm events, two major, were identified from the dune archive spanning the last 140 years. These appear to correspond to historical reports of major storm surges. Dunes appear to be only recording (at least at the sampling resolution used here) the highest storm levels that were associated with significant flooding. As such the approach seems to hold promise to obtain a better understanding of the frequency of large storms by extending the dune archive records further back to times when documentation of storm surges was sparse. © 2017 The Authors. *Earth Surface Processes and Landforms* published by John Wiley & Sons Ltd.

KEYWORDS: dunes; particle size; portable OSL; Norfolk; storms

Introduction

On the 5 December 2013, a deep depression north of Scotland, UK, in conjunction with spring tides, produced an extreme storm surge down the east coast of Britain (Sibley et al., 2015). During this water reached 6.05 m OD (Ordnance Datum, which approximates mean sea level) at Kings Lynn (Spencer et al., 2015) and 6.31 m OD at Wells-Next-The-Sea in Norfolk causing extensive damage to coastal infrastructure, housing and farmland (Figure 1). This was the worst since the disastrous flooding of southern North Sea coasts in 1953 (Baxter, 2005; Gerritsen, 2005) when several thousand deaths occurred across NW Europe (>300 on the east coast of the UK), as well as extensive breaching of coastal flood defences (Spencer et al., 2015). Knowing the long-term frequency of such high magnitude events as well as more frequent severe storms is critical for present coastal management (Lewis et al., 2013) particularly for low-lying coastlines where small changes in sea levels can translate into flooding a long way inland. It is also of increasing importance given rising sea levels (Church et al., 2013) and the potential for future increased storminess over central Europe (Zappa et al., 2013). North Sea storm surge levels are thought to be going to be substantially higher and more frequent by the end of this century (Vousdoukas et al., 2016). The return period for extreme water levels to that of the 1953 storm surge was forecast to be around 50 years but, given rising mean sea levels, will be less for an equivalent surge in the near future (Wolf and Flather, 2005). While hydrological modelling allows better prediction of peak storm-tide height along coastlines, further refinement requires better understanding of beach parameters and other coastal zone factors (Lewis et al., 2013). To achieve this also requires an understanding of the response of specific segments of the coastline over longer time-scales (Andrews et al., 2000). Coastal sand dunes may provide a sedimentary archive of past storm events.

Coastal dunes serve as an important buffer zone protecting low-lying coastal areas, and their growth is a function of accommodation space, sediment supply, wind and preservation. In particular wide beaches, providing a plentiful sediment supply, and a sequence of years without high-intensity storms promote dune development (Puijenbroek et al., 2017). During storm events they can be modified (Spencer et al., 2015). The nature of this modification is partly a function of how well dunes have coalesced to form a perpendicular barrier to the sea, the height above OD of the dune crest and any low points within the dunes. If waves come into direct contact with dunes then erosion may take the form of breaching and overwash aprons (Figure 2(a); Steers et al., 1979). This is more likely to occur where dunes are poorly developed (i.e. non continuous along the back beach or low in elevation) and/or the magnitude of the storm exceeds the height of the dunes. Alternatively, scarping may occur in which the leading slope of a dune is

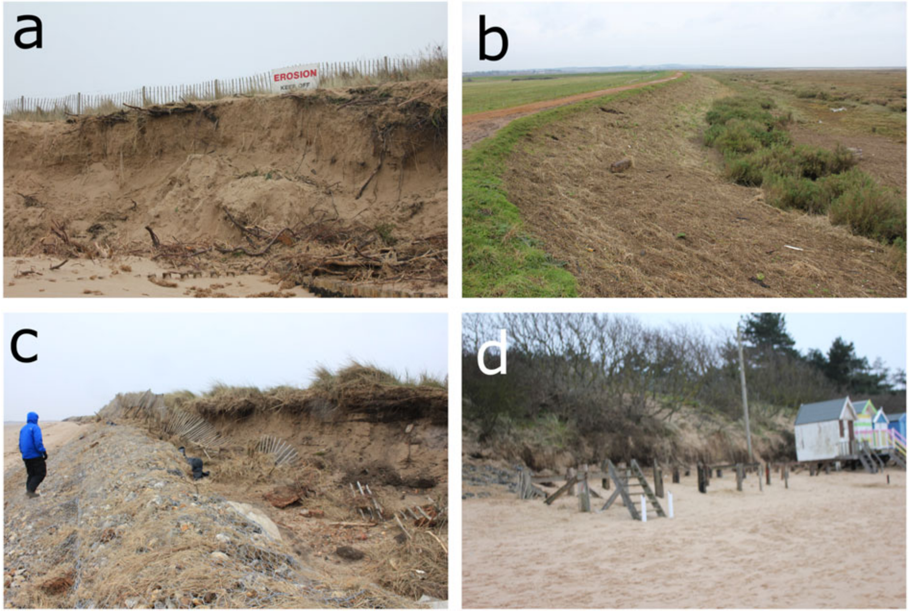

Figure 1. North Norfolk coastal damage resulting from the December 2013 storm surge in the North Sea. (a) Dune scarping at Brancaster, note metal pilings used to limit erosion on beach. (b) Flotsam left on an artificial sea-wall. The tidal surge reached the top but did not breach the wall on this occasion. (c) Erosion behind gabions placed to protect dunes at Brancaster. (d) Piles of former beach huts on Wells-Next-The-Sea destroyed in the storm surge. [Colour figure can be viewed at wileyonlinelibrary.com]

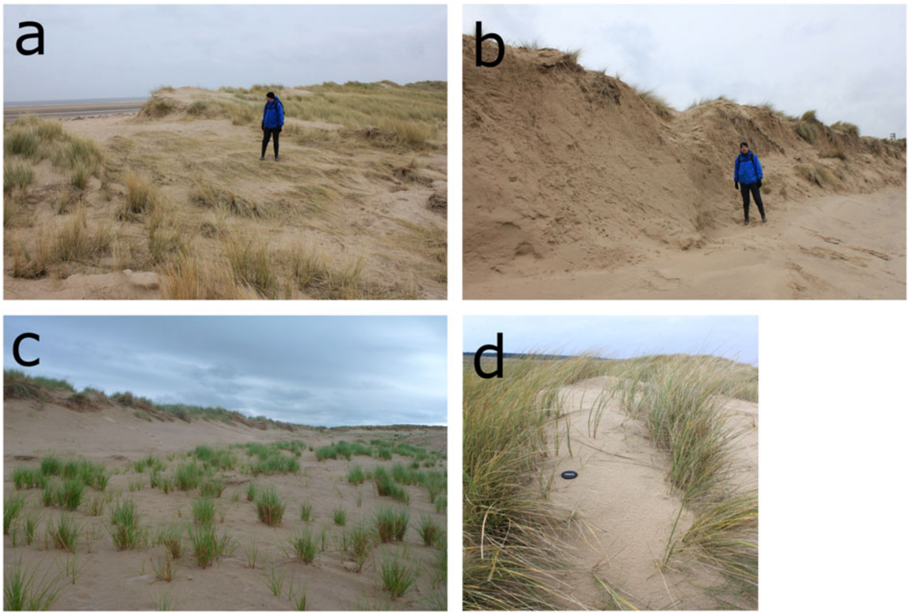

Figure 2. Impacts on coastal dunes of Storm surges. (a) Breaching of dune by waves forming sediment fan in newly formed interdune low. (b) Dune erosion forming 'scarped' vertical sand cliffs. (c) The same dunes as shown in (b) but 12 months on with collapsed and newly deflated sediment piled up against dunes. (d) Thin sheet of coarse grained sand deposited by 2013 storm event on dune crest. [Colour figure can be viewed at wileyonlinelibrary.com]

eroded away leaving a vertical face in the dune on the seaward side (Figure 2(b)). This vertical face in sand is unstable so after a storm event it collapses until a slope at the angle of repose is re-established (Figure 2(c)). Recovery can be quick (<5 years, Brooks et al., 2016). This is more likely to occur for well established dunes with high crestlines and/or during lower magnitude storm events in which waves are sufficiently high to reach dune fronts but not to over top them. Storms can also modify dunes through deflation and/or the deposition of coarser aeolian sediments moved on high winds during the storm (Figure 2(d)). It is these erosion layers and storm deposited sediments which raises the potential for actively accreting dunes to have recorded longer-term coastal storm records.

