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LETTER

Post-storm geomorphic recovery and resilience of a prograding coastal dune system

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Abstract

Geomorphic resilience is the capacity of a system to recover to pre-disturbance conditions following a perturbation. The 2013/14 Atlantic winter storm period had extensive geomorphological impacts and provides an opportunity to assess coastline resilience. This paper uses high spatio-temporal resolution data to quantify the beach-dune response and subsequent recovery of a prograding coastline following the 5 December 2013 North Sea storm surge. It demonstrates that despite the high water levels and destructive nature of the storm, the beach-dune system recovered sediment rapidly over the first post-storm year. Within four years the dune advance had exceeded the seawards position expected based on long-term coastal trends but had not yet recovered the pre-storm foredune profile. Cumulative evidence from numerous European locations suggests one of the stormiest periods on record triggered only a minor disturbance to what appear to be highly resilient beach-dune systems.

1. Introduction

The concept of geomorphic resilience in response to disturbance provides a framework for evaluating the impacts of natural and anthropogenic perturbations to geomorphic systems (Downes *et al* 2013, Phillips and Van Dyke 2016). It has resonances with landscape sensitivity and geomorphic effectiveness (Brunsden and Thornes 1979, Usher 2001) and strong links to ecological and biogeomorphic conceptual frameworks (Stallins and Corenblit 2018). Definitions of resilience all refer to the ability of a system to absorb the impact of, and recover from, a disturbance and return to its pre-impacted, or an alternative stable, state (Downes *et al* 2013). Geomorphic resilience reflects both the magnitude and frequency of disturbance, response time, relaxation time and recovery (Phillips and Van Dyke 2016). This framework has been applied to various systems and the focus here is on coastal response to storm events where the notion of resilience has gained considerable traction (e.g. Houser *et al* 2015, Walters and Kirwan 2016).

Climate change scenarios suggest changes to storminess and sea level may affect coastline susceptibility to erosion and flooding, and highlight the need to understand the implications of coastal resilience for geomorphology, habitat diversity, socio-economic impact and policy formulation (Lloyd *et al* 2013). The past 30 years have seen considerable improvements in both the quantity and spatio-temporal resolution of data available for evaluating coastal resilience (e.g. repeat aerial photography, beach profile monitoring, airborne and terrestrial Light Detection and Ranging - LiDAR) which allow the determination of the pre-storm state, and post-disturbance rate and nature of system response (e.g. Kandrot *et al* 2016, Pye and Blott 2016, Le Mauff *et al* 2018). Most studies of natural system resilience focus on local-scale sites over short-medium timescales. Downes *et al* (2013) argue that this focus limits consideration of wider scale processes even when broadly contextualised. However substantial variability in local response to the same disturbance event (Backstrom *et al* 2015, Masselink *et al* 2016, Crapoulet *et al* 2017) suggests sites exhibiting a range of representative antecedent conditions and/or

response dynamics are needed as building blocks to support a framework for understanding both local geomorphic resilience and the potential for interactions between different geomorphic (sub-)systems.

The Atlantic winter storm period of 2013/2014 was the most energetic since 1948 along the north west (NW) Europe coastline (Masselink *et al* 2016) and the stormiest on record for the UK (Matthews *et al* 2014). The storms had extensive geomorphological impacts including cliff retreat, beach rotation, dune scarping, washover of barrier islands (Castelle *et al* 2015, Spencer *et al* 2015, Masselink *et al* 2016, Pye and Blott 2016) and provided the opportunity to determine coastline resilience following a major disturbance using detailed modern pre- and post-storm datasets. Most research on geomorphic response to the 2013/14 storm season—and previous stormy periods—has focused on eroding coasts, thus understanding of the processes associated with storm-induced coastal retreat and realignment is considerably more developed than current understanding of the storm response and recovery of prograding coasts (Moore *et al* 2016, Ruggiero *et al* 2016). This paper provides a counter-point to this by focusing on the 2013/14 post-storm recovery of a prograding dune system. This is important because both prograding and eroding coasts can exist within the same sediment cell and may respond differently to a single disturbance event. Existing research highlights the importance of the nearshore profile, which can substantially affect post-storm foredune recovery on all coastlines, acting as a buffer to wave action and a reservoir of dry sand for dune formation (McLean and Shen 2006, Maspatud *et al* 2009, Hesp 2013). There is a marked asymmetry between the rapid storm erosion of dunes (typically hours) and relatively long time required to rebuild foredunes to their post-storm profile (volume, height; typically years) that means the sequencing, as well as magnitude, of storms has implications for dune stability and longevity (Thom and Hall 1991, McLean and Shen 2006, Hesp 2013, Castelle *et al* 2017). This paper quantifies beach-dune response and recovery of a prograding coastline following the December 2013 North Sea storm surge. Data are used to classify and assess the disturbance impact and geomorphic resilience of the site within the context of the regional (NW Europe) response to the winter 2013/14 storm season.

