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Southern North Sea storm surge event of 5 December 2013: Water levels, waves and coastal impacts

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ABSTRACT

The storm surge event that affected the coastal margins of the southern North Sea on 5–6 December 2013 produced the highest still water levels on record at several tide gauges on the UK east coast. On east-facing coasts south of the Humber estuary and north-facing Norfolk, water levels were higher than in the twentieth century benchmark surge event of 31 January–1 February 1953. Maximum significant wave heights were highest off the North Norfolk coast (peak $H_s = 3.8$ m offshore, 2.9 m inshore) and lowest off the Suffolk coast ($H_s = 1.5$–1.8 m inshore); comparable offshore wave heights in 1953 were 7–8 m and ca. 3 m. The lower wave heights, and their short duration, in 2013 explain both localised breaching, overtopping, and back-barrier flooding associated with gravel ridges and relatively low earthen banks as well as the lack of failure in more highly-engineered coastal defences. On barrier coasts and within estuaries, the signal of maximum runup was highly variable, reflecting the modification of the tide–surge–wave signal by inshore bathymetry and the presence of a range of coastal ecosystems. The landscape impacts of the December 2013 surge included the notching of soft rock cliffs and cliffline retreat; erosion of coastal dunes; and the augmentation or re-activation of barrier island washover deposits. Whilst surge event-related cliff retreat on the rapidly eroding cliffs of the Suffolk coast lay within the natural variability in inter-annual rates of retreat, the impact of the surge on upper beach/sand dune margins produced a pulse of shoreline translation landwards equivalent to about 10 years of 'normal' shoreline retreat. The study of east coast surges over the last 60 years, and the identification of significant phases of landscape change — such as periods of rapid soft rock cliff retreat and the formation of new gravel washovers on barrier islands — points to the importance of high water levels being accompanied by high wave activity. Future developments in early warning systems and evacuation planning require information on the variable impacts of such extreme events.

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1. Introduction

The impacts of storm surges — extreme, meteorologically-forced high water levels — on low-lying coasts threaten vulnerable human communities and infrastructure on a global scale. The recent impacts of Hurricane Katrina and hybrid Superstorm Sandy, engulfing New Orleans (Kates et al., 2006) and New York City (Tollefson, 2013) respectively, have demonstrated how severe flooding events can devastate and immobilise even major urban centres. To reduce risk and increase resilience (the ability of a system to absorb and recover from the effects of a hazard (UNISDR, 2009)) to storm surges, it is imperative to better understand both the underlying dynamics and the landscape impacts of such events.

Storm surge science can be advanced through the better definition of the spatio-temporal characteristics of major storm surges and observations as to how these characteristics are delivered to coastal receptors through a range of littoral pathways (e.g., Sayers et al., 2002; Narayan et al., 2012). No two surge events have exactly the same source, pathway and receptor characteristics. It is necessary, therefore, to undertake a modern synthesis of process environment records, detailed landscape change surveys, and socio-economic databases to build a detailed picture of the impact pattern for any individual surge event. Over time, it should be possible to assemble a library of comprehensive event records, allowing the exploration and explanation of surge event similarities and differences. These archives can then be used to improve storm surge modelling, where a much greater range of potential storm impacts, for particular coastal settings, can be explored.

Storm surge impacts are not simply linearly related to maximum water level but rely on more complex, non-linear interactions between tide–surge conditions, the associated wind wave field and thresholds to landscape change. Whilst considerable progress has been made in recent years in researching tide–surge interaction (e.g., Horsburgh and Wilson, 2007), less attention has been given to the other two components. The wave component contribution to elevated water level is not accounted for in the tide gauge records, as the gauges are located in sheltered locations within ports and harbours, water levels are modulated within stilling wells around the pressure sensors themselves and water level oscillations are time-averaged to a reporting interval of 15 min. Nevertheless it is clear that tide–surge–wave interactions can be significant; thus a case study in Liverpool Bay, UK, showed that the effect of wave setup on still water level may reach 10% of the overall wind-driven surge level (Wolf, 2008). And once surges enter very shallow water, and interact with coastal landforms and ecosystems, the effect of differences in landform topography and orientation, surface roughness characteristics and variable water depth can generate differences in maximum water levels at terrestrial boundaries that can easily exceed 1 m. A methodology that links high resolution measurements of maximum storm surge runup in different coastal settings with contextual records of tidal fluctuations, surge propagation and wind and wave fields during the passage of the surge allows these interactions to be studied in much greater detail than has been achievable in the recent past. Furthermore, by placing individual surge events within longer-term monitoring programmes of coastal change, it is now possible, at individual sites, to quantitatively assess the degree to which surge impacts either lie within the envelope of natural variability in shoreline dynamics over a particular time period or sit well outside such ‘normal’ patterns of shoreline migration, with all that implies for appropriate post-surge coastal management strategies. We consider these questions here in relation to storm surge impacts along the eastern coastal margin of the southern North Sea basin, with particular reference to the storm surge of December 2013.

The continental shelf sea of NW Europe's southern North Sea is susceptible to storm surges, narrowing to a restricted connection with the English Channel and being relatively shallow compared to the deeper basins to the north. This bathymetry thus funnels waves generated by vigorous eastward-tracking mid-latitude cyclonic systems onto low-lying coastal margins. When such wind and wave forcing coincides with high spring tides there is the potential for damage to coastal landforms, ecosystems and infrastructure, accompanied by extensive sea flooding. Lamb (1991) lists 26 major sea flood events along the North Sea coastline between 120 BC and AD 1978 (a conservative estimate). The NW European coastal floodplain supports a current population of ca 15 million people, and incorporates four large port cities (populations > 1 million): London, greater Amsterdam, greater Rotterdam and Hamburg (Hanson et al., 2011). Since these coastal areas are gateways to the rest of Europe, impacts (e.g., reduced port and airport activity, shutdown of power plants with coastal flooding) are likely to ripple out across a much greater area.

In modern times, the benchmark storm surge event is the storm surge of 31 January–1 February 1953, arguably, in terms of loss of life (>2000 deaths), the most devastating natural disaster to affect NW Europe during the last 100 years (Baxter, 2005; Gerritsen, 2005; although see also the 1962 storm surge impacts in Hamburg (Munich Re, 2012)). A southern North Sea event of comparable magnitude occurred between 5 and 6 December 2013, testing sea defences, damaging infrastructure and locally flooding urban centres and rural communities. The Thames Barrier, the Eastern Scheldt storm surge barrier and the flood gates protecting Hamburg were all closed in response to the surge. Initial estimates of insured losses have been put between €1.4 billion and €1.9 billion (Artemis, 2013). Ten lives were lost in the UK, Denmark and Sweden in the 2013 event, as a result of storm force winds rather than death by drowning. However, whilst the economic impact may have been high, the combination of (1) the nature of the surge–tide–wave characteristics of this event and (2) the backdrop of advances in coastal engineering (post-1953 flood defence structures, including the building of major coastal barriers and barrages), developments in storm surge forecasting methods and improved risk management systems averted a human catastrophe of similar magnitude to that of the 1953 storm surge.

The coastline of eastern England, between the macro-tidal estuarine systems of the Humber and the Thames (Fig. 1) is characterised by extensive areas of near sea level marshlands (both natural and reclaimed marsh), freshwater wetlands behind gravel barriers and sand dune-backed beaches, between cliffed sections in often highly erodible pre-glacial and glacial sediments. At a sub-regional level, 19 storm surges of varying severity are recognised by coastal authorities as having impacted the UK North Norfolk coast between November 1897 and November 2007 (Cambridge Coastal Research Unit, unpubl. data).

In December 2013, 210 residential and 45 commercial properties were flooded in the city of Hull and along the Humber estuary (and

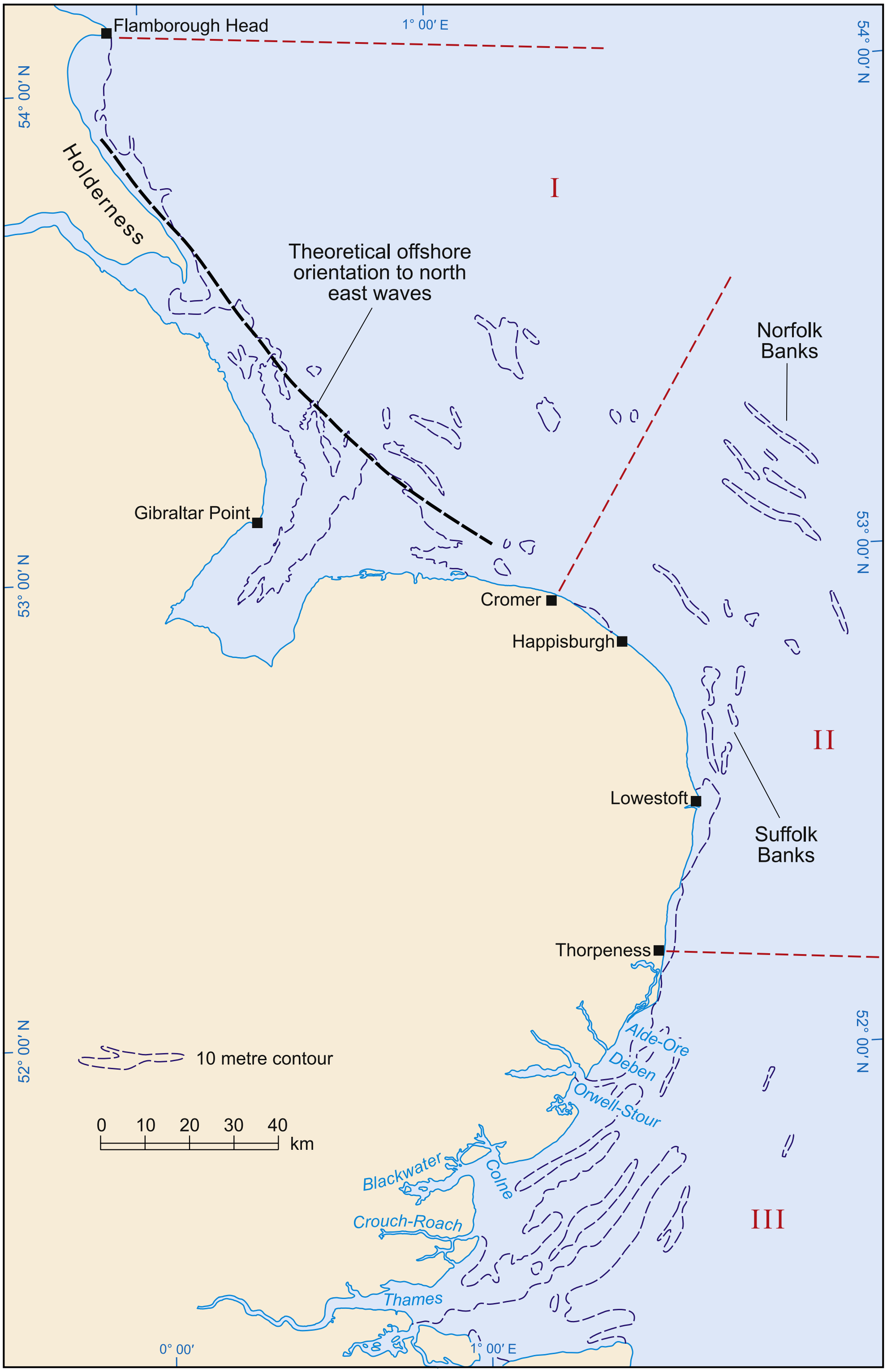

Fig. 1. Nearshore topography of the East Anglian coast (10 m bathymetric contour), Integrated Scale Coastal Evolution (ISCE) units I, II and III (after Pethick and Leggett, 1993) and location map, with locations referred to in the text. For site-specific locations mentioned in the text see Supplementary Material Figs. S1 and S2.

adjacent North Sea coast (East Riding, 2013)); 500 properties were flooded in North Lincolnshire (North Lincolnshire Council, 2013); 300 in Boston, where flood water reached the iconic 'Boston stump' in the town centre (Boston Borough Council, 2013) and in Lowestoft the main harbour and southern town centre were flooded (70 commercial and 60 residential properties (Suffolk Flood and Coastal News, 2014)) and road and rail infrastructure disrupted (Lowestoft Journal, 2014) (important note: all site locations mentioned in the text can be found in Supplementary Material Fig. S1). There was localised cliff slippage, collapse and subsidence of sea walls and promenades and extensive damage to access ramps, chalets and beach huts on the soft rock cliffs between Weybourne and Happisburgh, North Norfolk coast. Wave action severely damaged the pier decking at Cromer. Between Bacton and Walcott, 72 cliff top homes were damaged or destroyed during the surge (NNDC, 2013). Further south, on the Suffolk coast, 78 properties (27 commercial, 51 residential) were flooded in 10 locations between Southwold and Ipswich (Suffolk Flood and Coastal News, 2014).

In this paper we establish and present the tide, surge and wave characteristics of this event. We then concentrate upon the substantial geomorphological and ecological imprint along the coastline of eastern England. On frontages not actively managed for flood defence purposes, four types of coastal impact were observed. First, soft rock cliffs along the North Norfolk and Suffolk coasts were undermined, notched and/or showed local collapse (Fig. 2A). Secondly, vegetated

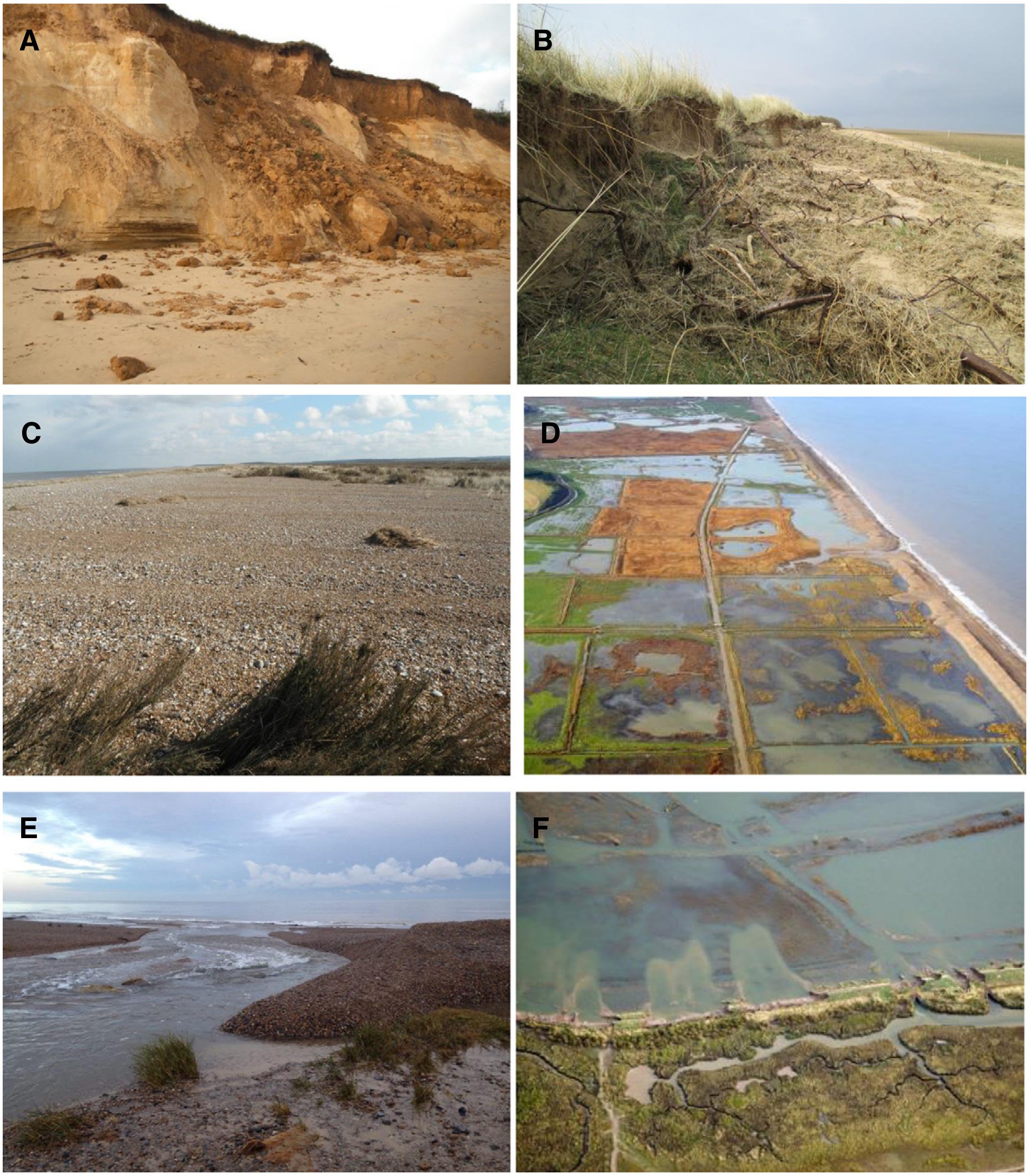

Fig. 2. Impacts of storm surge of 5–6 December 2103 (for locations see Supplementary Material Fig. S1). A) Fresh cliff falls overlying near basal notching, Covehithe cliffs, Suffolk; B) sand dune cliffing and retreat, Donna Nook, North Lincolnshire; C) large reactivated washover fan, central Scolt Head Island, North Norfolk coast; D) breaching of the Cley–Weybourne barrier, with flooding of freshwater marshes and development of new washover fans over back-barrier saline lagoons; E) breach in the Walberswick–Dunwich gravel barrier, Dingle Marshes, Suffolk coast; and F) multiple breaches in the NW section, earthen flood defence bank, Blakeney Freshes, North Norfolk (flooded freshwater marshes to top, saltmarsh to bottom of image). Photographs: A) T Spencer, 7 December 2013; B) B Evans, 27 March 2014; C) T Spencer, 3 March 2013; and D) M Page (http://mike-page.co.uk/), 9 December 2013; E) T Pryke, 17 December 2013; and F) M Page (http://mike-page.co.uk/), 9 December 2013.

dunes in North Lincolnshire (Fig. 2B) and North Norfolk were severely cut back, initially showing near vertical faces before dune face collapse restored more stable, lower-angled faces at more landward locations, located at some distance inland. Thirdly, low barriers showed breaching (as at Gibraltar Point, South Lincolnshire coast) and/or the development of back-barrier washover deposits, both developing new, and re-activating and expanding old, washover aprons (Fig. 2C). Fourthly, natural gravel ridges were breached, with accompanying freshwater marsh flooding and changes to saline lagoon hydrology, along the Blakeney to Weybourne gravel barrier, North Norfolk coast (Fig. 2D). Further south, on the Suffolk coast, similar breaching of gravel barriers took place between Benacre and Easton Bavents, and between Walberswick and Dunwich (Fig. 2E). Back-barrier and estuarine settings experienced the failure of earth embankments, often around areas of reclaimed saltmarsh developed for agriculture or nature conservation (Fig. 2F).