Given the above, for dunes to record a record of previous low frequency high magnitude storms within their stratigraphy they need to meet the folowing requirements:

- form a continuous back beach barrier (or inland barrier);
- have crest lines consistently higher than all but the most extreme storm events preventing overtopping and erosion away of the sediment archive;
- be in an area in which sediment supply is allowing active dune accretion thereby allowing dunes affected by storm scarping to be restored and dune crests to build up.

Proof of concept work has been carried out using innovative new portable optically stimulated luminescence (POSL) to establish high resolution relative coastal sand dune chronologies (Bateman et al., 2015). Actual age determinations are not possible with this method but total POSL counts can be viewed as a proxy for age, with older samples having a higher luminescence signal than younger samples. Unless the background dose creating the luminescence signal changes through time the POSL response with age should be linear. Down core dune profiles showed a pattern of very similar POSL signals suddenly stepping up in signal (Bateman et al., 2015). These were interpreted as similar aged sediment deposition through dune accretion with the steps indicating hiatuses in dune construction caused by storms or tidal surges (*ibid*). This study seeks to examine coastal dune stratigraphy using POSL profiles from coastal dunes to determine if dunes act as sedimentary archives of storm and surge activity.

Region of study

This study focuses on the Norfolk coastline near Holkham, ~20 km west of Hunstanton and 3 km east of Wells-Next-The-Sea. This is within the UK Environment Agency's 'Superfrontage 2' stretch of coastline for shoreline management purposes (East Anglian Coastal Group, 2010). This study area was chosen as the north-facing coastline has a long fetch and a long history of being impacted by storms and storm surges. It is fronted by broad sandy beaches and/or subtidal sand flats providing sediment to the ~6.5 km of well developed coastal dunes (Figure 3). Oronsaye (1990) showed dune accumulation was dominantly by wind with a northerly component. This makes the site idea for capturing the results of low frequency high magnitude storms from the north such as the 1953 storm surge rather than prevailing UK storms which are from the south-west. Despite a backdrop of sea levels rising over the past 7500 years on average by 0.6 ± 0.2 mm/a^{-1} (corrected for changes in tidal range; Shennan and Horton, 2002), Brooks et al. (2016) showed that the coastline around Holkham Bay is prograding, increasing the likelihood of dune sediment preservation. A map from 1781 by Biedermann shows dunes in existence at Holkham at this time (Hiskey, 2003) and based on historic maps and aerial imagery, dune formation has continued to the present.

The work of Bristow et al. (2000) at Holkham, using GPR, reported two items critical to the current study. First, it showed that the dunes have never been free dunes moving inland with time but always, once established, have been pinned by vegetation responding only to erosion and accretion without much lateral movement. The stacking of dune sediment, rather than overturning during movement, greatly enhances the potential for dunes to retain records of storm events and for successful application of luminescence dating. Second, Bristow et al. (2000) were able to identify erosion surfaces extending from the beach into the dunes which they attributed to creation of dune cliffs subsequently covered by latter dune foreslope

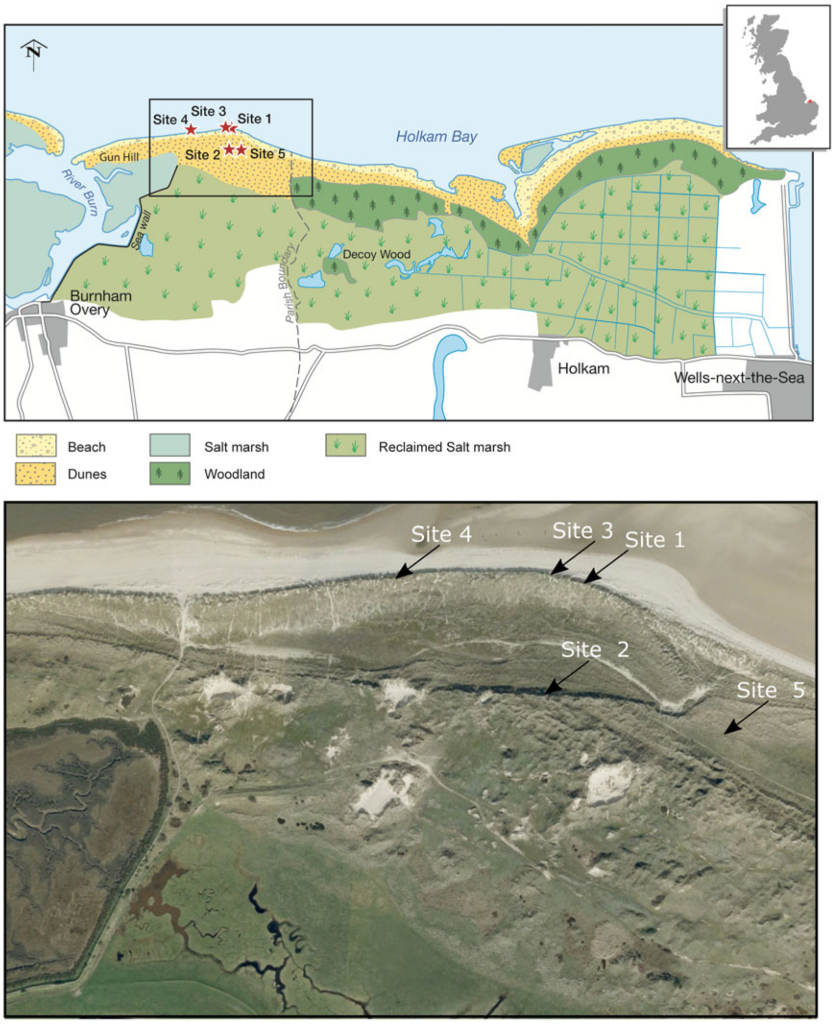

Figure 3. The coastal area between Burnham Overy and Wells-Next-The-Sea including the sampled dunes sites of this study. Sites 1, 3 and 4 were on the foredunes found at the back of the present day beach. Sites 2 and 5 in inland dunes. Lower image modified from 2007 Digital Globe/Get Mapping image on Google Earth. [Colour figure can be viewed at wileyonlinelibrary.com]

activity. These erosion events were linked to documented storms, although their age was unknown.

Three sets of dunes were selected for this study (Figure 3). The first set of sites (Sites 1, 3 and 4) were located at three positions along the dunes found at the back of the present beach. The second set of dunes (Site 2) was from a line of dunes parallel to the coast, approximately 300 m inland, and interpreted as an older formation than the back-beach dunes (Figure 3). The final set (Site 5) was on a less distinct set of dunes between sets 1 and 2 (Figure 3).

Methods

At all sample sites dune crest locations were selected and a Dormer engineering sand drill used to core down to dune base. The latter was established based on abney level surveys of the dune height above beach and from a change in sediment size from well-sorted medium sand to much coarser less sorted beach sand. At approximately 25 cm intervals, samples for POSL measurements and particle size analysis were collected in light-tight small plastic containers. Full optically stimulated luminescence (OSL) dating samples were also collected from near the dune surface, mid-core and base of core at most sites. This resulted in the collection of a total of 75 POSL and sediment samples and 12 samples for OSL dating.

For each POSL sample, any potentially light contaminated was removed and the sample material gently dried. All POSL measurements were undertaken with a SUERC portable OSL reader (Sanderson and Murphy, 2010) with measurements as per Bateman et al. (2015). Samples for full OSL dating were prepared as per Bateman and Catt, 1996), measured at the single aliquot level using a Risø luminescence reader and the single aliquot regeneration protocol (Murray and Wintle, 2003). Dose rates were determined from *in situ* field gamma-spectrometer measurements or elemental analysis. Results are shown in Table I (see Supplementary information for full details on the PSOL and OSL methods employed).