2. Study region and methods

2.1. 2013/14 North Sea storm surge
The 5 December 2013 North Sea storm surge was caused by a deep low pressure that intensified to an extratropical cyclone tracking east across Scotland (UK Meteorological Office 2014) (figure 1). The storm caused coastal flooding on the west coasts of Wales, England and Scotland but the effect was strongest along North Sea coasts where the storm surge travelled south and was funnelled between the European mainland and east coast of England. Maximum run-up levels varied from 5.02 to 5.83 m on the Lincolnshire coast and 5.64 to 6.37 m on the north Norfolk coast (Spencer *et al* 2015). Brooks *et al* (2016) identified 20 storm surges in the southern North Sea since 1883 but in the past 65 years, only two have been of comparable magnitude and impact (1953 c. 5.6 m; 1978 c. 4.7 m at Immingham). The 2013 storm surge caused cliff retreat up to 12 m, dune retreat of up to 19 m, washover of low dunes and breaching of gravel barriers on North Sea coastlines (Spencer *et al* 2015). The winter of 2013/14 featured multiple identifiable storm events which impacted the western and southern coasts of the UK, however these had less geomorphic impact on the North Sea coastline due to more southerly storm tracks.

2.2. Lincolnshire coast
The area of interest (AOI) on the Lincolnshire coast (53°21′43″N 0°15′03″E) (figure 1(b)) comprises a dissipative macrotidal beach (mean spring tidal range 6 m) up to 3.5 km wide, backed by established dunes (>6 m Ordnance Datum Newlyn - ODN). Prevailing winds are offshore from the southwest; easterly onshore winds occur with less frequency but higher magnitude than offshore winds. Offshore sand banks protect the shore and are a source of sediment to the beach-dune system along with eroded sediments from the Holderness Cliffs to the north. There has been seawards progradation of the coastline of c.2 m yr^{-1} over the past 120 years (Montreuil and Bullard 2012). Prior to the 2013 storm surge, the backshore was characterised by a semi-vegetated (10%–50% cover) hummocky incipient foredune. The site is within the Saltfleetby-Theddlethorpe Dunes National Nature Reserve and has no sea defences.