In summary, the aims of this paper are to:

(1) Review the synoptic meteorology and oceanography of the 5 December 13 storm surge along the UK east coast between Wick, Scotland and Lowestoft, England;
(2) Provide a detailed real-time record of water level elevations at the coastline, and synchronous inshore wave activity, from the southern margin of the Humber estuary to the estuaries of the Essex coast, greater Thames estuary during the surge;
(3) Assess in detail the changes in shoreline position and character in terms of (1) notching of soft rock cliffs and cliffline retreat; (2) erosion of coastal dune lines; (3) augmentation or re-activation of barrier island washover deposits; and (4) breaching of gravel barriers and earthen banks and back-barrier flooding;
(4) Evaluate the magnitude of surge-related shoreline change in the context of general shoreline dynamics over the past two decades, including the identification of thresholds for shoreline change;
(5) Compare 2013 surge characteristics with the benchmark storm surge event on the UK east coast, that of 31 January–1 February 1953, and offer explanations for the differing impact of these two events; and
(6) In the context of the 1953 and 2013 events, discuss likely near-future storm surge impacts and the issues raised for storm surge forecasting and coastal flood risk management.

In addressing these research questions, we have made extensive use of technological advances in environmental monitoring and measurement that have only recently become available. In particular, recent developments in the rapid capture of locational and elevational data have permitted, for the first time, a detailed reconstruction of storm surge impacts over a coastline length of over 450 km.

2. Regional setting

The nature of the UK southern North Sea coast, between the Chalk cliffs of Flamborough Head in the north and the Thames estuary in the south, is a response to both the underlying geological structure and stratigraphy along a shelf sea margin and the postglacial to present process environment, as determined by tidal dynamics and wave climate. These contexts become important when assessing storm surge impacts.

2.1. Large scale shoreline morphology

Pethick and Leggett (1993) have classified this coastline into three Integrated Scale Coastal Evolution (ISCE) units (Fig. 1). The first of these units is a bay, marked by the 10 m bathymetric contour, between Flamborough and Cromer and enclosing (from N to S) the rapidly eroding (estimated between 1.2 and 2.7 m a^{-1}; Quinn et al., 2009) glacial clay cliffs of the Holderness coast; the macro-tidal Humber estuary; the multi-barred sandy foreshore of Lincolnshire culminating in the complex spit system of Gibraltar Point; the large, infilling embayment of The Wash; and the barrier island and spit coastline of North Norfolk. Pethick and Leggett (1993) argue that the orientation and large scale dynamics of this unit represent a response to extreme waves from the NE. The second unit (Fig. 1) consists of two retreating (0.8–0.9 m a^{-1}; Cambers, 1976) cliff sections in glacial sands and gravels (Cromer to Happisburgh and Lowestoft to Thorpeness) separated by a section of low foreshore fronted by narrow dunes. General sediment movement is to the south, with local reversals at cuspate forelands, or 'nesses'. This relatively low energy 'inner shoreline' sits inside an offshore 'outer shoreline' characterised by the Suffolk and Norfolk Banks and adjusted to extreme waves from the SE (Pethick and Leggett, 1993). The third ISCE, south from Thorpeness (Fig. 1), is a deep and complex embayment characterised by a series of estuaries — the Alde/Ore, Deben, Orwell-Stour, Colne-Blackwater, Crouch-Roach and the Thames — and, offshore, by an extensive suite of subtidal sandbanks. These shoals are up to 80 km in length, 7.5 km in width and typically <5 m below mean sea level. They are separated by often 20 m deep intervening channels which link the Thames estuary to the southern North Sea basin (Burningham and French, 2011).

2.2. Tidal regime

The progress of the tidal wave from the Atlantic Ocean into and around the North Sea is shown by the co-tidal lines in Fig. 3. The wave enters from the north, travels south along the British east coast and then proceeds around two amphidromic points along the coastlines of The Netherlands, Germany and Denmark. The co-amplitude lines run parallel to the coast of eastern England and reflect the distance along the co-tidal lines from the relevant amphidromic point; thus mean spring tidal range is greatest at the northern and southern limits of the study area and least near Lowestoft, the most easterly settlement on the English coast.

2.3. Wave climate

The record of measured offshore and nearshore wave conditions obtained by the network of five offshore Directional Waverider (DWR) buoys and 20 inshore Acoustic Wave and Current meters (AWACs), under the UK Environment Agency Anglian Coastal Monitoring (EA ACM) Programme, provides a useful summary of wave conditions along the East Anglian coastline. On the Lincolnshire coast, wave measurements for the period September 2006 to September 2009 (Environment Agency, 2012) showed an annual mean significant wave height (H_s) of 1.08–1.15 m at West Silver Pit (station LWB1; 27 km offshore, 19 m water depth). Over the same time period, four inshore (5 m water depth) stations, between Donna Nook and Skegness, recorded annual mean significant wave heights (H_s) of 0.51–0.72 m, with annual mean maximum significant wave heights ($H_{s(max)}$) of 0.82–1.12 m. In March 2008, a maximum wave height of 3.52 m was recorded by the Chapel Point AWAC deployment. Predominant wave directions on this coast are from the NE to E.

For the same time period on the North Norfolk coast, an annual mean significant wave height of 0.80–1.00 m was recorded at Blakeney Overfalls (NWB1; 10 km offshore, 18 m water depth). Over the same time period, four inshore stations (5–7 m water depth), between Scolt Head Island and Horsey, recorded annual mean significant wave heights (H_s) of 0.49–0.73 m, with annual mean maximum significant wave heights ($H_{s(max)}$) of between 0.79 and 1.14 m. Maximum wave heights of 4.90 m at Blakeney Overfalls, and 4.0 m at Walcott, were recorded in November 2008 (Environment Agency, 2014a). Higher wave heights are unlikely at Blakeney Overfalls due to wave breaking over the offshore shoals here (D. Cox, pers. comm., 2014). Between 12/1985 and 6/1987, a

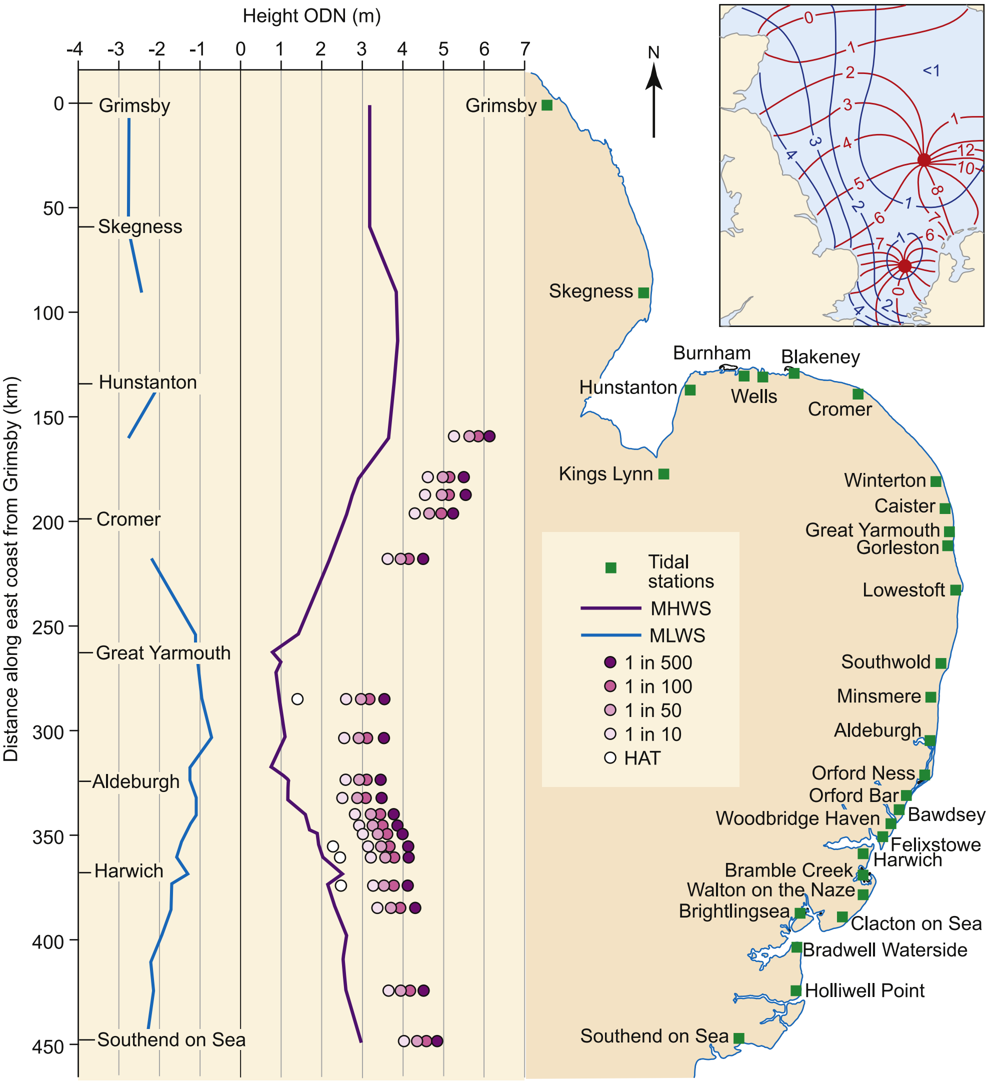

Fig. 3. Variations in tidal range (left) with stations plotted (right), Grimsby to Southend on Sea (ODN = Ordnance Datum Newlyn which approximates to mean sea level; MHWS = Mean High Water Springs; MLWS = Mean Low Water Springs; HAT = Highest Astronomical Tide (from Admiralty Tide Tables, 2000) and extreme water levels (from Environment Agency, 2011b; contains Environment Agency information © Environment Agency and database right). Inset top right: tides in the North Sea as derived from observations. Red lines are co-phase lines of the M2 tide, labelled in hours after the moon's transit through the meridian of Greenwich. Blue lines give the mean tidal range at spring tide (co-range lines of the sum of M2 and S2).
Source: Tomczak (1996).

maximum significant wave height ($H_{s(max)}$) of 4.81 m was recorded offshore (31 m water depth) from Cromer (Chini et al., 2010). On this coast the predominant wave direction is from N to NNE.

At Southwold Approach (SWB1; 7 km offshore, 23 m water depth) wave measurements for the period September 2006 to September 2008 (Environment Agency, 2009a, 2010a) showed an annual mean significant wave height (H_s) of 0.89 m and an annual mean maximum significant wave height ($H_{s(max)}$) of 1.41 m. Over the same time period, there were variations in monthly mean significant wave heights at four inshore stations (4 m water depth) between Southwold North and Bawdsey of 0.4–0.8 m. Mean monthly maximum wave heights (H_{max}) at these stations varied between 0.7 and 1.2 m. The maximum wave height recorded inshore on this frontage was 5.29 m (12/2006) at Southwold North. Whilst the offshore station recorded waves predominantly from the NE and S, inshore wave directions were generally in a broad arc between E and SE. Pye and Blott (2006, 455) describe the wave climate along the Suffolk coast as ‘moderate, with 37.7% of all waves being less than 1 m high and 76% of all waves less than 2 m high. The highest waves approach from the north and northeast, which is the direction of longest fetch’.

At South Knock, in the outer Thames estuary (EWB1; 37 km offshore, 20 m water depth) wave measurements for the period September 2006 to September 2008 (Environment Agency, 2010b, 2011a) showed an annual mean significant wave height (H_s) of 0.80–0.85 m and annual mean maximum significant wave heights ($H_{s(max)}$) of 1.28–1.35 m. The maximum wave height recorded here was 4.61 m (2/2006). Inshore stations show much lower wave heights, due to the energy dissipation effect of the extensive offshore banks and tidal flats fronting the open coast (Moller and Spencer, 2002). Over the same time period, there were variations in monthly mean significant wave heights (H_s) at four inshore stations (4 m water depth) of 0.4–0.7 m in the north (Felixstowe) to 0.2–0.5 m in the south (Maplin Sands). Mean monthly maximum wave heights (H_{max}) varied similarly, from 0.6–1.0 m to 0.4–0.8 m. Maximum wave heights recorded was 3.50 m at Clacton (5/2005) (Environment Agency, 2010b). Offshore wave directions are bimodal, forced by dominant southwesterly winds and northeasterly storms (Burningham and French, 2011); inshore wave directions are more variable, between NE and SW.

3. The 5 December 2013 event: meteorology and oceanographic setting

The winter of 2013–2014 over NW Europe was characterised by a powerful jet stream driving a succession of low pressure systems across the Atlantic Ocean (Wallace et al., 2014). The first of these major systems formed near Iceland on 4 December 2013 and deepened to form an intense easterly-tracking cyclone, passing across northern Scotland and accompanied by Beaufort Force 9 (strong gale) to 11 (violent storm) winds, on 5 December (UK Met Office, 2014; Fig. 4). Severe coastal flooding was experienced on the west coast of North Wales, in NW England and on the west coast of Scotland. The eastward track subsequently developed a south-easterly component as the system moved around the high pressure to the west of Ireland. Into 6 December, the storm then moved across Southern Norway and Sweden (Eqecat, 2013), intensifying further to reach its lowest pressure of 960 hPa over the Baltic Sea (Air Worldwide, 2013). Maximum gusts in excess of 100 km h^{-1} were recorded at most coastal stations from Scotland to eastern England on 5–6 December 2013. In Suffolk, maximum gusts above 56 km h^{-1} (Beaufort Force 7; near gale) were recorded between 0900 and 1800 UTC on 5 December, peaking at Wattisham at over 110 km h^{-1} (Beaufort Force 11; violent storm) between 1400 and 1500 UTC (UK Met Office, 2014). The combination of low pressure and strong winds led to a significant storm surge which propagated southwards with the high spring tide along the east coast of Scotland (Wick: 1245 UTC, 5 December 2013) and then England (Lowestoft: 2230 UTC), continuing around the southern North Sea to affect the coasts of Belgium (Ostend: 0200 UTC, 6 December 2013), The Netherlands, North Germany and Denmark.