All samples also underwent particle size analysis using a Horiba LA-950 laser diffraction particle size distribution analyser to detect changes in depositional environment. For this, sub-samples were riffled down and treated with 0.1% sodium hexametaphosphate, before dispersal in de-ionised water within the instrument using ultrasound and pumping. Resultant data were used to calculate the mean and median grain size of each sample (Φ), as well as sorting, skewness, and probability distribution (Table II). Particle size showed nearly all samples to be well to moderately well sorted, unimodal with mean values in line with those found for dunes elsewhere (Lancaster, 2013). Within this were thin layers of slightly coarser and less well sorted sand which are interpreted as being aeolian storm deposits. As shown in Figure 4 particle size distributions from what are thought to be a storm deposit are slightly coarser, with a coarser tail and the 5th and 95th percentile further apart indicating poorer sorting.

To provide a long-term context for the Holkham dunes two approaches were used. First, changes in coastline were reconstructed from historical maps (1st series Ordnance Survey), aerial imagery (Crown copyright Royal Air Force aerial photographs 1946, Norfolk County Council aerial survey 1988) and Get Mapping imagery 2007 (via Google Earth). This resulted in 11 time slices spanning 175 years back to 1840.

The second approach was to reconstruct a coastal storm flooding record from reported observations and secondary documentary sources (Table III). Brooks et al. (2016) reported 21 observed north Norfolk coastal storms from 1883 to 2013.

Table I. OSL related data for sampled sites within the Holkham dunes

Sample site	Sample code	Depth from surface (m)	Water content (%)	K (%)	U (ppm)	Th (ppm)	Cosmic dose rate (μGy ka^{-1})	Total dose rate (μGy ka^{-1})	D_e (Gy)	n	Age (years AD)
Site 1	Shfd13041	0.87	3.3	0.5	0.4	1.1	187 ± 9	835 ± 34	0.027 ± 0.014	24	1981 ± 16
	Shfd13042	3.68	3.6	0.5	0.34	1.0	129 ± 6	755 ± 35	0.034 ± 0.013	24	1968 ± 17
	Shfd13043	5.93	4.3	0.5	0.46	1.1	99 ± 5	753 ± 35	0.035 ± 0.013	24	1966 ± 17
Site 2	Shfd13044	0.80	3.4	0.5	0.4	1.1	189 ± 9	836 36±	0.071 ± 0.013	24	1938 ± 16
	Shfd13045	3.40	2.1	0.5	0.43	1.1	134 ± 7	798 ± 36	0.203 ± 0.013	24	<1758 ± 20
	Shfd13046	6.22	5.1	0.5	0.43	1.2	95 ± 5	743 ± 34	0.103 ± 0.014	24	1874 ± 20
Site 3	Shfd14097	1.00	3.2	0.5	0.38	1.0	185 ± 9	818 ± 46	0.038 ± 0.014	24	1968 ± 17
	Shfd14098	6.36	2.2	0.5	0.40	1.1	94 ± 5	747 ± 46	0.054 ± 0.013	25	1943 ± 18
Site 4	Shfd14099	1.00	2.9	0.4	0.37	1.0	185 ± 9	725 ± 38	0.013 ± 0.019	13	1995 ± 30
	Shfd14100	6.05	4.3	0.5	0.40	0.9	98 ± 5	734 ± 45	0.107 ± 0.018	17	1868 ± 26
Site 5	Shfd14101	0.84	3.9	0.5	0.31	0.9	188 ± 9	796 ± 46	0.036 ± 0.015	21	1965 ± 20
	Shfd14102	2.90	3.5	0.4	0.39	1.0	144 ± 7	687 ± 38	0.046 ± 0.014	22	1945 ± 20

Table II. Particle size measurement results. Entries shaded yellow indicate samples >5% coarser and/or where sorting is >5% worse than the average for that dune. Lines indicate where OSL shows a temporal hiatus in the dune record. Entries in red are those identified as potential storm deposits

Dune Phase	Depth (m)	Mean (M_z)	Sorting (σ_I)	Skew (SK_I)	Kurtosis (K_G)
Site 1 (Back-beach dune)					
1	0.64	1.70	-0.45	0.03	1.06
	0.87	1.82	-0.44	0.04	1.07
	0.96	1.79	-0.46	0.05	1.04
2	1.35	1.94	-0.45	0.10	1.08
	1.70	1.93	-0.44	0.07	1.06
	2.05	**1.75**	**-0.44**	**0.04**	**1.04**
	2.37	**1.81**	**-0.47**	**0.07**	**1.04**
	2.79	1.92	-0.45	0.07	1.06
	3.23	1.93	-0.44	0.06	1.05
	3.68	1.97	-0.44	0.07	1.07
	4.07	1.92	-0.40	0.06	1.07
	4.37	1.95	-0.42	0.07	1.06
	4.72	2.02	-0.42	0.07	1.11
	5.10	1.98	-0.45	0.07	1.06
	5.36	1.98	-0.42	0.04	1.09
	5.93	1.94	-0.44	0.08	1.05
Site 4 (Back-beach dune)					
1	0.57	1.71	-0.47	0.04	1.05
	1.18	1.74	-0.46	0.04	1.05
	1.35	1.92	-0.44	0.07	1.07
	1.65	**1.75**	**-0.49**	**0.07**	**1.05**
	1.93	1.87	-0.45	0.07	1.08
	2.21	1.92	-0.44	0.07	1.08
	2.54	1.84	-0.45	0.04	1.10
	2.83	1.81	-0.48	0.06	1.07
	3.09	1.83	-0.46	0.07	1.09
	3.38	1.80	-0.48	0.06	1.05
	3.91	1.80	-0.48	0.06	1.05
	4.21	1.84	-0.47	0.07	1.08
	4.50	1.75	-0.48	0.06	1.04
	4.77	**1.71**	**-0.46**	**0.07**	**1.04**
	5.07	1.93	-0.45	0.07	1.07
	5.31	1.88	-0.44	0.07	1.07
	5.54	1.81	-0.32	0.06	1.06
	5.85	1.67	-0.54	0.07	1.04
Site 5 (Inland dune)					
1	0.68	1.83	-0.48	0.07	1.06
	0.94	1.80	-0.47	0.06	1.06
	1.23	1.71	-0.47	0.04	1.04
	1.53	1.78	-0.49	0.06	1.04
	1.78	1.90	-0.45	0.08	1.05
	2.04	1.84	-0.48	0.06	1.07
	2.30	1.92	-0.44	0.06	1.06
	2.55	**1.59**	**-0.47**	**0.01**	**1.07**
Site 3 (Back-beach dune)					
	0.78	1.80	-0.47	0.04	1.08
	1.15	1.81	-0.46	0.05	1.08
	1.50	1.99	-0.43	0.07	1.10
	1.82	**1.77**	**-0.45**	**0.05**	**1.05**
	2.16	1.86	-0.46	0.06	1.07
	2.56	1.91	-0.45	0.08	1.07
	2.84	2.00	-0.44	0.06	1.11
	3.16	1.96	-0.42	0.05	1.09
	3.35	1.88	-0.43	0.05	1.07
	3.70	1.84	-0.45	0.06	1.08
	4.04	1.85	-0.44	0.06	1.07
	4.44	1.90	-0.47	0.11	1.08
	4.65	1.98	-0.44	0.07	1.08
	4.94	**1.80**	**-0.46**	**0.04**	**1.07**
	5.26	2.01	-0.43	0.07	1.10
	5.86	**1.80**	**-0.48**	**0.07**	**1.05**
Site 2 (Inland Dune)					
1	0.51	1.83	-0.46	0.05	1.05
	0.80	1.70	-0.47	0.04	1.05
	1.11	1.67	-0.46	0.01	1.06
2	1.41	1.62	-0.46	0.02	1.08
	1.72	1.60	-0.45	0.02	1.07
	2.00	**1.45**	**-0.48**	**0.04**	**1.08**
3	**2.36**	**1.43**	**-0.50**	**0.01**	**1.04**
	2.66	1.70	-0.48	0.04	1.05
	2.97	1.90	-0.44	0.05	1.07
	3.27	1.90	-0.46	0.05	1.06
	3.40	**1.71**	**-0.51**	**0.05**	**1.03**
	3.72	1.82	-0.47	0.04	1.05
	4.04	1.92	-0.47	0.06	1.05
	4.55	1.96	-0.44	0.05	1.05
	5.00	1.86	-0.49	0.06	1.03
	5.37	1.71	-0.47	0.02	1.04
	5.61	**1.68**	**-0.45**	**0.01**	**1.07**
	5.83	1.85	-0.46	0.04	1.07
	6.22	1.82	-0.44	0.03	1.06