2.3. Beach profiles, surveys and environmental data
Pre- and post-storm cross-shore topographic profiles made using RTK-GPS (UK Environment Agency - EA) were used to assess biannual changes of the beach-dune from January 2013 to January 2018 and analysed using the SANDS v8.1.1 Asset Management System. To quantify three-dimensional post-storm recovery a terrestrial LiDAR system (Leica ScanStation 2; ScanStation P20 - TLS) was used to survey a 40 × 50 m AOI of the beach-dune system incorporating the scarped dune face, incipient foredune and upper beach approximately once per month for 12 months from January 2014 with an additional survey in April 2015 (figure 2). The tripod-mounted LiDAR instrument was deployed at a minimum of three viewpoints with one scanning location always sited
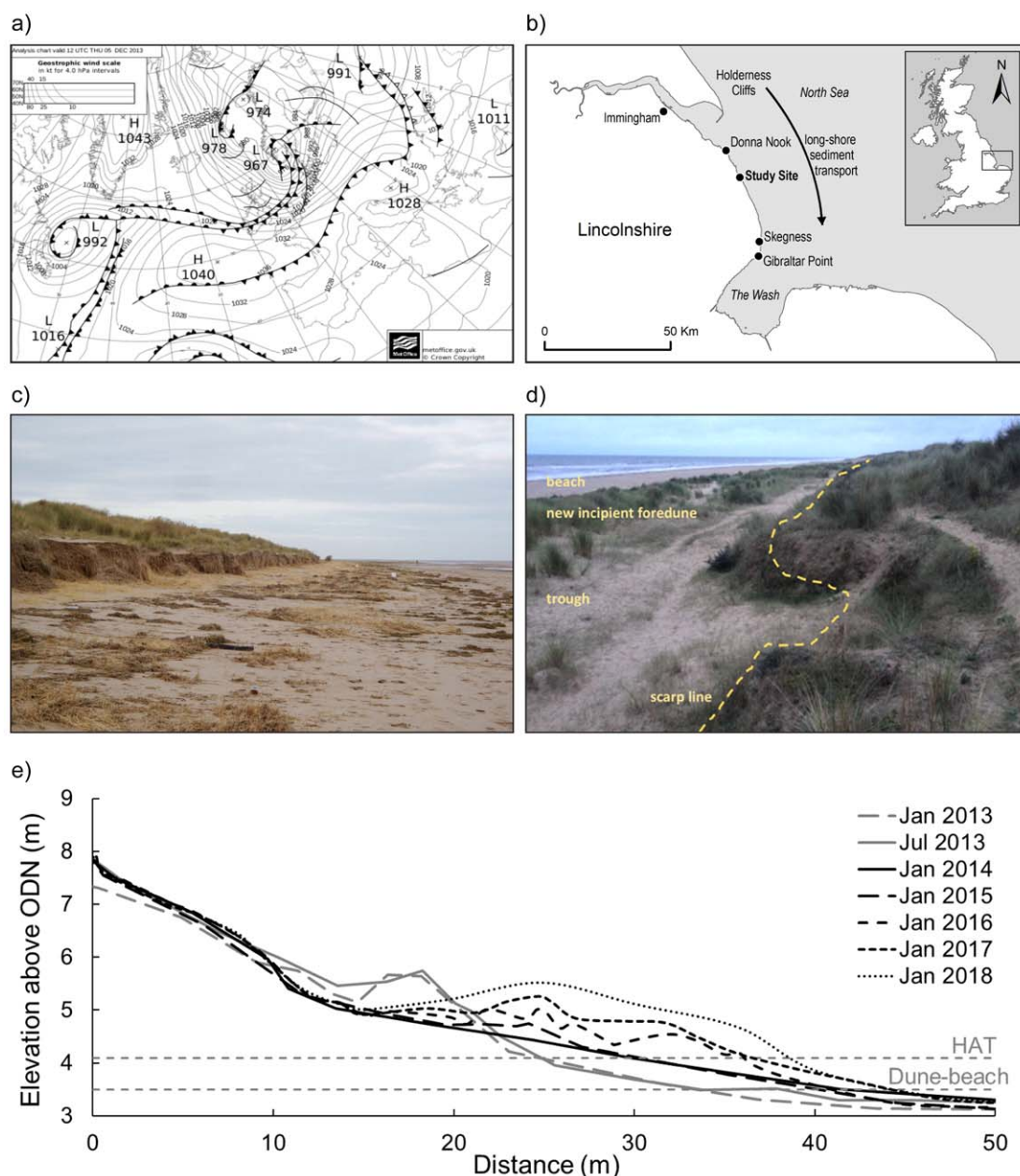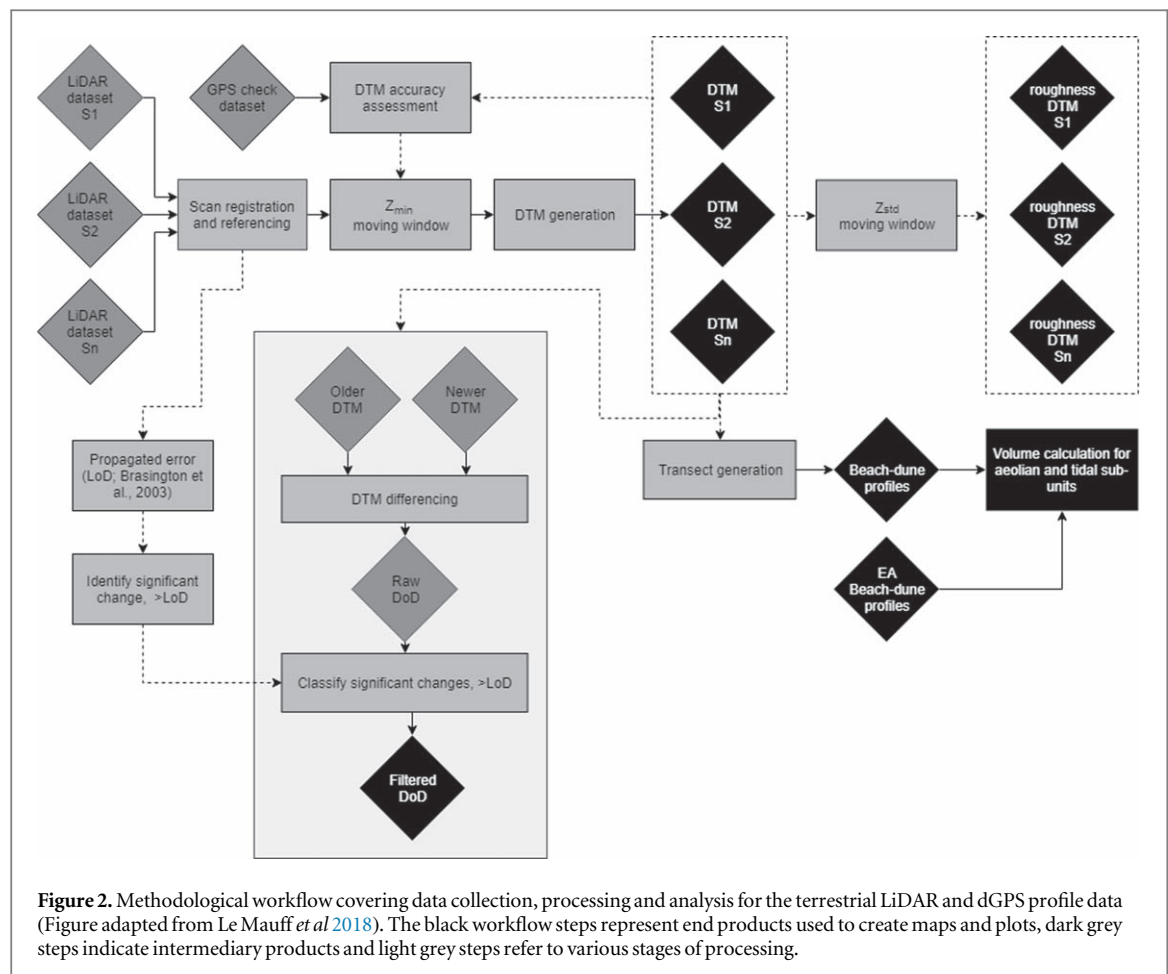
Figure 1. (a) Synoptic chart 5 December 2013 (UK Met Office 2014); (b) Study location; (c) Post-storm scarp at AOI (scarp height is c.2 m), photograph taken 15/11/13 looking north; (d) AOI looking south along former scarp line taken 18/10/17; (e) EA beach profiles.