3.1. Tide–surge water levels

Recorded still water levels for the period 4–6 December 2013 were available from the UK National Tide and Sea Level Facility (http://www.ntslf.org/) for the UK National Tide Gauge Network stations at Wick, Aberdeen, North Shields, Immingham and Lowestoft. Unfortunately, surge-associated wave action beneath Cromer Pier made the water level record at this location unusable for subsequent analysis and the Sheerness tide gauge was off-line at the time of the surge. Fig. 5 shows the tide–surge interactions, and resulting still water level change, at these stations, with detailed metrics in Table 1. Additional still water level records were obtained from the UK Environment Agency for tide gauges at King's Lynn and Wells-next-the-Sea (Supplementary Material Fig. S1). Observations were stored at all stations at 15-minute intervals (to exclude seiching and wind wave signals) and, with the exception of the Wells record, could be matched against harmonic tidal predictions at the same time steps to calculate the nontidal residuals (Pugh and Woodworth, 2014).

Table 1 shows the progressive increase in the peak nontidal residual along the UK east coast and its timing in relation to high water level. The residual at King's Lynn was recorded early on the flood tide and thus appears large; Horsburgh and Wilson (2007, 6) note that 'a feature common to … time series is that the residual is significantly greater at low water than at high water'. Similar anomalies at this location were commented upon by both Corkan (1950), for the storm surge of 8 January 1949, and by Rossiter (1954), for the surge of 31 January–1 February 1953, where the latter author argued that the anomaly was 'no doubt attributable to a combination of large stretches of shallow water in the Wash and the geographical shape and orientation of the Wash' (Rossiter, 1954, 382). It is well-established that surge maxima are non-randomly distributed, typically being found on the rising limb of the tidal curve (Rossiter, 1961; Prandle and Wolf, 1978; Wolf, 1981). Analysis of the timing of peak surge residuals for 5 tide gauges between

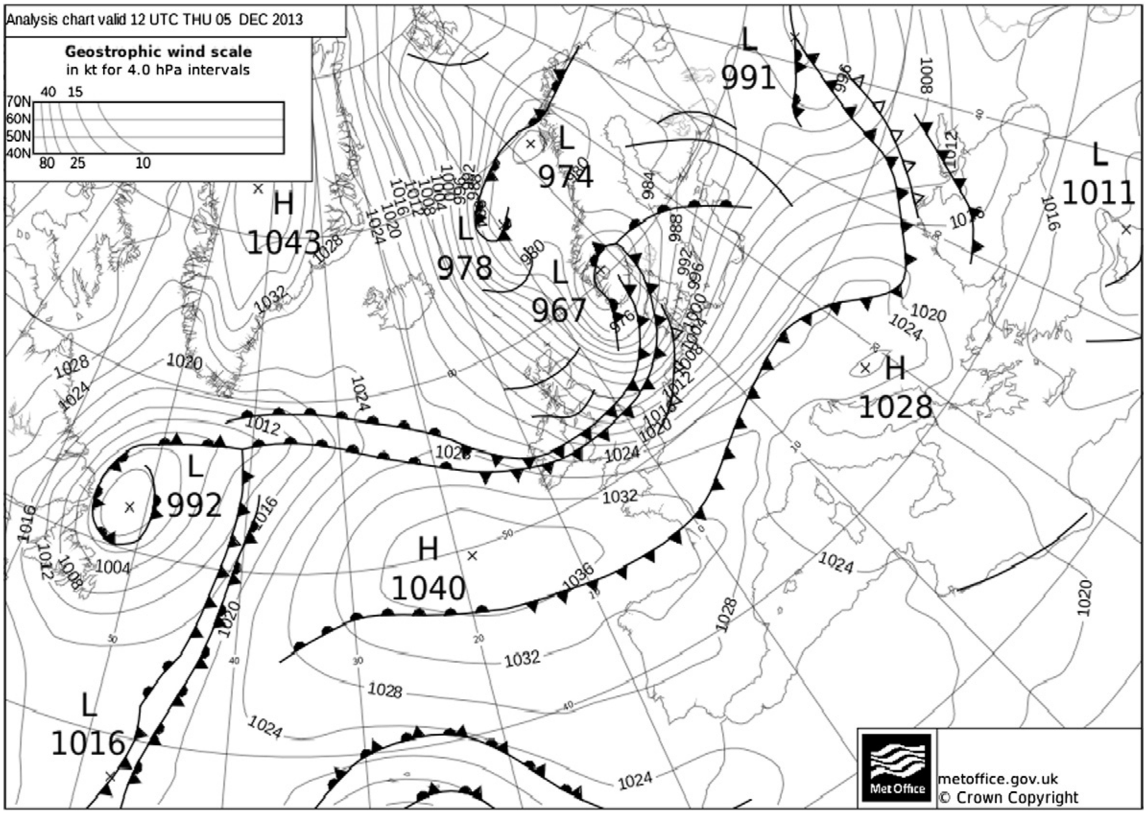

Fig. 4. Analysis chart at 1200 UTC 5 December 2013 (UK Met Office, 2014).
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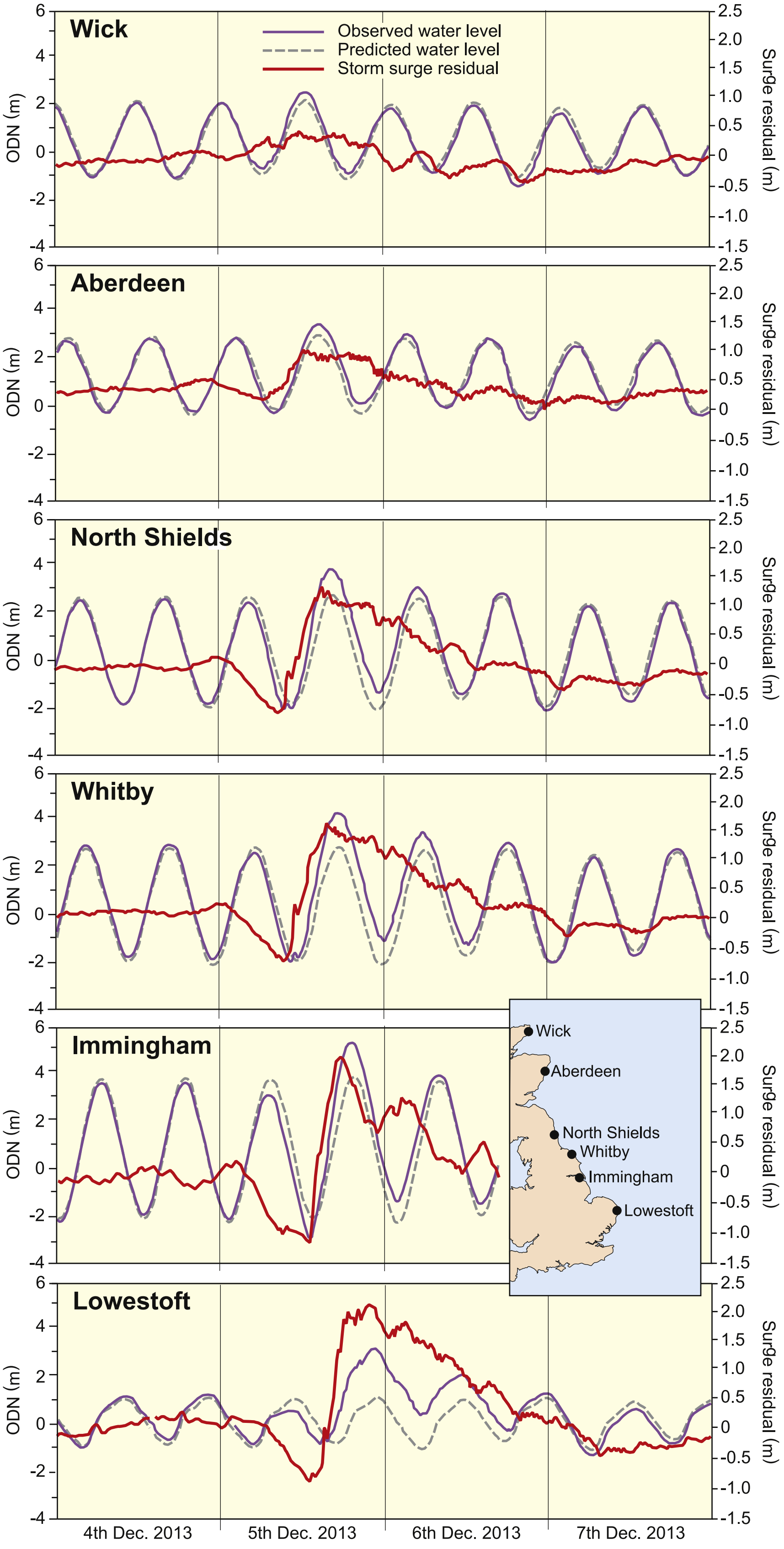

Fig. 5. Observed water level (i.e., with meteorological forcing), predicted water level (astronomical tide) and surge residual (observed–predicted level) at 6 tide gauge stations (see inset for locations), UK National Tide Gauge Network, 4–7 December 2013.
Contains data supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and Natural Environment Research Council.

Table 1
Metrics for the storm surge of 5–6 December 2013.
Source: National Tide and Sea Level Facility 'class A' tide gauges and (King's Lynn; Wells-next-the-Sea) UK Environment Agency. Contains (1) data supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and Natural Environment Research Council and (2) Environment Agency information © Environment Agency and database right.

Location (see Fig. 1)	Maximum surge residual	Time of maximum surge residual	Maximum still water level	Time of maximum still water level	Predicted still water level	Time of predicted still water level	Skew surge
	(m)	(UTC)	(m ODN)	(UTC)	(m ODN)	(UTC)	(m)
Wick	0.43	11.45	2.44	12.45	2.09	12.30	0.35
Aberdeen	0.74	12.15	2.98	15.00	2.34	14.45	0.64
North Shields	1.33	15.15	3.98	16.15	2.97	16.45	1.00
Whitby	1.63	15.45	4.32	17.15	2.85	17.30	1.47
Immingham	1.97	17.30	5.22	19.15	3.69	19.30	1.52
Kings Lynn	2.83	17.00	6.05	19.15	4.18	19.45	1.87
Wells-next-the-Sea			5.22	19.15	2.96	20.05	2.26
Lowestoft	2.18	22.00	3.26	22.30	1.20	23.00	2.06

Aberdeen, Scotland and Sheerness, outer Thames estuary, between 1950 and 2005 shows the modal occurrence to be 3.75 to 5 h before the next high water level (Horsburgh and Wilson, 2007). This positioning is considerably greater than that of the advance seen for the 5 December 2013 event (Table 1). However, the long-term frequency pattern is multimodal at the Aberdeen, North Shields and Immingham stations, with clear additional peaks 1.0, 1.5 and 2.5 h before high water respectively. The December 2013 surge appears to fit into this type of grouping of surge residuals. Nevertheless, the closeness of the peak residual to high water level is noteworthy as large residuals do not typically occur close to high water (Horsburgh and Wilson, 2007). This appears to have been particularly evident at Lowestoft, although here the pattern of tide–surge interaction was complex, with high (>2.0 m) surge residuals at 3.45 and 2.15 h before high water level and a broad peak of similar levels around high water itself (−1.30 to +0.15 h) (Fig. 5). The lowest tidal range on the east coast is close to Lowestoft (Fig. 3), so it is 'the longer half-wavelength of the surge that dominates the extreme high-water signature' (Muir Wood et al., 2005, 1412). Elsewhere, the surge signal showed a clear, single, pre-high water peak at North Shields, Whitby and Immingham, although the post-high water pattern of residuals at Immingham was more erratic, perhaps as a result of more complex surge–tide interactions and other effects in a shallow estuarine setting (Fig. 5).

3.2. Associated wave activity

The final contextual information on the storm surge of 5 December 2013 concerns wave activity associated with the passage of the event. Wave height and directional data were available for 7 DWR buoys, variously deployed by Gardline/UK Environment Agency and the Centre for Environment, Fisheries & Aquaculture Science (CEFAS), between Chapel Point, offshore from the North Lincolnshire coast, to South Knock in the outer Thames estuary. Data were downloaded using the 'WaveNet' portal (http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx), with a 30 minute reporting interval. Fig. 6 shows the location of the 7 directional waverider buoys and the directions of wave approach for the 12 hour period around the time of predicted high water (i.e., −6 h to +6 h) at Immingham (for Chapel Point, North Well, Blakeney Overfalls and Happisburgh DWR) and Lowestoft (for Sizewell, Felixstowe Pier and South Knock). Wave data collected at 30 minute intervals provide 24 directions of wave approach and the number of occurrences of each direction is plotted on the wave roses.

Fig. 7 shows the variation in wave heights at the individual wave buoys for the period between ca. 0700/0800 UTC on 5 December and 1000 UTC 6 December 2013. On the Lincolnshire and North Norfolk coasts, there was a close correspondence (1900–1930) between the height of predicted high tide at Immingham (Table 1) and maximum wave heights (significant wave height (H_s) = 2.5 m) at Chapel Point. The peak significant wave height of 2.1 m at the North Well waverider buoy was recorded much earlier, at 1500 UTC and coincident with the passage of the frontal system, suggesting locally generated wind waves in the entrance to The Wash. Significant wave heights were higher along the North Norfolk coast. The highest waves recorded during the passage of the surge, with a significant wave height (H_s) of 3.8 m, were seen at Blakeney Overfalls in a double peak at 1630 UTC and 1730 UTC (Fig. 7). This was 2.45 to 1.45 h before the time of maximum water level at Wells-next-the Sea (Table 1), although significant wave heights were still 3.2 m at 1915 UTC. The inshore wave recorder at Happisburgh, in much shallower water (10 m) than at Blakeney Overfalls (23 m), showed a similar time course to the Blakeney record but with a maximum significant wave height of 2.9 m at 1700–1730 (Fig. 7). Significant wave heights were lower on the Suffolk coast. At Sizewell, waves were still onshore (Fig. 6) but wave heights declined from a peak H_s of 1.81 m at 1230–1300, 10 h before the maximum water level, to just 0.9 m at 2230, the time of highest water level. The pattern at Felixstowe Pier was similar but with even lower wave heights; 1.50 m at 1230 and then 0.70 m at 2230 (Fig. 7). Finally, by South Knock, outer Thames estuary the wind had veered to the WNW to blow offshore by 1630, 6 h before the maximum water level at Lowestoft and that wind direction was maintained through the early hours of 6 December 2013 (Fig. 6).