This record was extended back to 350 BC and up to 283 storms by the addition of the works of Galloway (2013), Kington (2010), Zong and Tooley (2003), Harland and Harland (1980), Lamb (1977) and others (see Table III) based on a variety of archival documentary sources including floodstones (see http://floodstones.co.uk/), Parish records and the Times Newspaper. Only storms where coastal flooding around the North Sea had been reported were included. This storm record was refined by filtering out pre 1200 AD events where the record was limited ($n=12$), storms reporting only minor flooding not in Eastern England ($n=61$) and summer storms ($n=16$). The latter was on the basis that these were not near the Spring or Autumn equinox tides and more likely caused by rainfall related flooding rather than sea inundation. Finally the dataset was split into two: (1) storms where there was an explicit reference to them causing coastal flooding in eastern England ($n=189$); and (2) storms where there was major/catastrophic coastal flooding in NW Europe in which, while the sources do not explicitly state flooding in England, such flooding may have occurred ($n=21$). As with all such compilations of data, recording of storms is highly dependent on them being deemed at the time sufficiently out of the ordinary to merit recording and/or have caused significant damage/death. With increased coastal protection, coastal flooding is likely to have diminished with time. Data compilations are also highly dependent on survival of the original

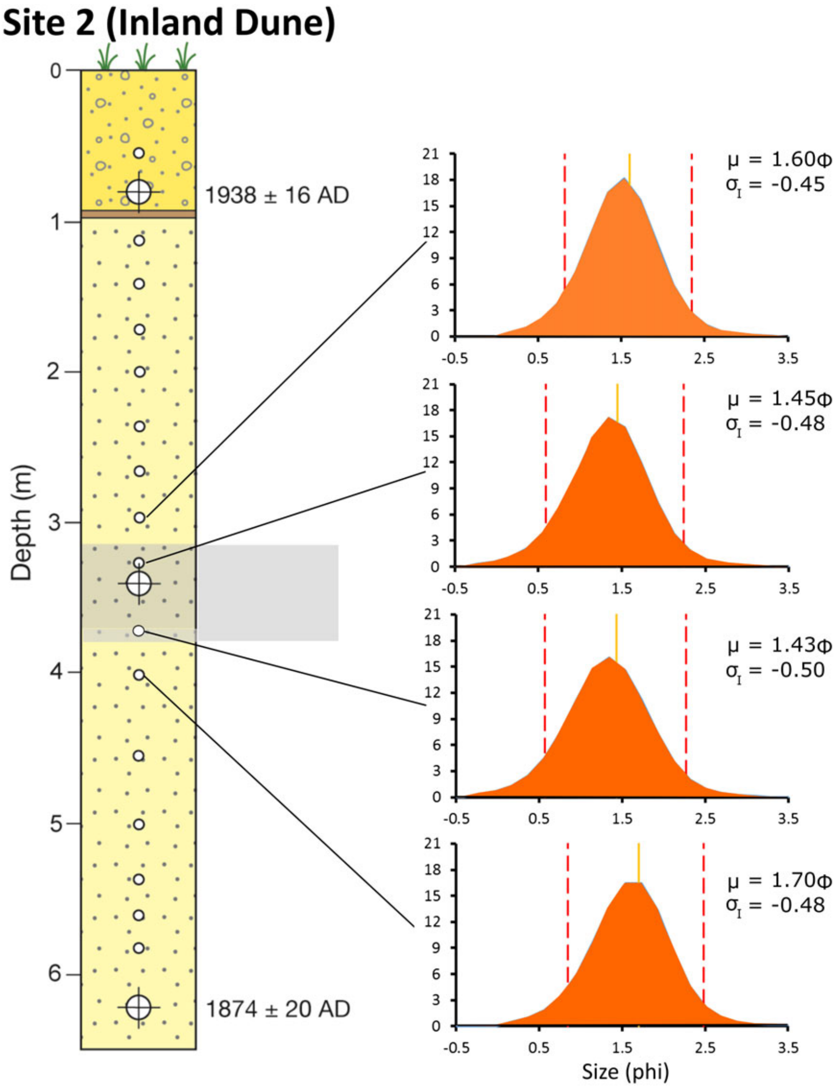

Figure 4. Down core stratigraphy and sample points of site 2 with particle size distributions from above, within and below what is interpreted as coarser aeolian unit deposited during a storm. Dashed red lines are the 5th and 95th percentiles and the orange solid line the 50th percentile. Note the shift to coarser sediment for the middle two samples, the extended coarse (left) tail and the greater width between the 5th and 95th percentile indicating poorer sorting. [Colour figure can be viewed at wileyonlinelibrary.com]

Table III. Main documentary sources used to compile coastal storm flooding record. Also shown is the number of storms corroborated by other sources in the database

Documentary source	Period covered (years AD)	Number of storms	Corroborated storms
Brooks *et al.,* 2016	1883–2013	20	8
Clemmensen *et al.,* 2014	1872	1	
Galloway, 2013	1287–1404	8	4
Cunningham *et al.,* 2011	1775–1176	2	
Kington, 2010	1099–2006	16	6
Pye and Blott 2007	1851–1856	2	
Zong and Tooley, 2003	1788–1993	132	14
Harland and Harland, 1980	1287–1978	16	10
Lamb, 1977	245–1973	117	17

documents and, given their very diverse nature, finding them for inclusion in the database. With the advent of the instrumental record, increased shipping and coastal activity and better record keeping so events are more likely to have been observed and recorded. Thus the compiled database can be expected to have an unquantified bias towards more storms being recorded more recently. A final caution stems from the judgement call of those compiling storm events (including the present authors) as to whether coastal flooding was entirely localised and thereby only of significance to the present study if Norfolk was mentioned or more regional but only recorded at specific places. We can be reasonably sure that Norfolk was affected by the storm of 27 October 1882 as it caused flooding to the south in London and to the north in Whitby (Zong and Tooley, 2003). However, the storm of 21 December 1881 is only recorded as causing flooding in London (Zong and Tooley, 2003) and it is unclear whether Norfolk was also affected but not recorded in the London Times.

Results

In this section the POSL, OSL dating and particle size analysis are initially looked at to establish the storm record as archived in the dunes. Major storm events are interpreted where both a phase change (step) occurs in the POSL profiles and there is evidence for coarser sediments within a dune. Minor storms are interpreted where there is evidence only for coarser sediments within a dune. The storm record interpreted from the dunes is then compared with the archived mapping of the area and documented storm record.

Dune archive

In the back-beach dunes (Sites 1, 3 and 4) POSL results show that most have similar POSL signals all the way down the cores (Figure 5). These are interpreted as showing that the majority of dune construction was essentially in a single phase (Figure 5). The only exceptions to this are the uppermost 1 m of sediments at Site 1 and Site 4 which have a lower POSL signal. These are interpreted as indicating more recent small-scale dune modification. The basal increase of POSL signal at Site 4 is believed to relate to the underlying beach rather than the dune itself. Full OSL ages support the POSL results. The dune at Site 4 dates to 1995 ± 30 years AD and the uppermost dune sediments at Site 1 dates to 1981 ± 16 years AD (dark brown shading in Figure 5). The lowermost dune sediments at Site 1 and the majority of dune sediments at Site 3 are attributed to around 1966 ± 17 years AD (mid-brown on Figure 5). The basal sediments at Site 3 show a phase change in the POSL and appear slightly older dating to 1943 ± 18 years AD (light brown shading in Figure 5).