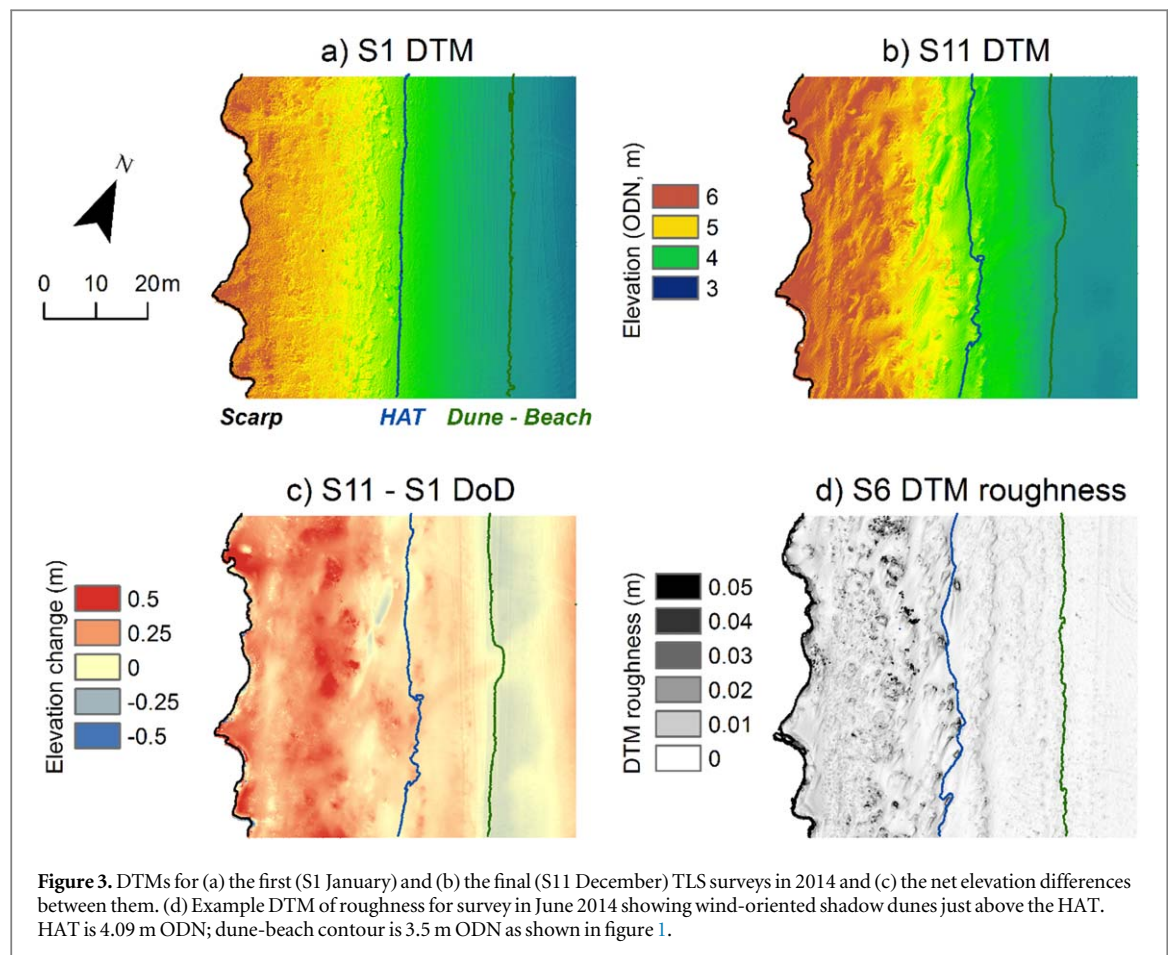
above the foredune scarp, to reduce areas of potential shadowing and ensure the density of point measurements (1 ppcm^2) was consistent across the AOI (Soudarissanane *et al* 2011). The separate point cloud datasets were registered into a single, locally-defined coordinate system using four high-definition survey (HDS) targets. This local registration process utilised a 3D bundle adjustment algorithm, implemented in Leica Geosystems' *Cyclone* software, which yielded a mean absolute error (MAE) of <4 mm for the survey series. The locations of the HDS targets were determined using a Trimble R6 survey-grade differential GPS (dGPS) system. In post-processing, the OS grid coordinates were transformed to a local OS-related system to improve the accuracy of referencing (⩽6 mm MAE between the TLS and local OS grid coordinate systems; Ackerley *et al* 2016). The point cloud datasets were georeferenced to a local plane grid and scaled with reference to the British National Grid OSGB36/ODN. Following the manual and automated removal of redundant points, the LiDAR datasets were clipped to the 40 × 50 m areal extent of the AOI.