4. Methodology for assessing storm surge impacts

4.1. Vertical elevation measurements

In the immediate (day +1) aftermath of the surge, and for two weeks thereafter, high resolution measurements of maximum water level elevations — from the highest, landward margins of unequivocal debris lines; soft rock cliff notching; erosional cliffing in earthen bank defence lines; and water marks on buildings — were established at a range of sites from the southern margins of the Humber estuary to the Blackwater estuary, Essex. This intensive measurement programme was then supplemented by further field campaigns over the next 3 months to confirm earlier measurements; to extend spatial coverage from the original data collection; and to establish heights for existing markers of earlier, most usually 1953, surge events. Measurements were made with a Leica Viva GS08 GNSS satellite survey (RTK) system; all stored measurements were characterised by a 3-D coordinate quality of <50 mm, and typically of <20 mm. Measurements were screened, with reference to field notes in particular settings, to exclude measurements where height determination was uncertain as well as measurements that could not clearly be related to the actual surge event. In addition, where shadowing effects prevented a satellite-based fix on a building having a clear watermark or on notching in soft rock cliff materials, short-distance levelling was undertaken using a semi-automatic Kern level from a local RTK-determined benchmark. Here closure errors

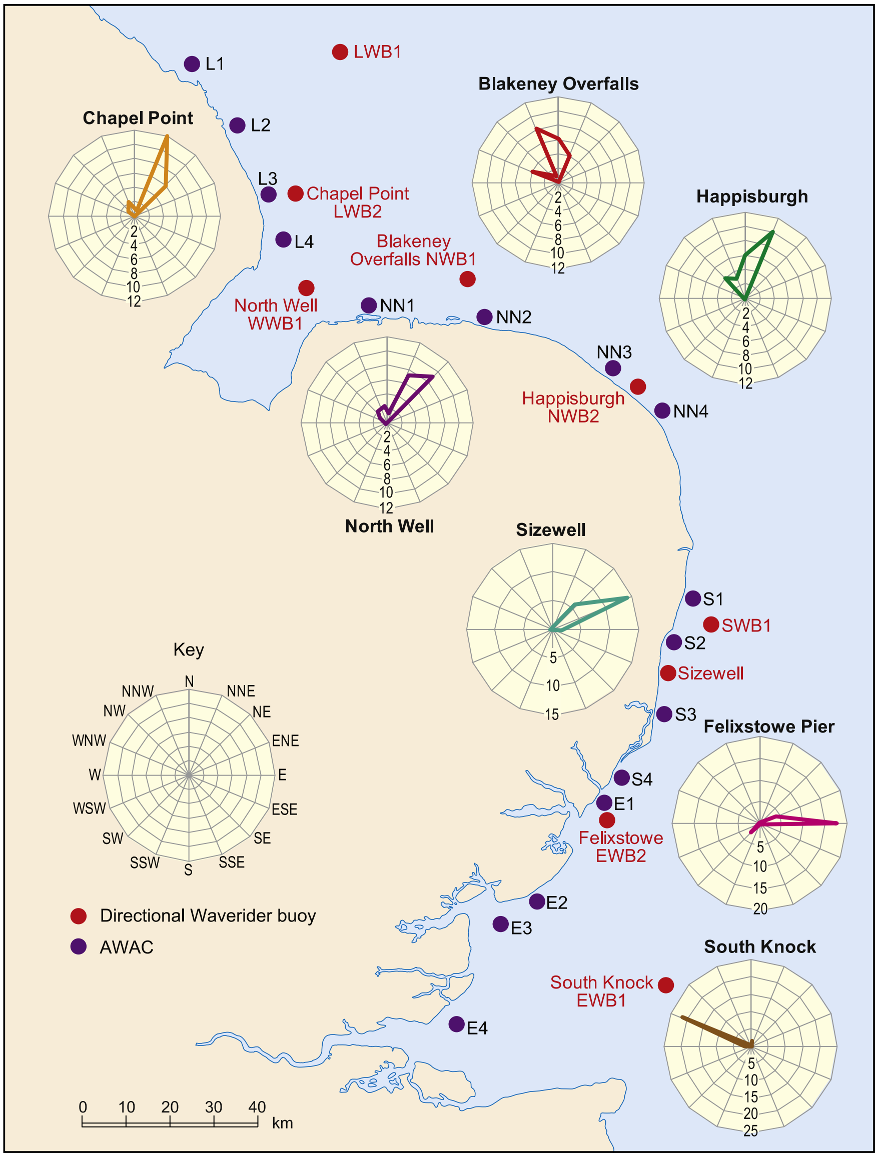

Fig. 6. Directions of wave approach at 7 offshore stations for the 12 hour period on 5–6 December 2013 around the time of predicted high water (i.e., −6 h to +6 h) at Immingham (for Chapel Point, North Well, Blakeney Overfalls and Happisburgh Directional Waverider buoys) and Lowestoft (for Sizewell, Felixstowe Pier and South Knock). Wave data collected at 30 minute intervals provide 24 directions of wave approach and the number of occurrences of each direction is plotted on the wave roses. See text for discussion of longer-term (variously 2005–2009) wave statistics for Directional Waverider buoys at West Silver Pit (LWB1) and Southwold Approach (SWB1) and at 16 inshore Acoustic Wave and Current meter (AWAC) stations.
Data courtesy of the CEFAS 'WaveNet' portal. The figure contains data supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and Natural Environment Research Council and public sector information licensed under the Open Government Licence v2.0. © Crown copyright, 2014.

were <30 mm. All height determinations were recorded with respect to Ordnance Datum Newlyn (ODN; where 0.00 m ODN approximates to mean sea level).

4.2. Horizontal positioning of the shoreline

Changes in shoreline position following the storm surge event were established by comparing field-derived x and y co-ordinate data, from the Leica Viva GS08 GNSS satellite survey system, to geo-referenced aerial photography from August 2013, kindly supplied by the UK Environment Agency (EA). Field survey results were imported into ArcMap 10 (www.esri.com) to create polylines of shoreline position immediately after the surge. Then for each 2013 aerial photograph, the shoreline position was digitised manually within ArcMap 10. The choice of an unambiguous marker of shoreline position, as well as digitisation errors, have been discussed previously for clifflines (Brooks and Spencer, 2010, 2012); the clifftop edge has been found to be the most unambiguous marker of shore position for cliffed shorelines and was used again here. For backshore to sand dune transitions, the shoreline was defined, both in the field and in aerial photography, by the position of permanent sand dune vegetation cover; this was particularly sharply delineated where there was an eroded duneline in December 2013. Shorelines established by both methods, in the British National Grid (OSGB36) co-ordinate system, were compiled for the analysis of shoreline change — recorded as Net Shoreline Movement (NSM) — between August and December 2013 using the Digital Shoreline Analysis System (DSAS) from the United States Geological Survey (version 4.3.4730) (Thieler et al., 2009). In addition, in barrier settings, field surveys were used to establish the landward contact alongshore between washover sands and gravels and vegetated upper saltmarsh.

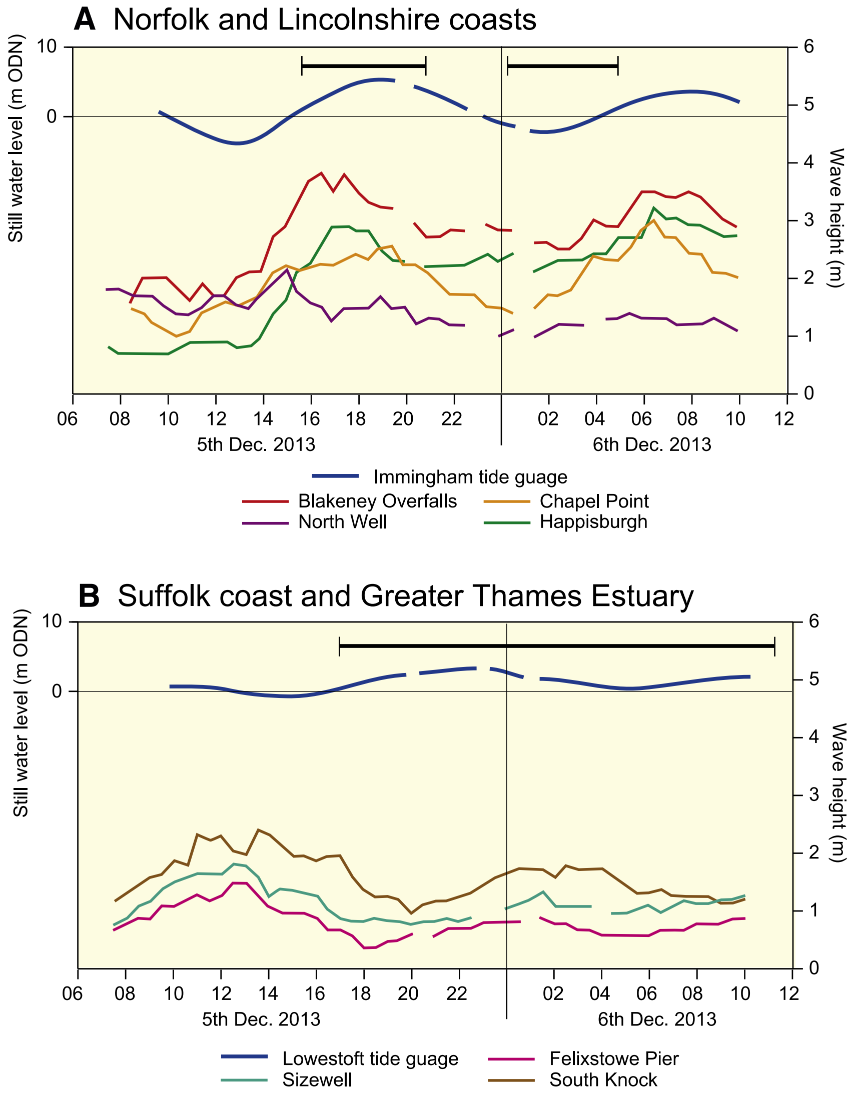

Fig. 7. Variation in wave heights (m) A for 4 Directional Waverider buoys (for locations see Fig. 6) on the Norfolk and Lincolnshire coasts in relation to predicted still water level (m ODN) at the Immingham tide gauge (for location see Fig. 5) and B for 3 Directional Waverider buoys (for locations see Fig. 6) on the Suffolk coast and Greater Thames Estuary in relation to predicted still water level (m ODN) at the Lowestoft tide gauge (for location see Fig. 5) for the period from ca. 0700/0800 UTC on 5 December to 1000 UTC 6 December 2013. Horizontal black bars show periods when the surge residual exceeded 1 m in the tide gauge records.

Data courtesy of the CEFAS 'WaveNet' portal. The figure contains data supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and Natural Environment Research Council and public sector information licensed under the Open Government Licence v2.0. © Crown copyright, 2014.

Assessments of shoreline change were undertaken at 4 geographically-spread locations, here listed from north to south along the east coast. At each location, analysis was possible to a very high level of spatial densification, with shore-normal transects being cast at an alongshore spacing of 5 m. At Donna Nook, north Lincolnshire, analysis was undertaken over a 150 m shoreline length to coincide with the cliffed dunes that were surveyed in the field. On the barrier island of Scolt Head Island, North Norfolk coastline, field survey was compared to aerial photography over a linear distance of 4.85 km, encompassing all but the western end of the island. This corresponded to 970 shore-normal transects. On the open coast 5 km further east, at Holkham Gap, analysis of the landward retreat of the outer duneline was established for both the western dunefield (a 150 m frontage) and the eastern dunefield (300 m). At Covehithe, Suffolk coast, post-surge cliff edge position was obtained over a cliffline length of 1.8 km (although two sections of cliffline had to be discounted because of a loss of positional lock). 258 shore-normal transects were cast for the analysis of shoreline change.

Aerial photographs were also obtained for all four locations from 1992 (the first year of systematic EA aerial photographic survey), 2000, 2010 and 2013. These were digitised, with polyline shapefiles created within ArcMap 10. The different shorelines were then analysed through DSAS, deriving the End Point Rate (EPR) statistic which measures the average annual change (m a^{-1}) between a pair of shorelines (Thieler et al., 2009). EPR for the period 1992–2013 provided a broad indication of the rate of change of shoreline position in the recent period and EPR statistics for the periods 1992–2000 and 2000–2010 permitted this record to be decomposed to show decadal-scale, historic assessments of shoreline change (for further discussion see Brooks and Spencer (2013)). These measures thus allowed the immediate shoreline change (NSM) associated with the storm surge impact to be set in a range of longer-term contexts. The same shoreline sections were used in the long-term analysis as in the post-surge assessment, except at Scolt Head Island where the analysis was extended by 1.05 km to include the western end of the island (1182 transects over 5.9 km shoreline length).

4.3. Spatial extent of flooded areas

Flooding behind coastal barriers and inside breached sea defences was further assessed through the analysis of over 250 oblique aerial photographs largely taken within two (Suffolk coast) to four (North Norfolk) days of the event (http://mike-page.co.uk/; by request). As flight lines broadly followed the shoreline, the analysis was restricted to a zone within ca 2 km from the coast, except where additional surveys were flown further inland. Mapping of flooded areas from this source material was checked against field observations of flooding limits and augmented by information on sea defence damage and breaching from coastal agencies and organisations in the immediate aftermath of the storm surge. Flood extents were digitised to create polygon shapefiles within ArcMap 10 from which flood area statistics were derived. The location and extent of defence breaches were also plotted, being derived from both field observations and survey and from Environment Agency, NGO and local government records.

5. Results

5.1. East coast surge-related water level elevations

Location-specific maximum, minimum and mean surge-related water level elevations along the coastline of eastern England between the southern margin of the Humber estuary and the Blackwater estuary, northern margin of the Thames estuary, are reported in Table 2 (note: locations of all sites for which surge-related water level elevations were measured are given in Supplementary Material Fig. S2). The record shows considerable variability at both inter-regional, inter-site and within-site locations.

At exposed, open coast sites — on outer dune lines, at the backshore of barrier island beaches and on the margins of gravel barriers — maximum run-up levels varied between 5.02 and 5.83 m ODN in North Lincolnshire, 5.64 and 6.37 m in North Norfolk and 3.50 and 3.80 m in Suffolk. At Harwich, Essex, at the confluence of the estuaries of the Rivers Stour and Orwell, the maximum water level elevation recorded was 3.63 m and at exposed West Mersea, Mersea Island, 4.40 m. Mean elevations attained were 4.96–5.53 m in Lincolnshire, 5.16–6.11 m in North Norfolk, 3.30–3.72 m in Suffolk, 3.59 m at Harwich and 3.86 m ODN at West Mersea.

At the sub-regional scale, on the barrier island coast of North Norfolk, Spencer et al. (2014) have documented considerable alongshore variability in surge-related maximum water levels which cannot be wholly explained by the underlying west to east decline in mean spring tidal range (Fig. 3). Compared to the open coast, recorded water level elevations near the heads of tidal channels connected to inlets between barrier islands, in locations fronted by significant (>500 m) widths of mid to upper saltmarsh and on the landward side of gravel barriers, were typically lower than open sites by at least 40 cm, thus allowing some quantification of wave energy dissipation in the presence of coastal ecosystems. In the Wells Harbour Channel, recorded water level elevations declined progressively from the Coastguard Station, Outer Harbour to The Harbourmaster's Office on The Quay, a decline of 35 cm over 1.58 km (22 cm km^{-1}).

In some estuarine systems, where defence lines were not significantly breached, there was evidence for the funnelling of the surge to give higher water levels at inner estuarine sites. Thus on the Stour estuary mean recorded water levels were 14 cm higher at Manningtree compared to Harwich and 29 cm higher at Maldon than at more seaward Tollesbury on the Blackwater estuary.

In other systems — such as the Blyth and Alde–Ore estuaries, Suffolk — lower recorded water levels were experienced up-estuary. This may have been a function of changes in morphology up-estuary, with wider channel margins, compounded by the over-topping and/or breaching of defence lines and the localised storage of significant volumes of flood water in the inundated areas. Thus in the Blyth estuary,

Table 2
Maximum, minimum and mean water level elevations surveyed for the storm surge of 5–6 December 2013. ODN = Ordnance Datum Newlyn where 0.0 m ODN approximates to mean sea level. See Supplementary Material, Fig. S2 for locations of all sites (site number is given in brackets after site name).

Location	N	Max (m ODN)	Min (m ODN)	Mean (m ODN)
Lincolnshire				
Donna Nook (outer dune) (1)	27	5.83	5.23	5.53
Donna Nook (sheltered) (2)	5	4.82	4.55	4.72
Howden's Pullover (exposed) (3)	9	5.33	5.01	5.07
Howden's Pullover (sheltered) (4)	4	4.85	4.57	4.69
Saltfleetby (5)	7	5.33	5.15	5.24
Seaview (6)	3	5.02	4.87	4.96
Rimac (7)	5	5.12	4.84	5.00
Total	60			
North Norfolk				
Snettisham Scalp (8)	7	6.29	6.12	6.22
Holme-next-the-Sea (outer dunes) (9)	13	6.30	5.81	6.11
Holme-next-the-Sea (inner golf course) (10)	4	4.43	4.37	4.40
Thornham (11)	1	5.64	5.64	5.64
Brancaster West Marsh (west side) (12)	1	5.49	5.49	5.49
Brancaster Beach (13)	2	5.64	5.57	5.61
Brancaster Staithe (14)	3	5.44	5.33	5.38
Scolt Head Island (Hut Marsh back-barrier) (15)	13	5.53	4.89	5.34
Scolt Head Island (Privet Hill) (16)	10	5.95	5.45	5.65
Scolt Head Island (Low Hills seaward drift line) (17)	9	5.90	5.63	5.78
Scolt Head Island (House Hills back-barrier) (18)	5	5.41	5.34	5.37
Scolt Head Island (House Hills seaward drift line) (19)	7	5.94	5.43	5.62
Scolt Head Island (Great Aster Marsh back-barrier) (20)	8	5.52	5.36	5.44
Scolt Head Island (Norton Hills back-barrier) (21)	17	6.17	5.34	5.57
Burnham Deepdale (22)	5	5.45	5.30	5.39
Burnham Overy Staithe (23)	4	5.52	4.94	5.12
Holkham outer dunes (back-barrier) (24)	21	5.63	5.05	5.32
Holkham Gap (seaward margin) (25)	14	6.37	5.22	5.63
Holkham Pine Plantation (26)	1	4.46	4.46	4.46
Wells Harbour Channel (Coastguard Station) (27)	3	5.61	5.59	5.60
Wells Harbour Channel (midpoint) (28)	6	5.43	5.36	5.40
Wells Harbour Harbourmaster's Office (29)	7	5.31	5.21	5.25
Stiffkey (30)	6	5.34	4.76	5.06
Morston (31)	15	5.24	5.14	5.19
Blakeney (32)	17	6.30	4.22	5.16
Cley (33)	33	5.14	4.17	4.86
Salthouse (34)	21	5.02	4.50	4.91
Total	253			
Suffolk				
Open coast				
Benacre Broad (S margin) (35)	9	3.56	3.50	3.52
Covehithe Ciffs (prominent notch) (36)	5	3.80	3.66	3.72
Blyth estuary				
Tinker's Marshes (outside defences) (37)	3	2.37	2.20	2.29
Tinker's Marshes (inside breached defences) (38)	14	2.28	2.14	2.22
Southwold harbour (Harbour Cottages) (39)	2	2.76	2.50	2.63
Robinson's Marshes (inside breached defences) (40)	13	1.96	1.87	1.92
Walberswick (outside defences to E–SE) (41)	19	2.93	2.12	2.44
Dunwich (Reedland Marshes) (942)	12	3.40	3.18	3.35
Alde–Ore estuary				
Aldeburgh (Slaughden) (43)	19	3.17	2.49	2.87
Hazlewood Marshes (44)	2	2.24	2.22	2.23
Iken Cliff (45)	8	2.97	2.92	2.94
Snape (The Crown Inn) (46)	1	2.94	2.94	2.94
Deben estuary				
Woodbridge (47)	6	3.37	3.35	3.35
Felixstowe Ferry (48)	6	3.50	3.19	3.30
Total	119			