Particle size results for the back-beach sites showed coarser layers at 2.0 m at Site 1, at 1.8 m, 5.0 m and 5.8 m at Site 3 and at 1.65 m and 4.8 m at Site 4 (see red stars in Figure 5). One of these coarser layers, that at 5.8 m at site 3, corresponds with a step up in POSL signal. This is interpreted as indicating a major storm event that modified the dunes through either erosion or dune movement and deposited a coarse layer before dune accretion resumed after the storm. This major storm event is dated at Site 3 to 1943 ± 18 years AD. The six other identified coarse layers (with no step up in POSL) are interpreted as resulting from three lower magnitude storms which caused dune accretion to briefly be interrupted with coarser sediment deposition before normal dune accretion resumed (similar to that shown in Figure 2(d)). The storm associated with the upper coarser layer at Site 4 dates to ~1981 ± 16 years AD. The coarser layer at 2.0 m in site 1 probably corresponds with the 4.8 m layer in site 4 and the 1.65 m layer in Site 3 and this storm event dates to ~1966 ± 17 years AD. The coarser layer at 5.0 m at site 3 is a third storm event which dates to after 1943 ± 18 years AD.

The inland dunes show a slightly more complex history. Site 5, based on the two phases separated by a step in the POSL data (Figure 5), appears to show an upper sand unit 2.5 m thick, which deposited in a single phase overlying a slightly older sand unit. This is confirmed by the full OSL ages which suggest the upper sediment accumulated around 1965 ± 20 years AD and the lower sediment at 1945 ± 20 years AD. Site 2 has three phases of accumulation recorded in the POSL data separated by two steps at around 1.4 m and 2.5 m. (Figure 5). An upper unit which full OSL ages date to 1938 ± 16 years AD and therefore is of similar age to the basal sediments at Site 5 (light brown shading in Figure 5), a middle unit that unfortunately was not sampled for OSL dating and a lower unit dated to 1874 ± 20 years AD (yellow shading in Figure 5). The inland dunes appear to have ceased accumulating after around 1945 ± 20 years AD with dune formation switching to the present-day back beach dunes by 1966 ± 17 years AD (Figure 6). Such a change in dunefield can likely be attributed to a significant storm event some time between 1945 and 1966. During this event sediment was likely eroded and moved off-shore before being fed back onshore supplying sediment to the present back beach dunes.

Particle size data from the inland dune sites shows a coarser basal sediment at Site 5 and a coarser layer around 2.15 m down the core at Site 2 (Table III). Both these coarser layers

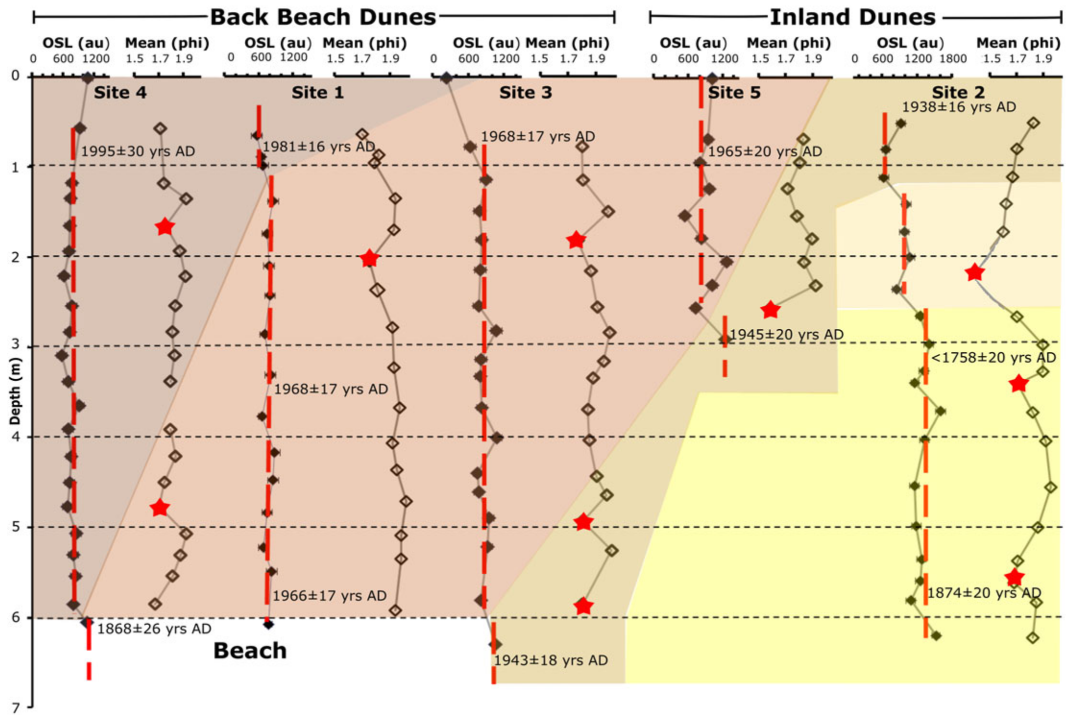

Figure 5. Downcore portable OSL and mean grain size for sampled dune sites. Phases of dune accumulation based on phases within dunes identified by portable luminescence (red dashed lines) and between dunes based on OSL ages. Coarser sediments inferred to relate to storms indicated with red stars. Note sites have been re-ordered based on their age and localities with sites 1, 3 and 4 from the dune found at the back of the beach dunes and sites 2 and 5 from inland dunes. The background colour changes indicate sediments of a similar age based on the full OSL ages. [Colour figure can be viewed at wileyonlinelibrary.com]

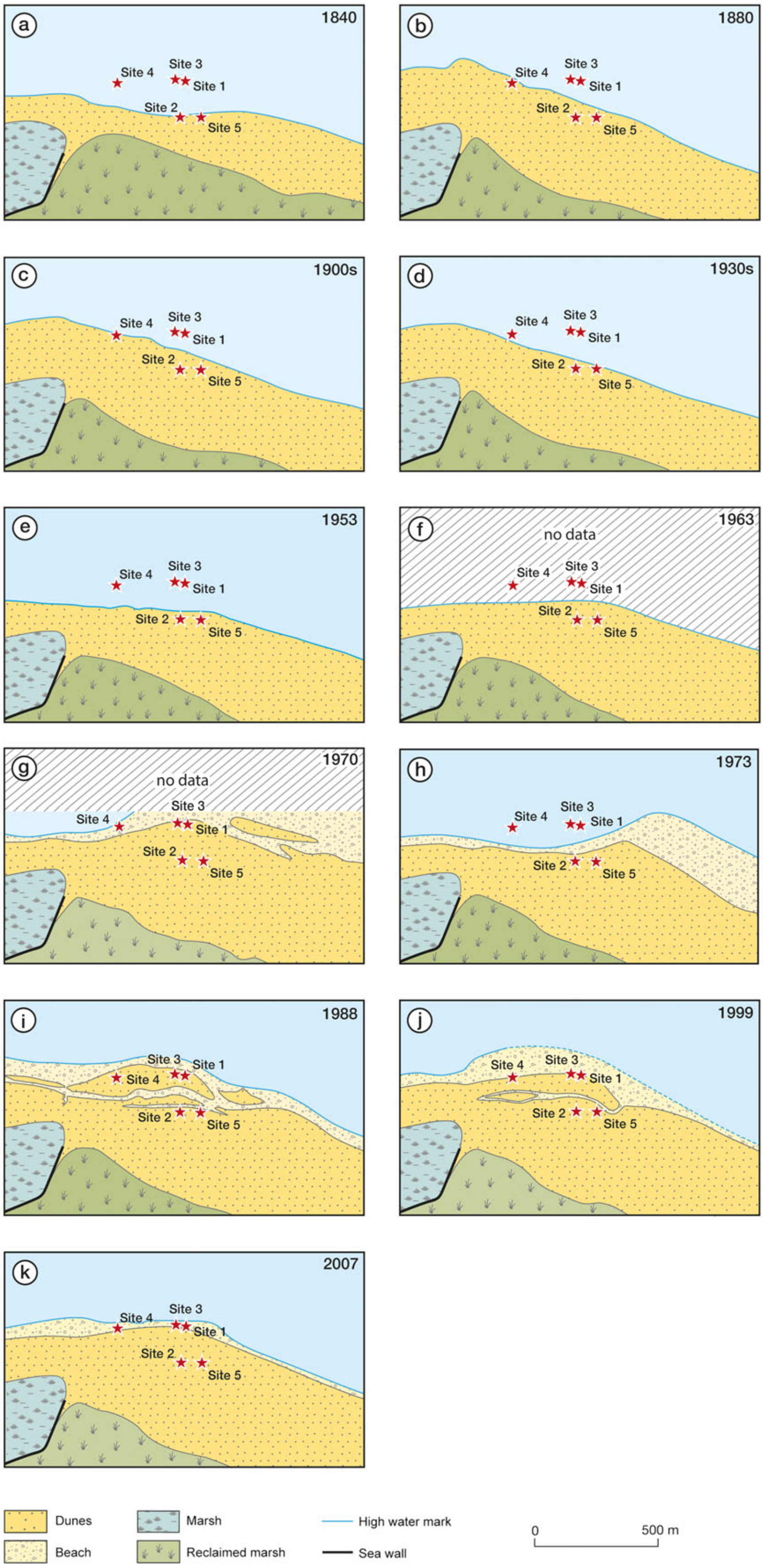

Figure 6. Historical map and imagery evidence for Holkham progradation of shoreline in relation to the sampled dune sites. Note the seawall acts as a point of reference for all time slices shown. [Colour figure can be viewed at wileyonlinelibrary.com]