Vegetation-induced errors from TLS surveys are common in coastal environments and can exceed other survey-related errors (Coveney and Fotheringham 2011). Vegetative material was present in all surveys and rooted vegetation increased in cover and height during the study. To focus on the morphological recovery of the beach-dune system, a moving window approach was employed to segment the point cloud into 'ground' and

Figure 2. Methodological workflow covering data collection, processing and analysis for the terrestrial LiDAR and dGPS profile data (Figure adapted from Le Mauff *et al* 2018). The black workflow steps represent end products used to create maps and plots, dark grey steps indicate intermediary products and light grey steps refer to various stages of processing.

'vegetation' components (Fan *et al* 2014). The optimal size of this local filter was determined using sensitivity analysis performed for over 100 dGPS-derived control points (Guarnieri *et al* 2009, Wang *et al* 2009). From this analysis a 0.05 × 0.05 m neighbourhood was found to provide the best compromise between the resolution and accuracy of surfaces produced from filtered data (mean absolute difference: 0.0218 m; Ackerley *et al* 2016). The lowest elevations within the moving window were interpolated to produce digital terrain models (DTM S1, DTM S2, … DTM S12). Significant changes in elevation between DTMs were identified as those exceeding the minimum level of detection (LoD), a sum of registration and georeferencing MAE (Brasington *et al* 2003), and included in DTMs of difference (DoDs). A local window calculating standard deviation over a 3-by-3 cell neighbourhood was additionally applied over the DTMs to generate maps of local surface roughness (roughness DTM S1, roughness DTM S2, … roughness DTM S12) which provided qualitative information on morphological form (Nield *et al* 2011). The areal extent of the standard deviation moving window was determined subjectively. Despite the filtering processes, landward of the scarp face vegetation cover was too dense to have confidence that changes were due to morphological, rather than vegetation, dynamics and is excluded from calculations of volume changes. Contours corresponding to the foredune scarp face (6 m ODN), highest astronomical tide (HAT 4.09 m ODN) and boundary between the primary foredune and upper beach active aeolian sub-units (3.5 m ODN) were overlain to the DTMs and DoDs. Changes in elevation above the 3.5 m contour line are interpreted as primarily aeolian-driven (dune unit) whereas changes below 3.5 m ODN are primarily marine-driven (beach unit).

Two key determinants of post-storm dune recovery are the frequency and direction of sand-transporting winds and water level. Hourly mean wind speed and direction measured at the nearest meteorological station, Donna Nook, were obtained from the British Meteorological Data Centre for December 2013 to April 2015. Wind data from the WainFleet No.2 station were adjusted to the same height as the Donna Nook station and substituted for the period 10/03/14 to 03/07/14 for which data from Donna Nook are not available. The occurrence of onshore (0° to <150°), alongshore (>170° to 330°, 330°–350°) and offshore (>170° to 330°) winds $\geqslant 8$ m s^{-1} (i.e. potential sand-transporting winds) was calculated for each survey period. Water level records are from Immingham (British Oceanographic Data Centre) and used to determine the frequency of events with water level $\geqslant 3.5$ m ODN and $\geqslant 4.09$ m ODN occurring between successive surveys (Montreuil *et al* 2013).

Figure 3. DTMs for (a) the first (S1 January) and (b) the final (S11 December) TLS surveys in 2014 and (c) the net elevation differences between them. (d) Example DTM of roughness for survey in June 2014 showing wind-oriented shadow dunes just above the HAT. HAT is 4.09 m ODN; dune-beach contour is 3.5 m ODN as shown in figure 1.