(continued on next page)

Table 2 (*continued*)

Location	N	Max (m ODN)	Min (m ODN)	Mean (m ODN)
Essex				
Stour estuary				
Harwich Pier (49)	3	3.63	3.52	3.59
Manningtree (50)	7	3.75	3.71	3.73
Hamford Water				
Landermere (Landers Lane) (51)	13	3.63	3.52	3.56
Walton Backwaters (Titchmarsh Marina) (52)	4	3.57	3.54	3.55
Walton Backwaters (Walton Yacht Club) (53)	2	3.58	3.57	3.58
Blackwater estuary				
The Strood (54)	11	3.95	3.72	3.88
Mersea Island (West Mersea) (55)	14	4.40	3.42	3.86
Tollesbury (Tollesbury Marina) (56)	6	3.87	3.48	3.72
Heybridge (Heybridge Creek) (57)	8	4.00	3.90	3.94
Heybridge Basin (lock gates) (58)	1	3.83	3.83	3.83
Maldon (The Hythe) (59)	5	4.07	3.90	4.01
Total	74			

where reclaimed marshes on the south side of the estuary were extensively flooded, peak water levels at the coast, at Walberswick, were 17–56 cm higher than on the northern estuary margin opposite Robinson's Marshes (at 1.2 km from the estuary mouth) and the outside of Tinker's marshes (1.4 km up-estuary) respectively. On the Alde-Ore, peak water levels of 3.18 m ODN were recorded on Havergate Island (A. Howe, pers. comm., 2014) and 3.17 m ODN at Slaughden but these levels had reduced to 2.97 m at Iken Cliff and 2.94 m ODN at Snape. Between Slaughden and Iken, a maximum level of 2.24 m ODN was measured at the landward margin of the flooded Hazlewood Marshes but this was located 500–700 m from the breached enclosing bank.

There were some locations where very local differences in exposure/sheltering produced large local differences in recorded water levels. Thus at Donna Nook, North Lincolnshire coast, sheltered dune faces recorded differences in maximum water level elevations over 1 m lower than exposed dune faces. On Scolt Head Island, drift lines piled up against dune fronts close to the seaward margin of the barrier, of often massive thickness and width where sites were exposed to westerly winds (Fig. 8A), recorded maximum levels of 5.90–5.95 m ODN. By comparison, back-barrier locations fronted by back-barrier marshes, showed drift lines at 5.52–5.41 m ODN (Fig. 8B). The most remarkable demonstration of this effect was at two extremely sheltered sites — a flooded golf course site at Holme-next-the-Sea (beyond the head of a small tidal channel but behind two lines of substantial sand dunes and intervening dune slacks) and a sea flooded hollow in a plantation of Corsican Pine (*Pinus nigra* var. *maritima*) behind the backshore at Holkham Gap — which recorded maximum water levels of 4.43 m and 4.46 m ODN respectively. By comparison, the exposed sites immediately seaward of these two locations recorded maximum water levels of +1.87 m and +1.91 m respectively on these base levels (Fig. 8C and D).

5.2. Landscape impacts

5.2.1. Soft rock cliffs

Adjacent to the southern margin of Benacre Broad, Suffolk coast, a clear surge-related debris line was recorded at 3.52 ± 0.02 m ODN. This compares with the maximum surge elevation of 3.26 m ODN reported from the Lowestoft tide gauge, 8 km to the north (Table 1). In the low (clifftop = 7.9 m ODN) cliffs between Benacre Broad and the village of Covehithe, there was evidence of a cliff front notch in the weakly- to moderately-cemented sands with gravel lenses which overlie a basal silt-clay platform (Brooks et al., 2012). Although the development of this notch varied alongshore, the base of the notch had a consistent level of 3.62 ± 0.14 m ODN. For those cross-shore transects where field survey could be compared to the vertical aerial photography of August 2013, the mean rate of retreat at the clifftop along this section was 5.87 m (Table 3). However, there was considerable alongshore variability in the retreat rate. In several cross-shore transects the DSAS NSM reached almost 12 m (Fig. 9A). For the longer-term analysis of cliff retreat rates, the entire 1.8 km long cliff section (359 transects) was used to calculate variations in the End Point Rate (EPR). Between 1992 and 2013 the EPR was 4.49 m a^{-1}, with very low alongshore variability ($\sigma = 0.61$). Over the period 1992–2000, the EPR was 6.12 m a^{-1} ($\sigma = 1.61$), whilst between 2000 and 2010 it was 3.08 m a^{-1} ($\sigma = 1.03$) (Table 3). The most recent period of analysis, 2010–2013 generated an EPR of 4.05 m a^{-1}, but results reported elsewhere (Brooks et al., 2012) suggest that this was largely related to a single event in November 2010 where, as in December 2013, up to 12 m of cliff retreat was recorded at some locations.

5.2.2. High vegetated dunes

In high (>3 m) coastal dunes vegetated with marram grass (*Ammophila arenaria*), the surge resulted in steep, often near-vertical, dunefaces immediately backing beach backshores. Repeat visits to several sites observed that dune sands collapsed down the seaward dune front for several weeks after the event, until the over-steepened cliffs regained a more stable profile. In some locations there was evidence for rotational failure of the dune front, with narrow landward tilting ledges on the dune front, still containing their surface cover of *Ammophila*.

Dune line retreat resulting from the surge was established in detail at Donna Nook, Lincolnshire coast and Holkham Gap and Scolt Head Island, North Norfolk coast (Fig. 9B, C). At Donna Nook, dune retreat and cliffing along the 150 m section was recorded as a mean Net Shoreline Movement of 13.59 m (Table 3). This retreat reversed the low, gradual progradation of this shoreline through the 1990s and 2000s; between 1992 and 2013 the shoreline advanced seawards at a rate of 0.21 m a^{-1}. This rate was 0.41 m a^{-1} during the 1990s whereas in the 2000s it was much lower, at 0.09 m a^{-1}. Over a much longer (5.1 km) frontage, Montreuil and Bullard (2012) report a shoreline progradation rate of 1.1 m a^{-1} between 1994 and 2010, and a longer-term seaward movement of 2.7 m a^{-1} between 1891 and 2010, with considerable alongshore variability over this period (0.39 m a^{-1} in the N and 3.77 m a^{-1} in the S). On Scolt Head Island, there was cliffing of two areas of high dunes that lie to the north and west of The Hut (midway along the island; Fig. 10A) and which characterise the Norton Hills towards the eastern end of the barrier respectively. In the central part of the island, the average Net Shoreline Movement was 5.49 m over a frontage of ca. 1 km, against a long-term (1992–2013) retreat rate for this section of 0.65 ± 0.16 m a^{-1} (Table 3). At the eastern end of the island, however, the average Net Shoreline Movement was more than double this figure, at 8.13 m over a distance of 1.25 km, with rates (±1 SD) varying between 5.20 and 11.06 m (Fig. 9C). For the period between 1992 and 2013, the End Point Rate was 0.24 ± 0.85 m a^{-1}, indicating a general trend of low shoreline retreat but with phases of more local accelerated retreat and shoreline advance, the latter accompanied by new foredune development at the eastern limit of the island. At Holkham, near-vertical dune faces, up to 11 m high, were cut into the outer duneline on the western side of the embayment (Fig. 10B). The average Net Shoreline Movement was 19.37 m for the 64 m long western dune front and 11.52 m over a 179 m shoreline length to the east (Fig. 9B; Table 3). For the period between 1992 and 2013, there was a general landward retreat of the dune front at this locality, at a rate of 1.06 m a^{-1} for the western dunes and 1.08 m a^{-1} for the eastern dunes. Simultaneously, however, the dunes prograded at their inward ends, at a mean rate of 2.04 m a^{-1}, thus coming closer together (Table 3). Thus the surge both accelerated the retreat rate in the main sections of both the western and eastern dunefields and reversed the progradational trends at the inner margins of both dunelines.

Fig. 8. Local variations in surge water levels, North Norfolk coast. A) Massive debris bank reaching 5.95 m ODN, Privet Hill, Scolt Head Island; B) typical back-barrier driftline (furthest right in image) at 5.52 m ODN, Great Aster Marsh, Scolt Head Island; C) drift at up to 6.30 m ODN on exposed seaward-facing dunes, Holme; D) water level line at limit of storm surge inundation (4.43 m ODN), Holme Golf Course; E) cliffing on seaward margin of Holkham Gap embayment (peak level of drift in dunes = 6.37 m ODN); F) driftline in pine plantation, Holkham Gap (water level 500 m to west = 4.46 m ODN).
All photographs by T Spencer: A) 3 March 2014; B) 14 February 2014; C) 26 December 2013; D) 6 December 2013; E) and F) 16 January 2014

Table 3
Short-term (Net Shoreline Movement (NSM)) and longer-term (End Point Rate (EPR)) rates of shoreline change on the Suffolk, North Lincolnshire and North Norfolk coasts (for locations see Table 2 and Supplementary Material, Fig. S2), as determined by the Digital Shoreline Analysis (DSAS) software. For details see discussion in text. Negative values indicate seaward shoreline progradation.

Location (see Fig. S2)	Geomorphic setting	EPR 1992–2000 (m a^{-1})	EPR 2000–2010 (m a^{-1})	EPR 1992–2013 (m a^{-1})	NSM Summer 2013–spring 2014 (m)
Covehithe	Soft rock cliffs	6.12	3.08	4.49	5.87
Donna Nook	Low sand dune	−0.41	−0.66	−0.21	13.59
Holkham Gap (west)	High sand dune	1.26	1.46	1.06	19.37
Holkham Gap (east)	High sand dune	1.43	1.71	1.08	11.52
Holkham Gap (dune ends)	High sand dune	−1.79	−2.96	−2.04	No data
Scolt Head Island	Barrier	1.10	0.27	0.65	5.49

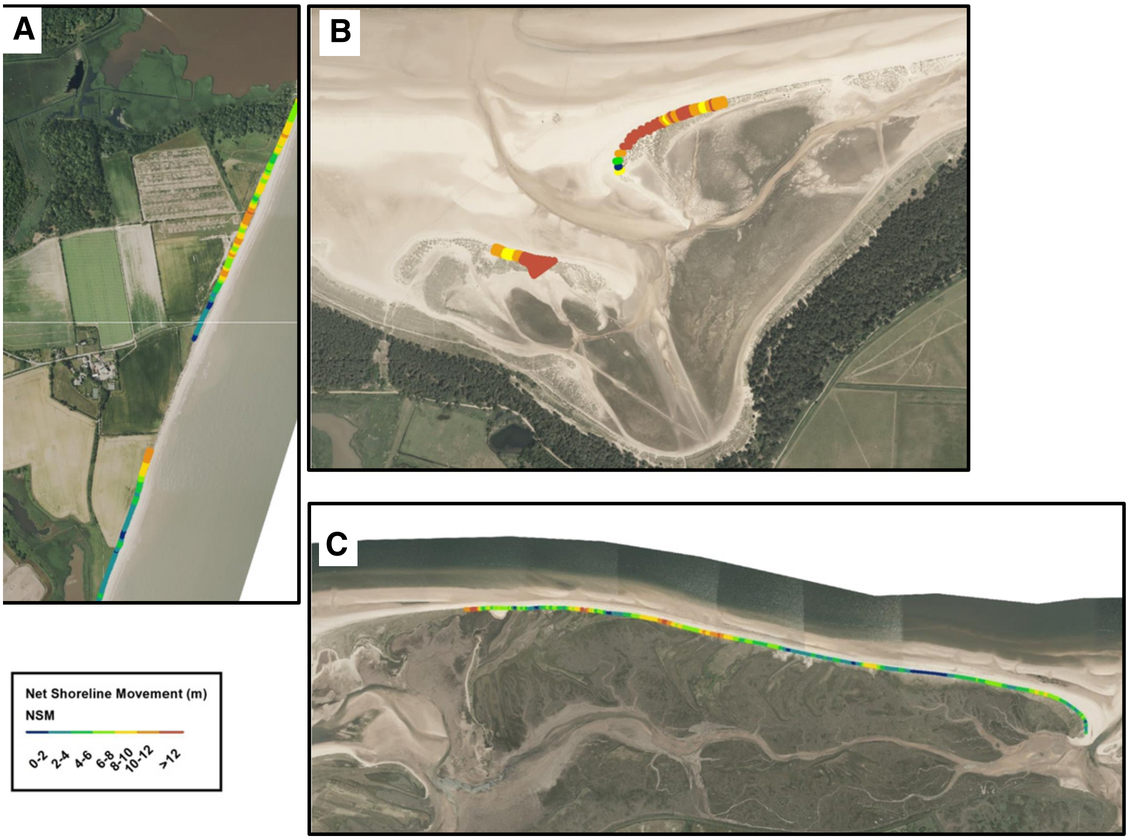

Fig. 9. Net Shoreline Movement (NSM; m) dynamics. A) Covehithe, Suffolk coast (August 2013–8 December 2013); B) Holkham Gap, North Norfolk (August 2013–16 January 2014); C) Scolt Head Island (August 2013–14 February and 3 March 2014). Note: differences in scale between locations.
Aerial photography basemaps courtesy of the Shoreline Management Group, UK Environment Agency; © Environment Agency and database right.

5.2.3. Low dunes and washover fans

Areas of very low dunes were susceptible to storm surge washover processes. Here we report on surge impacts in such environments on the barrier island of Scolt Head Island. To both the east (at Smuggler's Gap and Low Hills) and west of The Hut dunes on the island, there was ‘micro-cliffing’ of the very low (ca. 0.50–0.75 m high) dune face, with undercutting below the surface rhizophorous layer. In some locations, this surface vegetation/root mat was rolled up and moved backwards, resembling a rolled carpet (Fig. 10C). Shoreline retreat of 5.00 ± 1.79 m (area of eastern washovers, 2.1 km shoreline length) and 4.84 ± 2.09 m was measured in these settings, comparable to the mean rates of retreat of the high dunes between these two areas of washover (Fig. 9C). Subsequently beach sediments were piled up against the new low dune face (Fig. 10D). Where the dunes were already very low (ca. 1 m) or non-existent, then the surge either laterally extended active washover fan deposits or re-activated older washovers, described after the 1978 southern North Sea surge by Steers et al. (1979, 200) as ‘a series of arcuate aprons of sand and shingle on the landward side of the ridge, partly overtopping marsh deposits’. To the east of The Hut dunes, thin, sandy washover deposits characterised the back-dune environment at Smuggler's Gap but the most extensive washovers, extending over a distance of 2.5 km, were to be found between Low Hills and the beginning of the Norton Hills (Fig. 2C). Towards the western limit of this area, there was evidence of the formation of new washovers, with steep landward margins in gravel sized material reaching into dune vegetation. However, the majority of this zone, reaching widths of 125 m, appeared to represent a reactivation of earlier washover surfaces (described by Steers et al., 1979); in some locations it was clear that the 2013 washover deposition did not extend as far as the limits of earlier washover sand deposits. The washovers showed low landward-dipping surfaces from the now largely buried dune line, with evidence for both sheet flows and localised channelling of sands and gravels around obstacles and surviving dune vegetation (Fig. 10E). The extension of washover deposits was more marked at the seaward margin of the Wire Hills, associated with the washover fan initiated in March 2007. The washover limit was mapped by RTK survey on 31 January 2014. Comparison with the washover–saltmarsh boundary that is very clearly delimited on the ‘summer’ 2013 aerial photography shows that the area covered by the washover did not greatly change after the December surge (0.84 to 0.94 ha, an increase of 12%). However, the January 2014 survey showed that the area of the main washover had been extended to the west behind the duneline and that the December 2013 surge created a series of new washovers to the east of the main site over a shoreline length of 277 m (Fig. 10F). These new washovers have an area of 0.61 ha (thus increasing the total washover area at this location from 0.84 ha (summer 2013) to 1.55 ha (i.e., +85%)) and extend landward across former saltmarsh surfaces for up to 36 m from the former dune line.