correspond to changes in POSL and are interpreted as indicating major coastal storm events which modified the dunes. The coarser layer at Site 5 probably corresponds to that found at Site 3 and dates the storm to around 1945 ± 20 years. The site 2 coarser layer was not dated but falls within the periods 1874–1945 years AD. A further two coarser layers are observed at 3.4 m and 5.6 m depth at Site 2, which as the POSL does not change significantly, are attributed to lower magnitude storms which did not modify the dune and which occurred some time after 1874 ± 20 years AD.

Table IV. Summary of the storms extracted from the dune archive at Holkham

Storm date	Sites	Dunes affected	Evidence	Storm magnitude	Attributed storm
~1995	Site 4	Back-beach	Coarse sand layer, no POSL change	Minor	1978
~1966	Sites 1,3,4	Back-beach	Coarse sand layer, no POSL change	Minor	1961
~1945	Sites 3,5	Inland and Back-beach	Coarse sand layer, jump in POSL and dune system avulsed to back-beach dunes	Major	1953
~1938	Site 2	Inland	Dune system avulsed to dunes associated with site 5	Minor	1938
Between ~1874–1945	Site 2	Inland	Coarse sand layer, jump in POSL	Major	1897
Between ~1874–1945	Site 2	Inland	Coarse sand layer, no POSL change	Minor	1883
Between ~1874–1945	Site 2	Inland	Coarse sand layer, no POSL change	Minor	1875
Pre 1874	Site 2	Inland	Inland dune initiation and presumed dune avulsion from previous dunes	Major	1850's?

In summary, the dunes sampled provide a ~ 140 year record (Table IV). Within this, at least two major storm events modified the dunes and/or caused evulsion of the system and new dune-lines to be formed. One took place in the late 19th to early 20th century and a second in the 1950s. Five smaller storms are interpreted from the record to have occurred in the 1980s, 1960s, 1930s and two late in the 19th century.

In a reanalysis of synoptic pressure patterns using the Jenkinson daily weather type for the Lincolnshire coast, Montreuil and Bullard (2012) also reconstructed on-shore storms for the period 1870–2012. They found that wind storms were higher than average in terms of frequency between 1871 and the 1920s, relatively infrequent up to until 1955 and peaked 1955–1970, 1975–1988 and from the mid-1990s to 2000. This closely follows the documentary based storm record.

Archive mapping and storm record

Historical maps and imagery show that the inland dune sites (sites 2 and 5) could not have existed prior to 1840 as where they were found was part of the beach before this time (Figure 6). Coastal progradation after this date would have provided accommodation space for the formation of the dunes associated with Site 2. Maps show that site 1, 3 and 4 (presently at the back of the beach) only appear above the high-tide line after 1970 and first appears on an aerial photograph from 1988. Within the limits of the time slices available this confirms that over the last 160 years the coastline associated with the Holkham dunes has been prograding northwards. The mapping shows some erosion of dunes on the western side of the study area during the 1930s and 1950s as indicated by Site 4 being further offshore at these points. A significant re-organisation appears to have taken place between 1973 and 1988 whereby a formerly inter-tidal and beach area rapidly became dunes. The map/aerial imagery supports both the full SAR OSL ages and the POSL data.

Over the last *c.* 800 years, the record reconstructed from observations and documentary sources indicates that storms causing coastal flooding in eastern England occurred approximately once every nine years (Figure 7(a)). Relatively low storm frequency is apparent within the period 1400–1600 AD and a very large apparent increase in storminess has occurred since 1800. As previously discussed this can at least partly be attributed to better and more frequent records. Focusing on the period since 1800 and the East Anglia region (Figure 7(b)), once again storms causing coastal flooding appear to have increased with time, averaging over the whole period to two per decade. Of note are the decades of 1870s, 1900s, 1950s, 1970s, 1990s and 2000s, decades that all seem to have had four or more storms in East Anglia. There is no correlation between frequency of flooding in East Anglia and that of eastern England (correlation coefficient = −0.074).

Discussion

Documentary evidence and luminescence dating have rarely been combined in an integrated analysis (Benito et al*.*, 2011). This study is the first to attempt it on coastal systems. Based on the luminescence and particle size data the Holkham dune sedimentary archive has recorded two major storm events (one late 19th–early 20th century, one in the 1950s) of sufficient magnitude to modify dunes and/or cause evulsion of the system and a further five other storms (two late 19th century, 1930s, 1960s 1980s). Clearly the dune archive is not preserving a record of all the documented storms within this period (Figure 7(b)). Based on documentary evidence for the last 140 years, an average of three storms a decade affect East Anglia compared with the 0.5 storms per decade extracted from the Holkham dune archive. That the dunes at Holkham are not recording all documented storms in the region probably in part reflects that not all the documented storms impacted directly on Holkham. On average only 2.2 storms per decade are recorded if storms are restricted to only those documented as directly impacting on Norfolk. While reducing the mismatch, this still probably over-represents the number of storms directly experienced at Holkham.

The key to preserving a storm trace in the dune archive is the magnitude of the storm and any accompanying storm surge. Some storms simply will not be of sufficient magnitude to cause dune erosion and/or deposition of a coarse sand layer on the crest. Given the age ranges of the dated levels in the dune archive, an exact attribution to known high magnitude storm surges cannot be given. However, in the recent record, the last significant flooding event prior to 2013 was on 11 January 1978 (Figure 8; Table IV). During this storm surge extensive flooding occurred across north Norfolk (Harland and Harland, 1980; Brooks et al*.*, 2016). This may have laid down the uppermost coarse sand layers identified in the back-beach dunes. The storm identified as having deposited a coarser layer in the back beach dunes during the 1960s is less certain. Harland