3. Results

3.1. Geomorphological impact of the 5 december 2013 storm

Figure 1 shows the difference between the pre-storm profiles (January and June 2013) and the immediate post-storm profile (January 2014). The c.1 m high incipient foredunes at 15–20 m were eroded during the storm and the established foredune retreated 10 m. A scarp face developed at c.10 m and from the base of the scarp to 3.5 m ODN beach level increased due to redistribution of the upper beach sediments. The backshore was left devoid of rooted vegetation and vegetative matter removed during the scarping was strewn across the beach as wrackline debris (figure 1(c)).
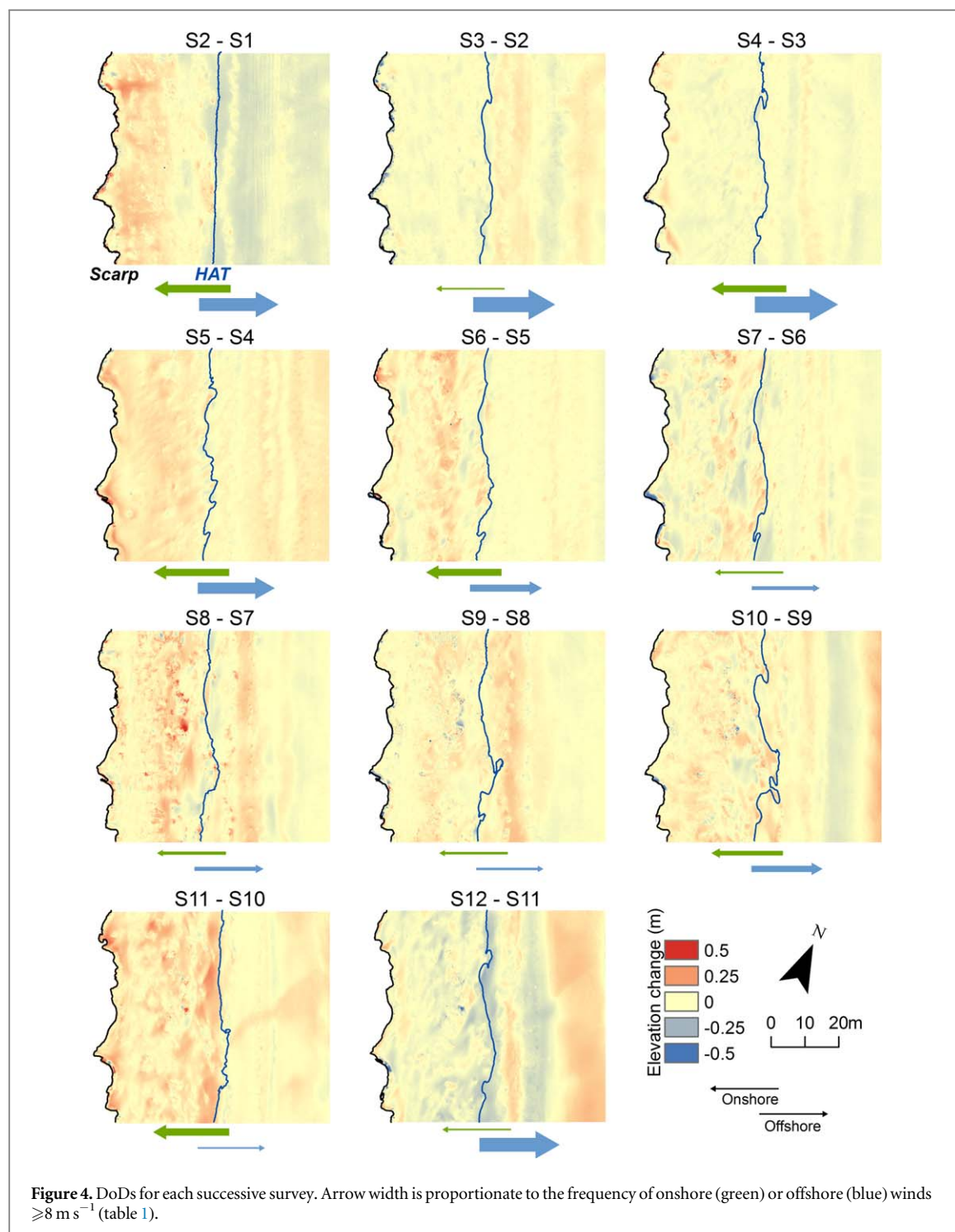
3.2. Post-storm geomorphological recovery

Following the storm surge, from January to December 2014 within the AOI there was a net loss from the beach of -2.61 m^3 and accumulation of $+180.1$ m^3 in the dunes (figure 3). From December 2014 to April 2015 the beach gained $+41.67$ m^3 and the dunes lost -59.83 m^3 of sediment.

During the first 4 post-storm months strong offshore winds dominated (table 1) and several low magnitude storms occurred (up to 1.45% of water levels $\geqslant$3.5 m). The volume of sediment above 3.5 m in the DEM decreased in March and April losing a cumulative -59.71 m^3 but the spatial pattern of sediment loss varies for each time period (figure 4). From 17/01/14 to 18/02/14 the DoD shows gains immediately seawards of the scarp line but erosion further seawards which may be due to further offshore redistribution of sediment due to high water levels (reaching up to 3.97 ODN).