5.2.4. Breaching and overtopping of gravel barriers and earthen banks

Two major breaches took place in the Blakeney–Cley–Salthouse gravel barrier, at Pope's Marsh and opposite the village of Salthouse (Fig. 11A). Breaching was accompanied by the development of extensive washover fans, the infilling of near-barrier saline lagoons and the inundation of 91 ha (one third of the total area of backbarrier wetland) of the Cley to Salthouse Marshes (Table 4). The breaches started to ‘self heal’ in early 2014. Oblique aerial photography (Fig. 11B) and a series of videos show that the breaches began to close between 18 and 22 January 2014, most probably as a result of the east to west transport of coarse materials under persistent easterly waves (Blakeney Overfalls

Fig. 10. Open coast and barrier island surge impacts, North Norfolk coast. A) Cliffing of high dunes, looking east from The Hut dunes, Scolt Head Island; B) vertical cliffing of high dunes, outer duneline, Holkham Gap; C) 'roll-up' of sand dune rootmat layer, seaward margin of Wire Hills, Scolt Head Island (observer's hands are under the mat); D) beach sands piled up against new low erosional dune front, Smuggler's Gap, Scolt Head Island; E) new washover deposits at the western end of reactivated washover, previously formed in 1978, looking west towards The Hut, Scolt Head Island; F) new washover deposits between the 2007 washover at Spartina Marsh and the seaward margin of the Wire Hills dunefield, looking west, towards Far Point.
All photographs by T Spencer (except B) by SM Brooks): A) D) and E) 3 March 2014; B) 26 December 2013; C) and F) 31 January 2014.

waverider buoy: 0.8–1.6 m high waves from 84 to 101° for 20 h on 18–19 January); further infilling of the Salthouse breach was recorded on 20 February 2014 (Changing Coastlines, 2014a,b,c,d,e). Gravel barriers on the Suffolk coast were breached in three places between Walberswick and Dunwich (Fig. 2E) — where Pye and Blott (2009) had previously documented 10 episodes of barrier breaching and overtopping and associated wetland flooding between February 1993 and November 2007 — with the inundation of 91 ha of freshwater grazing marsh, reedbeds and lowland fen. The smaller gravel barriers at Benacre Broad and Easton Broad were also breached. Breaching at Benacre has a different form of ecological significance as the failure of the enclosing barrier allows the drainage of the broad, converting the area of shallow open water into drying mudflat (Spencer and Brooks, 2012). Sequences of opportunistic aerial photography (http://mike-page.co.uk/; by request) since 1993, and particularly in the 2000s, provide a record of breaching and breach re-sealing at Benacre Broad. An overflight on 3 December 2013 showed the barrier to be intact but by 7 December a clear breach was visible. A subsequent flight on 13 March 2014, and a field visit on 3 April 2014, revealed that the breach was in the process of sealing; full closure was confirmed by a further overflight on 16 May 2014. Further south, two breaches were recorded at Minsmere and at Shingle Street (10 m wide with overtopping 120 m to the north

Fig. 11. Dynamics of the Cley–Weybourne barrier. A) Breach opposite the village of Salthouse, 9 December 2013; B) closure of breach captured on 24 January 2014. Aerial photography: M Page (http://mike-page.co.uk/).

and 30 m to the south of the breach), in places lowering the crest by up to 1 m where the Oxley Marshes behind the shingle ridge were inundated over an area of 48 ha (Table 4). There was scour of the shingle ridge 0.5 km south of the Martello Tower at Aldeburgh and further south on Orford Ness, extensive flooding (225 ha) of the King's and Lantern Marshes (Alde and Ore Partnership, 2013). The barrier south of the cuspate foreland at Thorpeness was overtopped but did not fail.

Table 4
Areas (ha) flooded behind breached and overtopped earthen banks on the North Norfolk and Suffolk coasts (see also Figs. 12 and 13 and Supplementary Material, Fig. S1).

Location	Area flooded (ha)
North Norfolk	
Brancaster West Marsh	29.00
Deepdale Marsh–Norton Marsh	217.54
Blakeney Freshes	141.60
Cley Marshes	26.89
Salthouse Marshes	64.37
Total	479.40
Suffolk	
Blyth estuary	
Robinson's Marshes	26.42
Tinker's Marshes	61.08
Open coast	
Corporation Marshes	12.36
Dingle Marshes	78.97
Alde–Ore estuary	
Oxley Marshes	47.76
Havergate Island	51.97
King's Marshes	100.10
Lantern Marshes	124.74
Hazlewood Marshes	69.82
Iken Marshes	86.23
Total	659.45

Away from the open coast, there were failures in earthen banks (Fig. 2F), with breaching of both old flood defences (many of composite age and structure, having been reinforced and raised after 1953) and more recent banks around coastal ‘managed realignments’. Elsewhere there was evidence of overtopping of sea defences without complete structural failure; this is discussed further below. Overtopping was seen at all the North Norfolk sites and reported at Chillesford, Orford (Gedgrave), Butley and Boyton, Aldeburgh (Slaughden) on the Alde/Ore estuary (Alde and Ore Estuary Partnership, 2013). In addition, there was overtopping of estuarine defences at Waldringfield and Kirton Creek on the River Deben and at Shotley, Levington and Wherstead on the River Orwell, Suffolk coast.

Whilst breaching also characterised the Lincolnshire coast (Jones, 2013), here we concentrate upon such bank failures in North Norfolk and Suffolk. In North Norfolk, there were failures at Brancaster West Marsh (a major breach on the western margin and 3 failures on the eastern boundary to the re-alignment); Deepdale and Norton Marsh (6 breaches between Burnham Deepdale and Burnham Overy Staithe); and, in particular, 13 breaches around the Blakeney Freshes embankment. The areas of reclaimed marsh flooded at these three localities were 29, 218 and 142 ha respectively (Table 4; Fig. 12).

Similar patterns were seen on the Suffolk coast (Fig. 13). On the Blyth estuary, Suffolk, there were 5 breaches on the southern margin where 26 and 61 ha were inundated at Robinson's and Tinker's Marshes respectively. In the Alde/Ore estuary, the margins of Havergate Island were breached and 52 ha (of the total area of 108 ha) inundated. The earthen bank to the west of Aldeburgh Marshes at Slaughden was locally overtopped but did not fail but at the Hazlewood Marshes 3 breaches in the southern margin led to 70 ha being flooded (Alde and Ore Estuary Partnership, 2014). A partial breaching of the seawall at Ham Creek, immediately to the north of the Hazlewood Marshes, and the inundation of 40 ha, was reported (Alde and Ore Estuary Partnership, 2013). Further up the estuary, 86 ha were flooded at Iken and at Snape, the north bank was overtopped by almost 0.5 m for up to 3 h. 20 ha were flooded behind the defence line, with water depths of up to 80 cm on the outskirts of Snape village. There were three breaches reported from the River Deben (1 at Ramsholt and 2 in Martlesham Creek) and three on the River Orwell (2 at Levington and 1 at Shotley). The total area flooded was over 600 ha (Table 4; Fig. 13).

Following the 1953 storm surge, Cooling and Marsland (1954) and Marsland (1957) identified four mechanisms for earthen bank failure from field studies on the Essex and Kent coasts: (1) erosion of the seaward face by wave action; (2) erosion of the landward face following over-topping; (3) slipping or slumping of the landward face caused by seepage through the bank; and (4) building-up of water pressures in pervious layers underlying the bank, leading to complete failure of the bank. As observed in 1953, there was little evidence in December 2013 for extensive erosion of the seaward face in estuarine and harbour channel settings beyond decimetre-scale micro-cliffing and micro-notching at levels near to maximum surge levels. Far more extensive was erosion of the landward face. In some instances, this took the form of a sequence from vertical fissures on the upper backslope (Fig. 14A), to basal lobes of bank material backed by vertical inner walls. In other locations, the pattern was one of localised ‘scalloping’ of the inner wall, with evidence for rotational failure with backward inclined blocks still retaining their grass cover. It is not clear how the larger breaches were formed. In some instances, the vertical inner bank walls (Fig. 14B) suggest that breaching was the product of the seaward migration of, and ultimate breakthrough from, inner wall erosion (Fig. 14C). However, in other localities, the areas landward of the breaches were covered by arcuate fields of clay boulders clearly derived from the breach and suggesting a more catastrophic failure mechanism

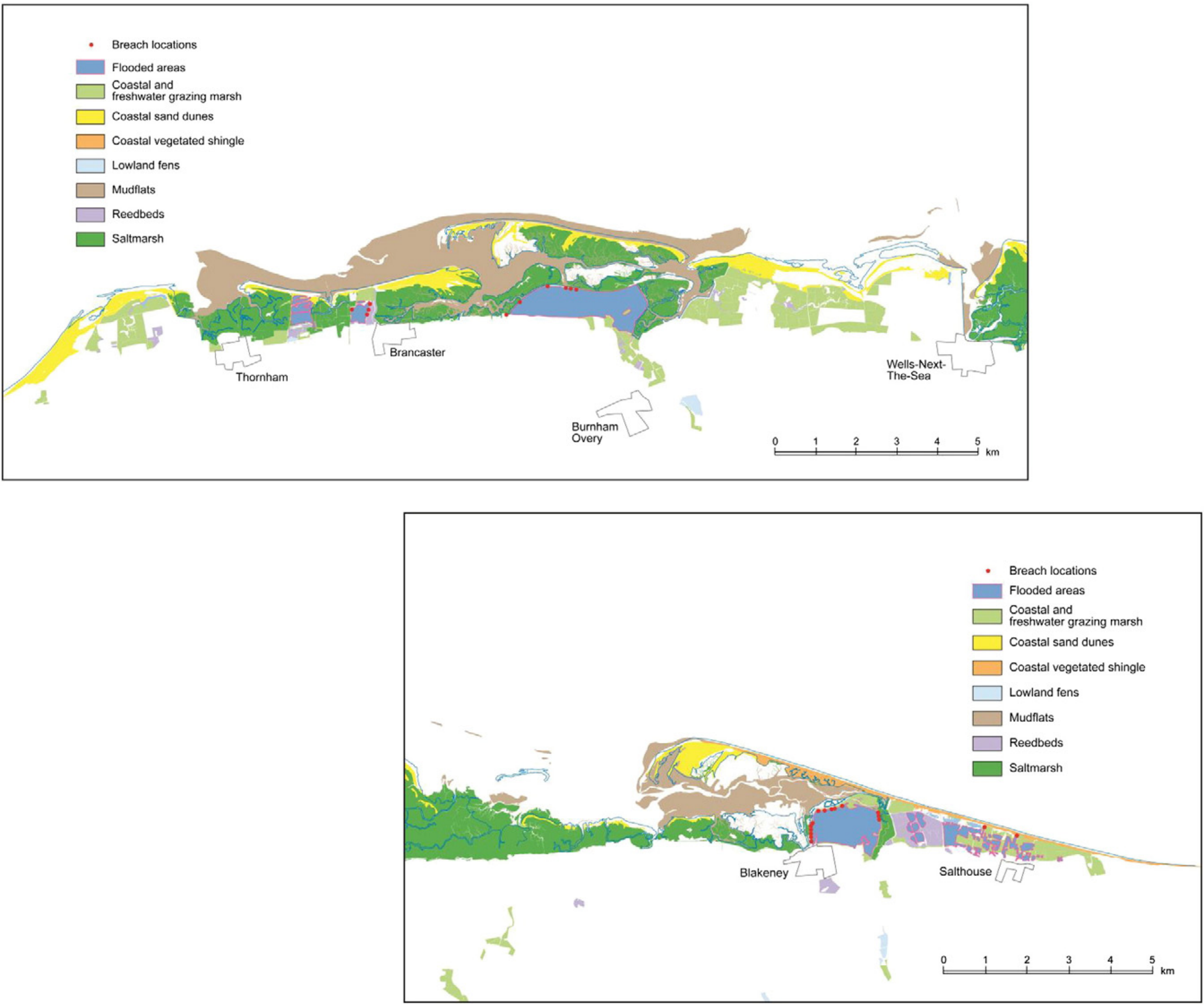

Fig. 12. Flooded areas on the North Norfolk coast as a result of earthen bank breaches and overtopping. Habitats from Natural England (2013).
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(Fig. 14C). In 1953, in Essex, such mud lump fields were found up to 1200 m from breaches and explained as an 'uplift failure' of the bank with high pore water pressures in silty sands near the base of the bank (Marsland, 1988). In general, and although in some locations (such as at Blakeney Freshes) deep pools developed immediately behind the line of the defence, the floors of the breaches themselves did not extend to elevations below the fronting saltmarsh, suggesting, as argued from breach geometries in 1953 (Muir Wood and Bateman, 2005), a relatively resistant footing.

5.2.5. Saltmarsh surfaces

Remarkably, but as observed in the storm surges of 1953 (Steers, 1953) and 1978 (Steers et al., 1979), there appeared to be very little erosion of saltmarsh surfaces, although at Burnham Norton–Burnham Deepdale and Cley, North Norfolk coast, blocks of saltmarsh retaining intact vegetation, were plucked from upper marsh surfaces and deposited on the landward sea defence embankment (Fig. 14D). The primary impact on saltmarshes was the scarifying of leaf litter and other plant debris which was then deposited to form often prominent lines of drift. Such winnowing of plant debris was particularly characteristic of areas of reedbed affected by the surge; here the sheer volume of plant detritus created serious problems for local authorities charged with post-surge clear-up operations. The patterns of debris accumulation also reflected local patterns of wave approach. Thus, at Scolt Head Island, particularly large debris accumulations comprising plant detritus and general marine flotsam and jetsam, and having widths of tens of metres and depths in excess of 1 m, were banked up against NW-facing gravel ridges vegetated with shrubby *Suaeda fruticosa* (Fig. 8A).