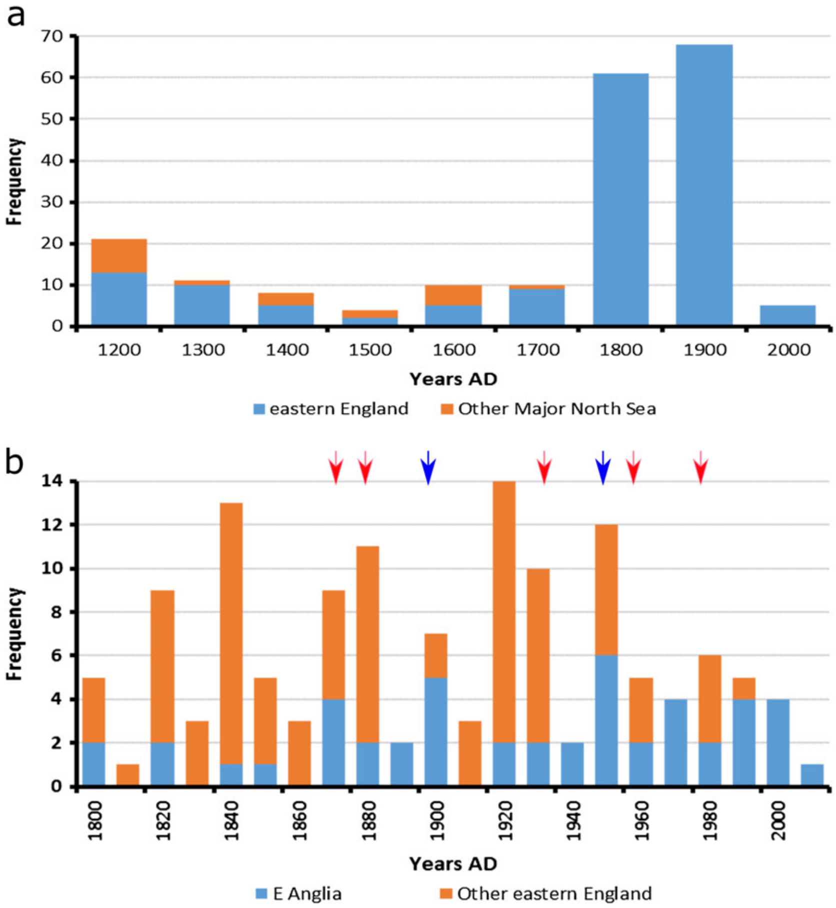

Figure 7. Storm record compiled from published records (see text for details). (a) Storm record since 1200 AD (number of storms per century) including those reported for eastern England and major storm events elsewhere in southern North Sea known to have cause significant flooding/loss of life. (b) Storm record back to 1800 AD (number of storms per decade) for East Anglia and elsewhere in eastern England. Blue arrows denote the approximate age when the Holkham dune archive indicates that a new line of dunes formed. [Colour figure can be viewed at wileyonlinelibrary.com]

and Harland (1980) describe the 20 March 1961 storm as causing 'heavy seas, strong winds and damage and destruction' but no sea elevation data is known. More certain is the 1953 storm surge which attained a sea elevation of 5.15 m OD at Wells-Next-The-Sea (Brooks et al., 2016; Figure 7) and caused major flooding in the area (Figure 8). It would seem likely that the coarser layers with associated erosion found in Sites 3 and 5 along with the change in dune position from the inland dunes (before 1950s) to the present-day back beach dunes (post 1960; Figure 5) relates to this major event (Table IV). In a study of the UK's Lincolnshire coastline, Montreuil and Bullard (2012) noted the symbiotic relationship of storms initially causing coastal erosion but then transporting back onshore large quantities of sediment to reform dunes. 15 February 1938 saw a storm surge which flooded the Brancaster marshes and the contours of beach and sandhills (dunes) completely changed (Harland and Harland, 1980). Sea elevations during the storm surge are not known. This may be recorded in the sand dune archive as the upper most sediment unit at Site 2 after which mapping shows the dunes avulsed to those associated with site 5 (Figure 6). The major storm event associated with the middle sand unit at Site 2 could relate to the flood associated with the storm of 28 November 1897 (Figure 8) in which flooding reached 4.49 m OD (Brooks et al., 2016; Table IV). The minor storms identified in the lower Site 2 dune sediments could be from 11 March 1883 storm which flooded to 5.49 m OD at Wells-Next-The-Sea (*ibid*) and the storm of 14 October 1875 which flooded coasts from London to Whitby (Zong and Tooley, 2003; Table IV). While undated, if dune-line initiation occurs post a major coastal storm event (as per the 1953 flooding) then the establishment of the inland dunes around site 2 must have been before ~1878. The line of inland dunes could therefore relate to dune avulsion after the series of powerful storms in the 1850s which are recorded as having breached Spurn Head near Hull and caused coastal flooding from Hull, the Fenlands down to London (Zong and Tooley, 2003).

Future Directions

Overall, from the above it would appear that, with the appropriate interrogation, coastal dunes can act as sedimentary archives of storm surge activity. If such research ultimately aims to give coastal managers a better understanding of return intervals of coastal storm surges and spatial extent of flooding then moving beyond the instrumental record is required. They also show that while dune erosion/breaching during major storms may be dramatic, providing they are followed by a number of years without such storms, dunes appear to recover by either rebuilding or re-establishing a new dune line. At Holkham, extending the record to older inland dunes should uncover sedimentary archives for documented storms in March 1820, November 1794, February 1736, January 1734 and even potentially November 1404 (Kington, 2010, Harland and Harland, 1980, Galloway, 2013). All these are reported to have had major storm surges associated with them (ibid).

Research on the dune sedimentary archive will only really add value to coastal managers when it is able to, with confidence, identify previously unrecorded storm surges at localities

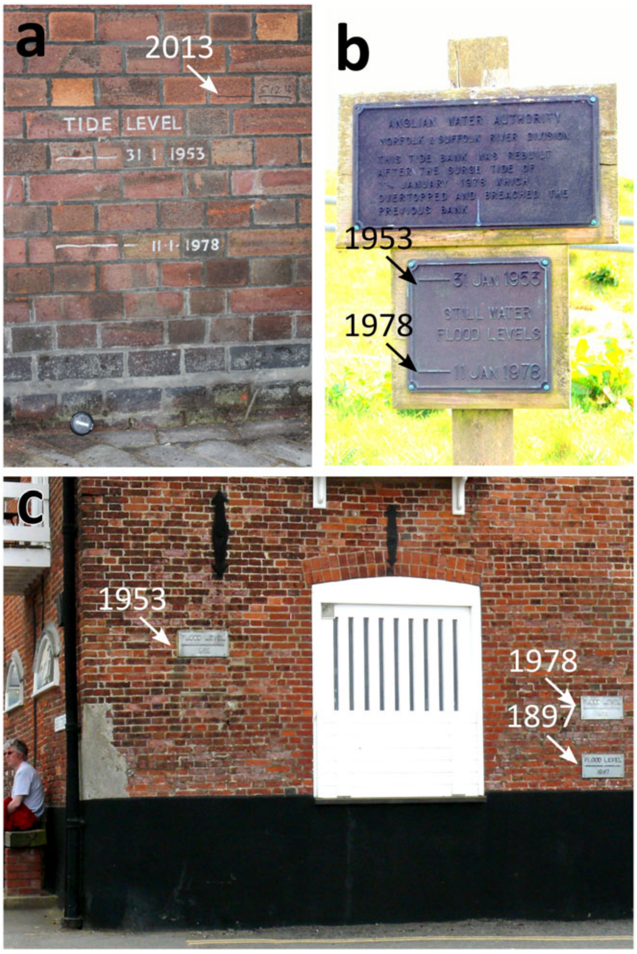

Figure 8. Preserved flood markers around North Norfolk. (a) Flood markers for 2013 at 6.31 m OD, 1978 at 5.94 m OD and 1953 at 6.15 m storms found on the Granary building, Wells-Next-The-Sea. (b) Flood markers for 1978 at 5.93 m OD and 1953 at 6.13 m OD storms found on Beach Road Wells-Next-The-Sea. (c) Flood markers for 1953 at 6.55, OD, 1978 at 5.98 m OD and 1897 at 5.54 m OD storms recorded on the Quay building in Blakeney. [Colour figure can be viewed at wileyonlinelibrary.com]

and/or extend the record back to where documentary evidence is patchy. Before this is achieved further evaluative steps should be undertaken:

- A better understanding is required as to whether subsequent events could, through erosion, 'overwrite' earlier storm archives and closely spaced events might be combined in the dune archive. This may account for the decades where four or more storm events have been documented (e.g. 1900s and 1950s, Figure 7(b)), but only one or less events are recorded in the dunes. Use of ground penetrating radar, as employed by Cunningham et al. (2011), and continuous or more high resolution sampling for POSL might help in this regard.
- That the dunes at Holkham are not recording all documented storms in the region also probably reflects that not all these storms impacted directly on Holkham. Sixteen coastal dune fields exist for Norfolk and Suffolk (Pye et al., 2007). Future research extending the examination of the dune archive to this extensive regional dune record would remove the current mismatch between comparing a regional documentary storm record with a site-specific dune archive record. This would also allow a more rigorous evaluation of the efficacy of the dune archive in recording storm events.
- An alternative explanation for the difference between documented storms and the Holkham dunes is that only high magnitude events erode and/or deposit sand on dunes and so it is only high magnitude events that are recorded in the dune archive. Further research would be needed to establish a better idea of a threshold above which storm events sufficiently impact on dunes for them to be recorded in the sedimentary record. Such an approach has been successfully undertaken in the context of the relationship between beach storm ridges and tropical cyclone activity in Australia (Forsyth et al., 2010).