The dunes had a net sediment gain of 63.69 m^3 in the spring (mid-April to mid-June) during which the frequency of water level $\geqslant$3.5 m was the lowest for the survey period. This also included the first survey period when onshore winds were more frequent than offshore winds (S5–S6). Discrete nebkha accumulated between the HAT line and the scarp base. There was little change in sediment volume from June to July and then from July to December 2014 the dunes rapidly gain sediment. Relatively low wind speeds and a low percentage of winds $\geqslant$8 m s^{-1} suggests this sediment gain was caused by sand-trapping vegetation which recovered over the summer and captured wind-blown sediment in an incipient foredune. This is particularly clear in August 2014 where discrete nebkha form and develop, merging to form a larger near-continuous incipient foredune about

Table 1. Summary of the meteorological and marine conditions, and surface changes experienced over the data collection period.

	Efficient winds			Wind speed			Water level		Volume change (m^3)	
					Velocity in ms^{-1}			Event frequency %		
	Offshore	Onshore Frequency%	Along-shore	Min	Mean	Max	⩾3.5m	⩾4.09m	Beach 0–<3.5 m	Dunes ⩾3.5 m
13 December 2013–30 January 2014	30.76	0.95	10.57	1.54	7.79	18.52	1.31	0.17	n/a	n/a
30 January [S1] – 18 February 2014	21.74	12.89	8.20	0.51	7.81	20.06	0.46	0.00	−18.90	2.30
18 February [S2] – 18 March 2014	25.34	2.58	6.37	0.51	6.48	14.40	1.12	0.00	5.95	−37.63
18 March [S3] – 16 April 2014	27.06	11.29	0.43	0.62	7.02	16.85	1.45	0.00	−7.38	−22.08
16 April [S4] – 15 May 2014	18.52	12.01	2.89	0.62	6.70	16.22	0.18	0.00	15.02	50.64
15 May [S5] – 17 June 2014	5.06	11.72	1.07	0.62	5.50	12.48	0.00	0.00	−1.62	35.12
17 June [S6]– 16 July 2014	6.25	3.63	4.36	0.62	5.14	13.89	0.93	0.00	−3.38	−4.15
16 July [S7] – 21 August 2014	7.05	5.35	2.79	0.51	5.39	15.95	1.30	0.00	−2.00	68.46
21 August [S8] – 1 October 2014	1.89	4.11	2.42	0.51	4.82	15.43	0.56	0.03	−3.98	14.59
1 October [S9] – 13 November 2014	10.37	7.78	4.09	0.51	6.22	17.49	1.65	0.00	1.29	12.61
13 November [S10] – 9 December 2014	2.61	12.40	3.10	0.51	5.54	17.49	1.52	0.00	12.39	60.22
9 December [S11] – 20 April 2015 [S12]	23.03	2.66	2.44	0.51	6.43	18.00	2.67	0.45	41.67	−59.83

Figure 4. DoDs for each successive survey. Arrow width is proportionate to the frequency of onshore (green) or offshore (blue) winds $\geqslant 8\,\mathrm{m\,s^{-1}}$ (table 1).

0.5 m high by December 2014. Early winter conditions were atypical with strong onshore winds dominant. A comparison of December 2014 with April 2015 indicates a small loss of sediment particularly between the HAT and 3.5 m contours.

The summer and winter profiles show removal of the pre-storm incipient foredune and scarping of the established foredune forming a flat beach (January 2014; figure 1(e)). The summer 2014 profile highlights the initiation of an incipient foredune c. 5 m wide just above the HAT at c. 25 m from the scarp. By winter 2014 the incipient dune has extended to 20 m wide (15–35 m from scarp) with a height of 0.75 m and continues to grow reaching c. 1.5 m by January 2018. There is limited deposition/infilling at the base of the scarp and a trough persists between this and the developing foredune. The foredune toe is located 15 m further seawards in January 2018 compared to the pre-storm position.

4. Discussion

4.1. Foredune recovery on a prograding coast

The December 2013 storm surge caused considerable dune scarping along the Lincolnshire coast. Within the AOI dunes retreated 15–20 m which sets the dune-line back around ten years of advancement based on Montreuil and Bullard's (2012) long-term estimate (1891–2010) of annual shoreline accretion of 2 m yr^{-1} or up to twenty years based on recent accretion rates (c.1 m yr^{-1}: 2005–2010). This accords with 13.59 m of coastline retreat at Donna Nook, 12 km to the north, following the December 2013 storm, where long term progradation rates of 0.21 to 1.1 m yr^{-1} also indicate erosion equivalent to at least ten years of advancement (Spencer *et al* 2015). By January 2018 the incipient foredune toe was c.15 m seawards of the pre-storm position which suggests rapid recovery and progradation beyond the pre-storm position, and seawards of the expected position assuming resumption of the long-term 1–2 m yr^{-1} rate of advance. Accretion along this coast is associated with retreat of the up-drift Holderness cliffs to the north so this rapid progradation may be associated with up-drift storm erosion during 2013/14 (Montreuil and Bullard 2012).