6. Discussion

6.1. 2013 event in its historical context

It is important to place the 2013 storm surge in its historical context, not least because the need to consider the appropriate management responses to such an event. In terms of the level of observed high water (historical tide gauge maxima documented at http://www.ntslf.org/data/uk-network-real-time), the December 2013 storm surge does not feature in the 10 highest levels recorded at Wick in the period 1991–2012. At Aberdeen, it was the second highest level on record (after the surge of 11–12 January 2005 associated with the severe Atlantic

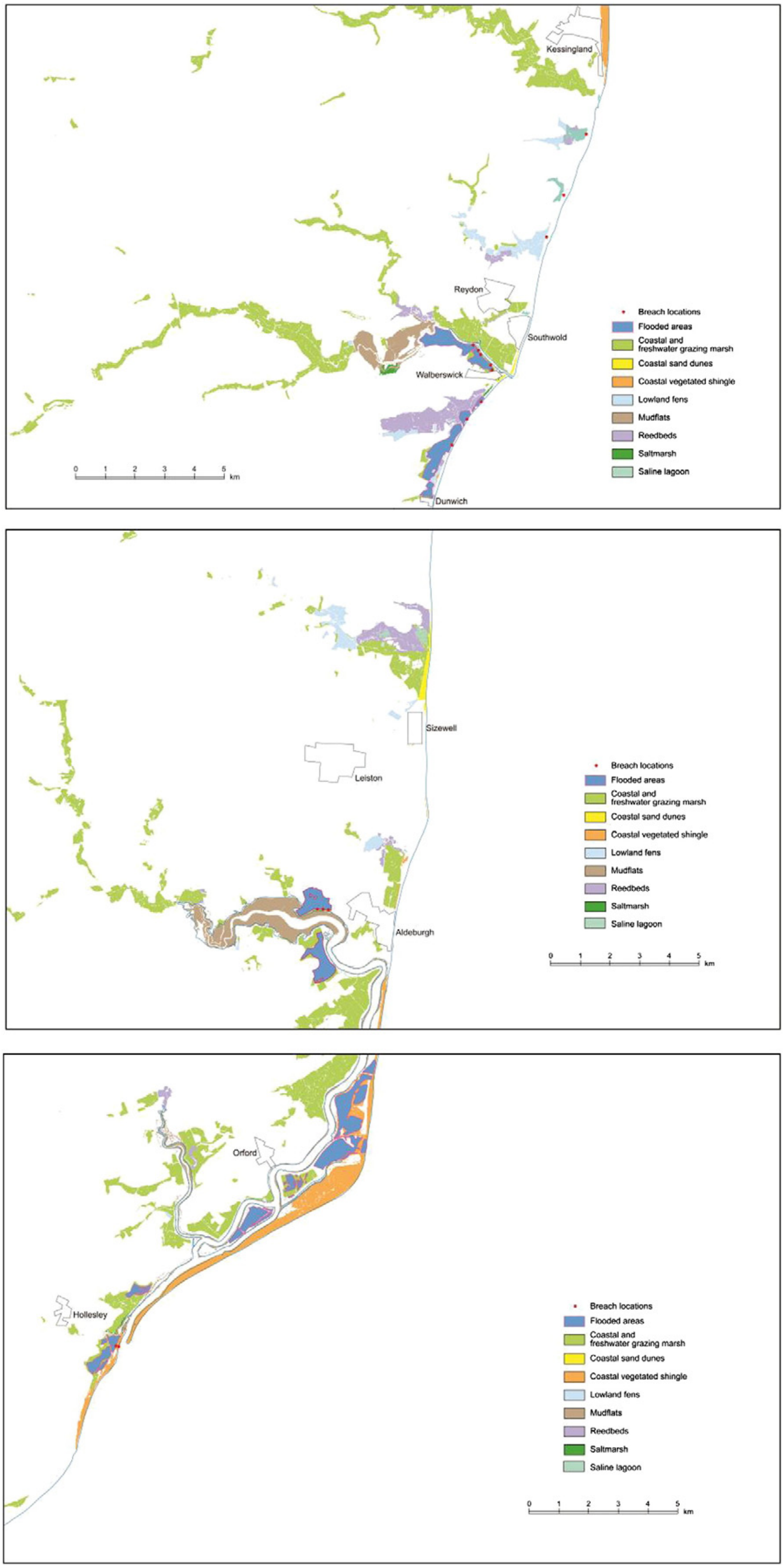

Fig. 13. Flooded areas on the Suffolk coast as a result of earthen bank breaches and overtopping. Habitats from Natural England (2013).
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Fig. 14. Failure mechanisms in earthen banks, North Norfolk. A) Vertical fissures in landward face following overtopping, Burnham Norton seawall (reclaimed marsh to left); B) breach in earthen bank, west margin of Brancaster West Marsh managed realignment, looking west to exterior saltmarsh. Note vertical landward faces on either side of breach; C) arcuate mud boulder debris field beyond boundary fence inside breach (seen lower left) at Burnham Deepdale; D) reeds on plucked wetland block, Cley seawall.
Photographs: A) T Spencer 14 February 2014; B) A Martin 25 March 2014; C) T Spencer 16 February 2014; D) G Fuller 9 March 2014.

windstorm ‘Gero’, recorded at 3.06 m ODN). At North Shields, Whitby and Immingham, the 2013 event was, however, the highest recorded water level in the tide gauge record (record lengths: 1953–2012, 1983–2012 and 1953–2012 respectively).

Table 1 reports the ‘skew surge’ for the December 2013 event at 8 east coast tide gauges. This is defined as the maximum observed water level minus the maximum predicted tidal level during a tidal cycle, irrespective of whether or not the maximum water height occurred at the expected time of the high tide. These two measures are almost completely independent of one another. Thus it has been argued that the skew surge is a more reliable measure of meteorological effects on water levels than the nontidal residual (Van den Brink et al., 2003; Batstone et al., 2013). Recently, estimation of extreme water level probabilities has begun to develop methodologies based around skew surge values rather than simply relying on the earlier ‘joint probability method’. This method derives the probability distribution of extreme sea-levels by convolution of the probability distributions of predicted tidal level and the nontidal residual (e.g., Pugh and Vassie, 1980). Such skew surge-based analyses suggest that whilst the return periods for the December surge at Wick and Aberdeen are quite modest (less than 1 in 25 years), at Whitby to Lowestoft the return periods lie between 1 in 200 and 1 in 1000 years, and are at the top end of this range at Whitby and, in particular, Immingham (Environment Agency, 2011b; Batstone et al., 2013). For both the Immingham and Lowestoft gauges, Fig. 15 places the 10 highest recorded water levels from these stations (Table 5) in this context and specifically positions (plotted by eye) the 1953 and 2013 maximum water levels on these extreme water level trend lines. The difference in the status of the 2013 event at these two stations is clear.

6.2. 2013 event compared to the 1953 event

As the December 2013 surge has frequently been referred to as the highest storm surge on the east coast of England for 60 years (e.g., Meikle, 2013), it is instructive to compare the impacts of the recent event with those experienced as result of the storm surge of 31 January–1 February 1953. The consequences of any storm surge are the product of a chain that proceeds from source characteristics, through pathway characteristics to the nature of the receptor environment (e.g., Sayers et al., 2002; Narayan et al., 2012). No two surge events have exactly the same source, pathway and receptor characteristics. We discuss the similarities and differences in source characteristics between 1953 and 2013 below. In terms of natural pathway characteristics, we acknowledge that water depths on east coast foreshores, and the foreshores themselves, have changed considerably since 1953. These changes will have had implications for wave focussing and patterns of maximum and minimum wave run-up under storm surge

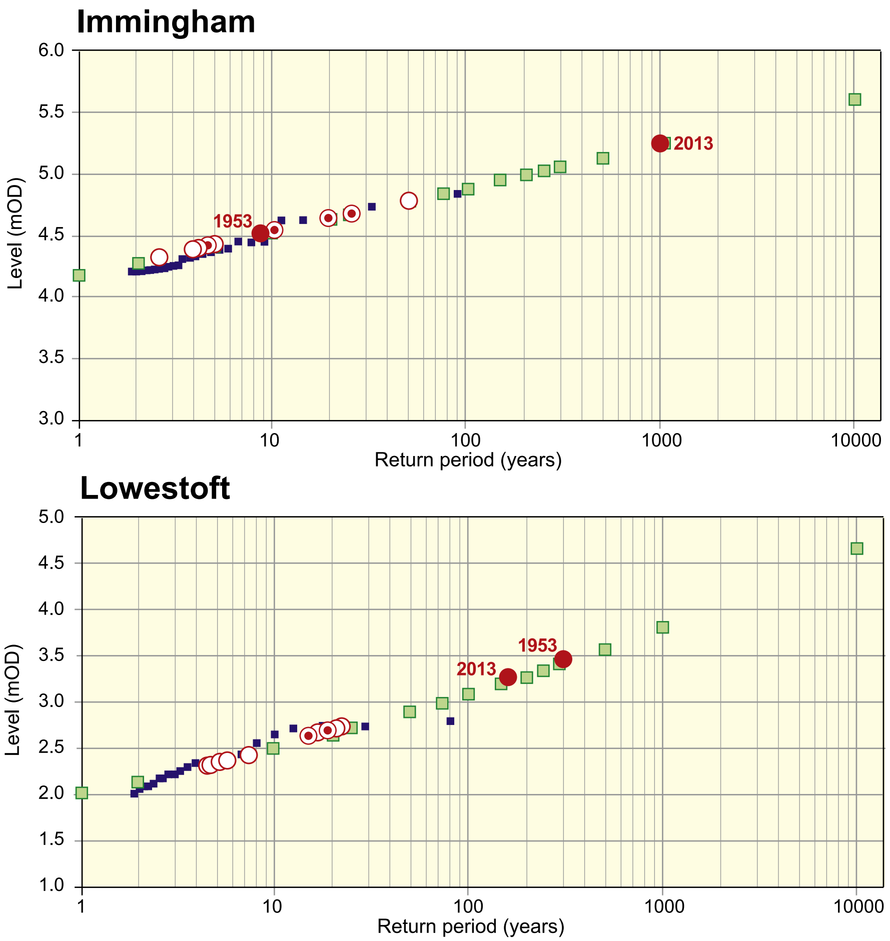

Fig. 15. Statistical analysis of return periods of extreme water levels at A) Immingham and B) Lowestoft. Analysis based on one maximum annual sea level value (AMAX; black squares) or (Immingham) skew surge joint probability method (SSJPM; green squares) or (Lowestoft) interpolated growth trend (green squares). Open circles show 10 highest water levels on record (documented at http://www.ntslf.org/data/uk-network-real-time); central point in circle indicates reported landscape change and/or significant coastal flooding (Cambridge Coastal Research Unit, unpubl. data). 1953 and 2013 storm surge maximum water levels indicated by a red circle.
After Environment Agency (2011b); contains Environment Agency information © Environment Agency and database right.

conditions (e.g., see Pethick (2001) on changing patterns of wave refraction under sea level rise on the Norfolk coast). And we know that human impacts on pathway characteristics and particularly receptor characteristics are framed by economic, political and social forces and that these forces have changed markedly since the post-WWII period. Nevertheless, some general observations are possible from a focus on natural, landscape receptors. We also include some comparisons with the geomorphological consequences of the storm surge of 11 January 1978 which were documented at several of the localities that form the focus of this paper (Steers et al., 1979).

6.2.1. Source characteristics

In terms of source characteristics, the general pattern was for water levels to have been significantly higher than in 1953 in the Humber estuary (although Barnes and King (1953) report a common level of 5.33 m ODN between Immingham and Gibraltar Point on the Lincolnshire coast) and higher, with much site-to-site variability (Spencer et al., 2014), on the North Norfolk coast. However, 2013 water levels were lower than 1953 levels on the Suffolk coast and slightly lower on the Essex coast (Table 6). At King's Lynn, the storm surge was slightly higher than the surge event of 11 January 1978, variously recorded as reaching 5.92 m (Steers et al., 1979) to 6.03 m ODN (King's Lynn Conservancy Board, 2014). The equivalent maximum water level here for the 1953 storm surge was 5.65–5.85 m ODN. At Lowestoft, the December 2013 surge level was the highest on record between 1965 and 2012 (Pye and Blott, 2009; http://www.ntslf.org/data/uk-network-real-time) but not as high as the 1953 storm surge which Rossiter (1954) reported as reaching 3.44 m ODN in Lowestoft harbour and which is recorded at 3.50 m ODN on the banks of the Blyth estuary, Southwold, 19 km to the south (Steers et al., 1979).

Muir Wood et al. (2005) identify three categories of North Sea storm surge on the basis of the synoptic climatology of the generating low pressure system and the adjacent high pressure cells: (1) SE tracking (such as in 1953); (2) E tracking (e.g., 3 January 1976); and (3) southern North Sea (e.g., 11 January 1978) events. The event we describe here showed the characteristics of a SE tracking surge: an intensifying circulation moving in a south-easterly direction around a high pressure system located to the west of Ireland. In such settings, the clockwise rotation of the deep cyclone around the anticyclone strengthens the pressure gradients on the right hand side of the depression, giving high windspeeds over the western North Sea (Muir Wood et al., 2005). The winds are then directed southward with their persistence being determined by the rate of movement of the low pressure system. Wolf and Flather (2005) have argued that the 1953 surge was exceptional as a result of the northerly gales (up to hurricane force (Steers, 1953)) west of the storm centre, the track of the depression along the axis of the North Sea bringing the gales to bear on the shallow waters in the west and south, and the slow speed with which the storm moved away, increasing the duration of the northerly gales. By comparison, the 2013 event was more short-lived and showed a more easterly

Table 5
The highest recorded water levels at the Immingham (1953–2012) and Lowestoft (1976–2012) tide gauges with 1953 and 2013 water levels and evidence for landscape impact. Source of water level data: http://www.ntslf.org/data/hilev?port=Immingham and http://www.ntslf.org/data/hilev?port=Lowestoft. Data supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and Natural Environment Research Council.

Still water level (m ODN)	Time (UTC)	Date (dd-mmm-yy)	Landscape impact
Immingham			North Norfolk coast impacts
5.22	19.15	05-Dec-13	This paper
4.78	20.00	01-Feb-83	
4.66	7.00	29-Sep-69	Flooding at Burnham Overy Staithe and Wells harbour quay
4.61	20.00	11-Jan-78	Major event, Holme to Salthouse (Steers et al., 1979)
4.57	19.00	03-Jan-76	
4.52	19.00	31-Jan-53	Major event, Holme to Salthouse (Steers, 1953)
4.43	19.15	09-Feb-97	
4.41	7.00	07-Oct-90	Flooding at Cley and Salthouse
4.39	7.00	13-Nov-77	
4.39	19.00	12-Jan-05	
4.33	6.00	17-Sep-78	
Lowestoft			Suffolk coast impacts
3.44	22.19	31-Jan-53	Rossiter (1954)
3.26	22.30	05-Dec-13	This paper
2.71	10.00	29-Sep-69	
2.69	23.00	01-Feb-83	
2.68	9.00	21-Feb-93	Significant breaching or overtopping of the Walberswick–Dunwich barrier (Pye and Blott, 2009)
2.68	21.00	03-Jan-76	
2.63	8.15	09-Nov-07	Significant breaching or overtopping of the Walberswick–Dunwich barrier (Pye and Blott, 2009)
2.47	0.00	14-Dec-73	
2.41	9.30	28-Jan-94	
2.36	20.30	01-Jan-95	
2.33	22.00	27-Nov-11	
2.33	21.00	14-Nov-93	

track; whereas the 1953 storm crossed the north German coast, the 2013 event exited the North Sea basin over southern Sweden and the Baltic Sea.

These differences become particularly important when considering the levels of wave action experienced on the coast of eastern England under both events. It is, however, difficult to provide a definitive analysis. It is only possible to compare an estimated wave height in 30 m water depth for 1953 with recorded wave heights in 18 m water depth for 2013. Furthermore, it is a major assumption to assign reductions in wave height seen between offshore and inshore wave heights under 'normal' conditions to storm wave conditions. Nevertheless, with these caveats, some observations are offered below.

In both 1953 and 2013, the coast of North Norfolk was subject to onshore winds and waves. On 5 December 2013, the maximum wave height recorded at the Blakeney Overfalls DWR, in 18 m water depth, was 3.8 m. A comparison of mean annual significant wave heights between the Blakeney Overfalls DWR and the Scolt Head Island and Cley coastal AWAC stations (NN1 and NN2 respectively) for the years 2007–2009 show reductions inshore of 43% and 30% respectively (Environment Agency, 2014b). If these relationships also hold for storm waves, then peak wave heights at Scolt Head Island and Cley in December 2013 might have been of the order of 2.2 to 2.7 m respectively. It has been difficult to reconstruct wave heights during the 1953 storm surge but Wolf and Flather (2005, 1362) provide model estimates for a significant wave height of 7.8 m 'just off' the North Norfolk coast for a 30 m water depth. It is even more difficult to know what wave heights would have been experienced at the shoreline. However, if we apply the same offshore to inshore reduction in wave heights to this figure, this would suggest typical at-the-shore wave heights of 4.4 m at Scolt Head Island and 5.5 m at Cley in 1953. What is particularly striking, however, is the difference in the duration of onshore winds and waves. In 2013, wave heights of over 3 m were maintained for only a 4 hour period at the Blakeney Overfalls DWR. By comparison, weather records from the Dowsing Light Vessel (53°35′N, 0°55′E) show that windspeeds in excess of 20 m s^{-1} (Beaufort Force 9, strong gale) were maintained for a 24 hour period over 31 January and 1 February 1953.

Information on wave conditions in 1953 on the Suffolk and Essex coasts is even more difficult to interpret, with considerable differences between recorded, modelled and visually observed wave heights offshore at the Smith's Knoll (52°43′N, 2018/E) and Galloper (51°44N, 10°58′E) Light Vessels (Wolf and Flather, 2005). Furthermore, modelled significant wave heights of >8 m (Smith's Knoll) and >5 m (Galloper) have been estimated as falling rapidly inshore to a significant wave height of <3 m south of Lowestoft (Wolf and Flather, 2005). Nevertheless, this figure has to be seen in the context of the peak wave height of 1.5 to 1.8 m recorded for the December 2013 surge at Sizewell and Felixstowe respectively (Fig. 6), and with these wave conditions being experienced ahead of the time of maximum water level, rather than

Table 6
Differences in storm surge water levels in 2013 and 1953. See text for further discussion.
Sources: A: data supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and Natural Environment Research Council; B: Environment Agency (2014b); Environment Agency information © Environment Agency and database right; C: King's Lynn Conservancy Board (2014); D: Steers et al. (1979); E: RTK field surveys, this paper; and F: Rossiter (1954).