Conclusions

Application of POSL profiling with supporting luminescence ages and detailed particle size analysis to coastal dunes, as well as providing information of dunefield evolution can also provide information of past coastal storms. In this study, seven storm events, two major, were identified from the dune archive. These spanned the last 140 years and seemed to fit well with documentary evidence of major storm surges which have affected north Norfolk. Targeting of dunefields, which stack sediment rather than overturning, greatly enhances the potential for dunes to retain records of storm events and for successful application POSL profiling. Dunes do not appear to be recording (at least at the sampling resolution used here) all recorded storm events only ones in which sea elevations were particularly elevated and significant flooding occurred. As such the approach seems to hold promise to extend the dune archive records further back in time when less is known about storm surges to get a better understanding of their frequency, and older dunes and extending the record to a regional level would allow this. The work also has coastal management implications in that, providing high intensity storm events are followed by a number of years without such storms, dunes recover by either rebuilding or re-establishing a new dune line.

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References

Andrews JE, Boomer I, Bailiff I, Balson P, Bristow C, Chroston PN, Funnell BM, Harwood GM, Jones R, Maher BA, Shimmield GB. 2000. Sedimentary evolution of the north Norfolk Barrier coastline in the context of Holocene sea level change. In *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*, Shennan I, Andrews J (eds), Vol. **166**. Geological Society, London, Special Publications: London; 219–251.

Bateman MD, Catt JA. 1996. An absolute chronology for the raised beach and associated deposits at Sewerby, East Yorkshire, England. *Journal of Quaternary Science* **11**: 389–395.

Bateman MD, Stein S, Ashurst RA, Selby K. 2015. Instant luminescence chronologies? High resolution luminescence profiles using a portable luminescence reader. *Quaternary Geochronology* **30**: 141–146.

Baxter PJ. 2005. The East Coast Big Flood, 31 January–1 February 1953: a summary of the human disaster. *Philosophical Transactions of the Royal Society of London* **363A**: 1293–1312.

Benito G, Thorndycraft VR, Rico MT, Sánchez-Moya Y, Sopeña A, Botero BA, Machado MJ, Davis M, Pérez-González A. 2011. Hydrological response of a dryland ephemeral river to southern African climatic variability during the last millennium. *Quaternary Research* **75**: 471–482.

Bristow CS, Chroston NP, Bailey SD. 2000. The structure and development of foredunes on a locally prograding coast: insights from ground-penetrating radar surveys, Norfolk, UK. *Sedimentology* **47**: 923–944.

Brooks SM, Spencer T, McIvor A, Möller I. 2016. Reconstructing and understanding the impacts of storms and surges, southern North Sea. *Earth Surface Processes and Landforms* **41**: 855–864.

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D, Unnikrishnan AS. 2013. Sea level change. In *Climate Change 2013: The Physical Science Basis*, Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK and New York, NY, USA.

Clemmensen LB, Bendixen M, Hede MU, Kroon A, Nielsen L, Murray AS. 2014. Morphological records of storm floods exemplified by the impact of the 1872 Baltic storm on a sandy spit system in south-eastern Denmark. *Earth Surface Processes and Landforms* **39**: 499–508. https://doi.org/10.1002/esp.3466

Cunningham AC, Bakker MAJ, van Heteren S, van der Valk B, van der Spek AJF, Schaart DR, Wallinga J. 2011. Extracting storm-surge data from coastal dunes for improved assessment of flood risk. *Geology* **39**: 1063–1066.

East Anglian Coastal Group. 2010. *North Norfolk Shoreline Management Plan Final Plan*. http://www.eacg.org.uk/docs/smp5/the%20smp%20main%20report.pdf. [last accessed 9/5/17]

Forsyth AJ, Nott J, Bateman MD. 2010. Beach ridge plain evidence of a variable late-Holocene tropical cyclone climate, North Queensland, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **297**: 707–716.

Galloway JA. 2013. Coastal flooding and socioeconomic change in eastern England in the later middle ages. *Environment and History* **19**: 173–207.

Gerritsen H. 2005. What happened in 1953? The Big Flood in the Netherlands in retrospect. *Philosophical Transactions of the Royal Society London* **363A**: 1271–1291.

Harland MG, Harland HJ. 1980. *The Flooding of Eastern England*. Minimax Books: Norwich.

Hiskey C. 2003. *The Drainage of Holkham Marshes*. Unpublished report for Holkham Estate Archives.

Kington JA. 2010. *Climate and Weather*. Collins: London.

Lamb HH. 1977. *Climate Past Present and Future. Volume 2, Climatic History and the Future*. Methuen and Co: London.

Lancaster N. 2013. *Geomorphology of Desert Dunes*. Routledge: Oxford.

Lewis M, Schumann G, Bates P, Horsburgh K. 2013. Understanding the variability of an extreme storm tide along a coastline. *Estuarine, Coastal and Shelf Science* **123**: 19–25.

Montreuil A-L, Bullard JE. 2012. A 150-year record of coastline dynamics within a sediment cell: Eastern England. *Geomorphology* **179**: 168–185.

Murray AS, Wintle AG. 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements* **37**: 377–381.

Oronsaye WI. 1990. Wind action and sand movement near Holkham Bay, North Norfolk Coast, England. *Environmental Geology and Water Sciences* **15**: 77–82.

Puijenbroek MEB, Limpens J, deGroot AV, Riksen MJPM, Gleichman M, Slim PA, van Dobben HF, Berendse F. 2017. Embryo dune development drivers: beach morphology, growing season precipitation and storms. *Earth Surface Processes and Landforms* **42**: 1733–1744.

Pye K, Blott, S. 2007. Holderness Erosion and Evolution of the Spurn Peninsula. Unpublished report. http://www2.hull.ac.uk/science/PDF/ECSA%20Ken%20Pye.pdf [last accessed 9/5/17]

Pye K, Saye SE, Blott SJ. 2007. Sand dune processes and management for flood and coastal defence. Parts 1–5. Joint DEFRA/EA Flood and Coastal Erosion Risk Management R and D Programme, R and D Technical Report FD1302/TR. DEFRA/EA, London, 5 volumes.

Sanderson DW, Murphy S. 2010. Using simple portable OSL measurements and laboratory characterisation to help understand complex and heterogeneous sediment sequences for luminescence dating. *Quaternary Geochronology* **5**: 299–305.

Shennan I, Horton BP. 2002. Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science* **17**: 511–526.

Sibley A, Cox D, Titley H. 2015. Coastal flooding in England and Wales from Atlantic and North Sea storms during the 2013/2014 winter. *Weather* **70**: 62–70.

Spencer T, Brooks SM, Evans BR, Tempest JA, Möller I. 2015. Southern North Sea storm surge event of 5 December 2013: water levels, waves and coastal impacts. *Earth Science Reviews* **146**: 120–145.

Steers JA, Stoddart DR, Bayliss-Smith TP, Spencer T, Durbidge PM. 1979. The storm surge of 11 January 1978 on the east coast of England. *The Geographical Journal* **145**: 192–205.

Vousdoukas MI, Voukouvalas E, Annunziato A, Giardino A, Feyen L. 2016. Projections of extreme storm surge levels along Europe. *Climate Dynamics* **47**: 3171–3190.

Wolf J, Flather RA. 2005. Modelling waves and surges during the 1953 storm. *Philosophical Transactions of the Royal Society of London Series A* **363**: 1359–1375.

Zappa GZ, Shaffrey LC, Hodges KI, Sansom PG, Stephenson DB. 2013. A multimodel assessment of future projections of North Atlantic extratropical cylclones in the CMIP5 climate models. *Journal of Climate* **26**: 5846–5862.

Zong Y, Tooley MJ. 2003. A historical record of coastal floods in Britain: frequencies and associated storm tracks. *Natural Hazards* **29**: 13–36.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article.

Figure S1. Example radial plots of OSL palaeodoses (De) for the three samples from site 2 (left column) and the two samples from site 5 (right column).