Location	2013max (m ODN)	1953 max (m ODN)	1953 mean (m ODN)	2013–1953 diff. max water level (m)	Source
Immingham (tide gauge still water level)	5.22	4.52		0.70	A
Boston	5.91	5.30		0.61	B
King's Lynn (tide gauge still water level)	6.05	5.85		0.20	B, C
Thornham	5.64	5.49	5.34	0.15	D, E
Scolt Head Island (Norton Hills back-barrier)	6.17	5.37		0.80	D, E
Burnham Overy Staithe	5.52	5.49		0.03	D, E
Wells Harbour Quay	5.31	5.13		0.18	D, E
Stiffkey	5.34	4.57		0.77	D, E
Blakeney	6.30	6.07	4.27–4.88	0.23	D, E
Great Yarmouth	3.32	3.30		0.02	B
Lowestoft (2013 tide gauge still water level; estimated 1953)	3.26	3.44		−0.18	A, F
Southwold harbour (Harbour Cottages)	2.76	3.50		−0.74	D, E
Aldeburgh (Slaughden)	3.17	3.78		−0.61	D, E
Harwich	3.45	4.02		−0.57	B
Clacton	3.76	4.10		−0.34	B
West Mersea, Mersea Island	4.40	4.43		−0.03	D
Southend-on-Sea	4.10	4.60		−0.50	B

being coincident with it. In summary, the overall conclusion is that inshore wave conditions were much greater in 1953, with extreme conditions being sustained for a much longer time period.

6.2.2. Pathway characteristics

When the effect on pathway characteristics from the strengthening and raising of coastal defences post-1953 is, in addition, considered alongside the much reduced wave conditions, then the impacts of the two events can be seen to be markedly different. For the 500 km of sea defences in the Essex estuaries almost half were overtopped in 1953. There were 839 breaches, up to 45 m wide and to 1.5–6.0 m below the former crest elevation (Snell, 1954). In North Kent, there were 400 breaches in 1953, some reaching up to 200 m in width (Muir Wood and Bateman, 2005). A striking comparison can be made for the eastern coastline of The Wash embayment, between Wolverton Creek, north of King's Lynn, and the town of Hunstanton. In 1953, the ca 10 km long shingle ridge here was lowered and driven inland by 18–27 m, with three major breaches cutting down to beach level. The earthen bank behind the shingle ridge was breached in 40 places. Grove (1953) reports that over 4000 ha was flooded between Heacham and Downham Market. Of the concrete sea walls, the Heacham South Beach structure was completely destroyed, a 270 m section of the Heacham North Beach wall was demolished and the parapet of the Hunstanton South Beach wall was overturned over a distance of 18 m (Doran, 1954). In 2013, there were two breaches in the shingle ridge but neither cut down to beach level. There were numerous smaller washovers and evidence of overtopping but the shingle ridge remained in place and there was no breaching in the earthen bank behind the ridge. Although there was severe basal scour around some sea wall structures, exposure of older pilings and overtopping at Hunstanton South Beach, there was no wall failure (S. Boreham, pers. comm., December 2013). Similarly, the western boundary to the harbour channel at Wells-next-the-Sea which failed spectacularly in 1953 (Steers, 1953) and again in 1978 (Steers et al., 1979), recorded only superficial notching in 2013. As a result of the scale of breaching in 1953, some 83,400 ha, perhaps as much as 88,200 ha, were flooded between the Humber estuary and North Kent (Steers, 1953). Equivalent flood areas are not known for December 2013 but, where detailed flood inundation statistics are known, for North Norfolk, and for the Suffolk coast within 2 km of the shoreline between Kessingland and Shingle Street, the total area inundated amounted to just 1138 ha (Table 4).

6.2.3. Landscape receptor characteristics

Some comparison of geomorphological change as a result of storm surge between the 2013 and 1953 events is possible but precise information for the earlier event is very fragmentary. Furthermore, it is difficult to compare at-a-point observations (1953) with more extensive alongshore datasets (2013); shoreline retreat rates are often highly variable spatially, especially in soft rock cliffs (Brooks and Spencer, 2010). Nevertheless, the average cliff retreat rate of 5.9 m at Covehithe, Suffolk coast in December 2013, with at-a-point rates approaching 12 m, is comparable to Grove's (1953) estimate of 6–12 m of cliff retreat in 1953. As far as we are aware, there are no comparable dune retreat rates for the North Lincolnshire coast to compare 2013 and 1953; the only reported earlier figure (Barnes and King, 1953) is for dune retreat north of Gibraltar Point of 9.4 m. The ca 5 m of barrier retreat measured at Scolt Head Island in December 2013 compares with maximum figures of 9–18 m for the 1953 storm surge (Grove, 1953). For the 1978 surge, Steers et al. (1979) reported an average of 20 m of retreat between Smuggler's Gap and Norton Hills, based on the width of the zone of exposed rootmat on the upper foreshore. Similarly extensive rootmat exposure was seen after the December 2013 event but it seems likely that this represents not only dune line retreat but also upper beach lowering which exposes old rootmat. We believe, therefore, that the estimates of shoreline retreat for the 1978 event may have over-estimated the true landward shoreline displacement at this time. In terms of barrier island retreat, therefore, the conclusion is that landscape responses in 2013 were at worst comparable to, but generally, of lower magnitude compared to 1953.

Beyond the 1953 versus 2013 comparisons, new methods of spatial analysis allow a fuller, more detailed evaluation of surge-related coastal change in relation to shoreline dynamics under the average coastal process regime. Comparison of surge event Net Shoreline Movement (NSM) with decadal shoreline retreat, as reported by the End Point Rate (EPR), shows that at upper beach/sand dune margins the December 2013 surge resulted in a pulse of shoreline translation landwards equivalent to about 10 years of ‘normal’ shoreline retreat (Table 3). On the highly erodible soft rock cliffs of the Suffolk coast, the landward movement of the cliffline after the surge was within the envelope of annual variability in cliff retreat rates. Ever since Williams (1956) reported coastal retreat rates of up to 26 m following the 1953 surge on this coast, there has been a tendency to equate bursts of rapid shoreline retreat with storm surge impacts. More recently, however, and in the same study area, Brooks et al. (2012) have demonstrated that thresholds for marine driven cliff retreat include non-surge related controls, principally near-gale force onshore wind blowing for 6 h or more accompanied by rainfall totals in excess of 40 mm. When such events occur — which may or may not coincide with storm surge events — it is predicted that over 7 m of cliff retreat will result (Brooks et al., 2012).

We believe that the same principles apply to washover dynamics. It was the combination of storm surge and high wave activity that led to the ‘breakthrough’ along the central spine of Scolt Head Island in 1953. The next major break in the Scolt barrier took place in 2007, not as a result of the widely reported November 2007 surge (when the significant wave height (H_s) peaked at 2.0 m at the Blakeney Overfalls DWR) but in March 2007. A significant surge event occurred on 18 March (the 5th highest water level on record (1993–2002) at Cromer 50 km to the east) and was followed by northerly, near-gale force windspeeds of 60 km h^{-1}. Significant wave heights (H_s) of 3.2 m occurred at 1530 and 1600 at Blakeney Overfalls with significant wave heights of 2.73–2.77 m and peak wave heights (H_{max}) of 5.07 m immediately offshore from Scolt Head Island (Environment Agency, 2009b). It is clear that in 1953 and March 2007, the surge plus wave energy threshold to dune collapse and duneline breaching was surpassed. By comparison, in December 2013 (and in November 2007 and most probably in January 1978 when wave heights at maximum water levels were low (R. Chestney, in Steers et al., 1979)), wave energy levels associated with the surge were not able to initiate new breaches. The impact under these events was to reactivate existing washovers and only extend these washover areas laterally where the dune line was very low (<0.75 m).

Thresholds to gravel barrier breaching are more difficult to define. This is because many of these barriers have a history of breaches being artificially closed, and cross-barrier profiles being unnaturally steep, as a result of a management regime using heavy machinery. The barrier at Blakeney–Cley–Salthouse was breached in 1897, 1921, 1953 and 1996 and overtopped in 1976, 1978 (when the ridge was lowered by 1 m (Steers et al., 1979)), 1993, 2003 and 2006. However, a re-analysis of this breaching history for the North Norfolk Shoreline Management Plan came to the conclusion that re-profiling operations were contributing to the instability of the ridge and may have been a causal factor in the breach of the ridge, and scale of the flooding, experienced in 1996. Since the winter of 2006, therefore, this barrier has been allowed to evolve naturally. Between 2006 and 2008, the height of the ridge crest reduced from just under 10 m ODN to ca. 8–9 m ODN and the formation of new washover fans translated the shoreward limits of the ridge by 40 m in one case; by 60–80 m in three cases; and in one case by 100 m (Petchey et al., 2011). Similar management decisions, and similar barrier evolution towards more frequent overtopping and breaching have been described for the Walberswick–Dunwich barrier on the Suffolk coast (Pye and Blott, 2009). It is in this context that the impact of recent storm surges on barrier dynamics will need to be evaluated, along with the nature conservation issues that arise from the more frequent flooding of back-barrier freshwater wetland habitats protected under European Union legislative frameworks.

6.3. Storm surges, global environmental change and southern North Sea coasts

Synthesising an observational and modelling literature, Horsburgh and Lowe (2013) have argued that changes in extreme water levels in the southern North Sea over the twenty first century will be governed by mean sea level rise, both directly through increased water depths (the additive effects of eustatic sea level rise, glacio- and hydro-isostatic processes and geological subsidence (Shennan et al., 2012)) and indirectly through changes in tidal dynamics in the southern North Sea (Pickering et al., 2012). Future extreme levels might also be the result of increased storminess, delivering higher and/or more frequent storm surge events on higher mean sea levels. However, neither the IPCC Special Report on extremes (Field et al., 2012) nor the regional assessment in the IPCC Fifth Assessment Report (Kovats et al., 2014) find unequivocal evidence for either systematic long-term changes in storminess or detectable change in storm surge incidence.

Woodworth et al. (2009) have estimated that geocentric (or 'absolute') mean sea level (AMSL) around the UK rose by 1.4 ± 0.2 mm a^{-1} over the twentieth century; Wahl et al. (2011) considered this to be the best estimate for 20th century sea level changes in the North Sea basin as a whole. More recently, for Lowestoft (where Shennan and Horton (2002) estimated the twentieth century mean sea level rise at 1.81 ± 0.48 mm a^{-1}), the tide gauge record shows a linear trend in relative mean sea level (RMSL) of 2.7 ± 0.4 mm a^{-1} for the period 1900–2011, 3.6 ± 0.5 mm a^{-1} for the period 1980–2011 and 4.4 ± 1.1 mm a^{-1} for the period 1993–2011 (Wahl et al., 2013). In comparing the 1953 storm surge as it occurred in 1953 with the same surge characteristics were it to happen in 2075, modelling by Wolf and Flather (2005) used a regional sea level rise figure of +40 cm for the period 1953–2075 (i.e., a rate of 3.30 mm a^{-1}), derived from the IPCC Third Assessment Report (Church et al., 2001); a glacio- and hydro-isostatic term of −0.5 mm a^{-1} from Lambeck and Johnston (1995); and modelled changes in tidal and surge dynamics from the resulting greater water depths. This exercise produced a 42–50 cm increase in predicted maximum sea level along the coast of eastern England, with the higher values being applicable to the coast from North Norfolk to the Thames estuary. Whilst the isostatic component of sea level rise has not been significantly revised subsequently (Shennan et al. (2012) report a range of 0.3 to 0.6 mm a^{-1} for the east coast between Lincolnshire and the Thames estuary), the sea level rise term should now most probably be revised upwards. This would result in a greater increase in maximum sea level for a 1953 type storm surge in 2075 than that envisaged by Wolf and Flather (2005) along southern North Sea coasts.

7. Conclusions

For the surge of 5 December 2013, records of still water level in a series of tide gauges along the eastern margin of the southern North Sea showed a progressive increase in the peak nontidal residual southwards, with the peak closely preceding the predicted time of high tide (Table 1). At North Shields, Whitby and Immingham, these dynamics resulted in the highest recorded water levels in the tide gauge record (record lengths: 1953–2012, 1983–2012 and 1953–2012 respectively). These levels exceeded those recorded during the twentieth century benchmark event, the storm surge of 31 January–1 February 1953, at North Shields and Immingham, although further south and east, at Lowestoft, the recorded water level was ca. 18 cm lower in 2013 than in 1953 (Table 5).

At the regional scale, maximum runup levels on open coasts reached 5.0–5.8 m ODN in Lincolnshire and 5.6–6.4 m ODN in North Norfolk but only 3.5–3.8 and 3.6–4.4 m ODN in Suffolk and Essex respectively (Table 2). These differences reflect not only the underlying changes in tidal range around the East Anglian coast (Fig. 3) but also the variation in wave heights associated with the passage of the surge. Maximum significant wave heights were highest off the North Norfolk coast (peak $H_s = 3.8$ m offshore, 2.9 m inshore) and lowest off the Suffolk coast ($H_s = 1.5$–1.8 m inshore); by the outer Thames estuary, winds and waves were offshore during the surge. Although direct comparisons are speculative, it seems likely that wave heights reached 7–8 m and ca. 3 m offshore from the North Norfolk and Suffolk coasts respectively in 1953. What is not disputed, however, is the difference in duration of high wave activity: in 2013, wave heights of over 3 m were maintained for only a 4 hour period offshore from the North Norfolk coast whereas in 1953 onshore gale force winds were sustained for a 24 hour period over 31 January and 1 February. The association of comparable, or even higher, still water levels in 2013 compared to 1953 but with a much reduced wave component explains the breaching and overtopping, and back-barrier flooding, associated with gravel ridges and relatively low earthen banks in 2013, alongside the lack of failure in more substantial, more highly-engineered coastal defence structures.

In 2013, when better-placed to record maximum water levels in a range of settings, considerable variability in maximum runup was apparent. Compared to the open coast, surge levels in estuaries showed a mixed signal. Where estuarine flood defences remained intact, funnelling of the surge led to higher water levels up-estuary whereas in systems characterised by over-topping and/or breaching of defence lines, and the storage of flood water in the inundated areas, there were lower maximum runup heights at more inland locations. At finer scales, where the surge interacted with narrowing back-barrier tidal channels, or passed over significant (>500 m) widths of mid to upper saltmarsh and/or freshwater marshes and reedbeds on the landward side of gravel barriers, maximum runup levels were typically lower than adjacent open coast sites by at least 40 cm. These contrasts were magnified when comparing open coasts with sites subject to tidal exchange but highly sheltered; here differences in maximum runup approached 2 m in magnitude. Overall, therefore, it can be concluded that tide–surge interactions provide a general regional scale framework for the spatio-temporal pattern of storm surge impacts. The surge-related wave climate adds further complexity to this pattern, as tide–surge–wave dynamics interact with varying nearshore and estuarine bathymetries and coastal ecosystems. It is only by immediate, wide-ranging post-surge field surveys of the maximum runup signal, sensitive to the range of coastal landscape settings present, that this variability in storm surge impacts can be captured.

The landscape impacts of the December 2013 surge included the notching of soft rock cliffs and cliffline retreat; erosion of coastal dunes; augmentation or re-activation of barrier island washover deposits; and the breaching of gravel barriers and earthen banks, accompanied by significant back-barrier flooding (over 1000 ha were inundated on the North Norfolk coast and in the Suffolk estuaries). Whilst surge event-related cliff retreat on the rapidly eroding cliffs of the Suffolk coast lay within the natural variability in inter-annual rates of retreat, the impact of the surge on upper beach/sand dune margins produced a pulse of shoreline translation landwards equivalent to about 10 years of 'normal' shoreline retreat (Table 3). The study of east coast surges over the last 60 years, and the identification of significant phases of landscape change events — such as periods of rapid soft cliff retreat and the formation of new gravel washovers on barrier island coasts — again points to the importance of high water levels being accompanied by high wave activity. Thus significant landscape change is not an inevitable consequence of storm surge occurrence alone.

For future planning, adaptive coastal management strategies need to cope with the progressive acceleration in sea level rise as well as the less predictable impacts of large storms or phases of enhanced storminess. Environmental modelling provides the best chance of understanding and planning for this combination of sea level and storminess as multi-scenario outcomes can be explored that can feed into storm surge forecasting. This paper suggests, from detailed new evidence, that there are complex interactions between (1) tidal stage, surge dynamics and surge event-related wave fields and (2) the coastal landscape encountered. New models will need to be able to account for these variable spatio-temporal effects. For people whose lives and livelihoods are likely to be affected by future storm impacts, such a more nuanced strategy offers the promise of greater environmental security, through the implementation of improved early warning systems and evacuation planning.

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