Recent research provides insight into the processes contributing to the observed morphological changes. Dune recovery comprised initial accumulation at the base of the scarp through slumping but also lee side deposition due to flow separation of offshore winds initiated by scarp development (Lynch *et al* 2010). Within 3 months a beach ridge had developed between the HAT and 3.5 m (dune-beach) contours and persisted throughout the survey period. After 3–6 months, post-storm discontinuous echo dunes formed parallel to, and c. 0.5–1 m from, the scarp base. These formed during offshore winds from a combination of sand transport from the landward dunes deposited downwind from the scarp base, and possible flow reversal transporting sediment from the upper beach to the seaward dune face, with the separation between dune and scarp likely maintained by topographically-steered winds (Bauer *et al* 2015) (figure 1(d)). These echo dunes persisted and grew during the year responding to summer onshore sand transport (Hesp *et al* 2009). Within 4 months of the storm discrete nebkha or shadow dunes are visible from the DoDs (figure 4) and form around debris and vegetation on the backshore. In the first 6 months these features are dynamic, changing in extent and orientation in relation to wind regime (figure 3(d)) and then coalesce to form a continuous incipient partially-vegetated foredune (Goldstein *et al* 2017). Sediment incorporated into these dunes may be from offshore winds depositing sand on the backshore or by trapping sand blown onshore from the beach (Bauer *et al* 2012, 2015). During the first year of recovery the nebkha and incipient dunes form in a similar position relative to ODN to the pre-storm dunes (just above HAT), but are located further seawards (20–35 m from the scarp) than their predecessors (15–25 m from scarp) (figure 1). During the subsequent 3 years the position of the incipient dune is unchanged but the breadth and height both increase. These stages of recovery add detail to Hesp's (2002) suggested post-storm geomorphic response of a prograding dune system.

Foredune development and post-storm recovery has been linked to nearshore characteristics, particularly along coastlines characterised by dynamic dry bars and saturated troughs (ridge and runnel topography) which can segment the dry fetch length and limit onshore aeolian transport to the dunes (Vanhée *et al* 2002, Aagaard *et al* 2004, Anthony *et al* 2008). Anthony *et al* (2008) model of cross-shore fetch segmentation on a macrotidal beach suggests sediment delivery from beach to dunes is most likely when strong cross-shore or oblique onshore winds coincide with neap tides, and most restricted when the upper beach trough is close to the foredune. The Lincolnshire coast features multiple dynamic intertidal bars that migrate cross-shore in response to tidal cycles (Van Houwelingen *et al* 2008) and longshore to the south at rates of up to 30 m per month (van Houwelingen *et al* 2006). The biannual EA profiles for the site (which extend to c.450 m and −3 m ODN) suggest the storm caused flattening of the bar-trough topography on the upper beach (cf van Houwelingen *et al* 2008) but little change in topography below 0 m ODN. The bars on the upper beach re-established before January 2015. Given the known longshore dynamics of the bars it is not possible to link the monthly records of bar migration to foredune recovery for this site.

4.2. Coastal resilience to the 2013/14 North Atlantic winter storms

Evaluating geomorphic resilience requires understanding of the pre-disturbance conditions to which the system might return. Phillips and Van Dyke (2016) argue that for coastal systems meaningful indicators of pre-disturbance conditions are long-term stability, accretion or erosion, and a state transition would require a shift from one to another of these states rather than merely an alteration to the rate of change. They describe five classes of disturbance based on system response:

(1) 'minor disturbance' where pre-disturbance and post-disturbance states are the same;

(2) 'transitional disturbance' where the post-disturbance condition is a new state but one previously occupied by the system;

(3) 'clock-resetting event' where disturbance returns the system to its original incipient state

(4) 'state space expansion event' which results in a system condition or configuration that has never previously existed;

(5) 'extinction event' that completely obliterates the system.

From other studies of geomorphic recovery following the 2013/14 storms, most suggest that coastal system states have remained unchanged or show clear signs of rapidly returning to the pre-storm state. Pye and Blott (2016) concluded that despite 2013/14 being the stormiest period for 143 years, the geomorphic effects on the Sefton coast, England were '*virtually insignificant*' within the long-term context from late 18th century to present. Significant beach-dune recovery occurred within 1 year of the storms and long-term trends had not changed. Similarly at Truc Vert, SW France, post-storm recovery was very rapid during the first ten months and within 18 months the beach-dune system had returned to its pre-winter volume, although not to the pre-winter foredune profile (Castelle *et al* 2017). As the foredune toe remained more than 10 m landward of the pre-2013/14 position towards the end of 2015, Castelle *et al* (2017) concluded that foredune recovery was a slower process than beach recovery. Kandrot *et al* (2016) examined the Rossbehy barrier beach-dune system on SW coast of Ireland and determined that although the response to the 2013/14 winter storms was 'exceptional', in the long term context, the overall trend of erosion was unchanged. A breach in the barrier system caused by a minor surge in 2008 had a potentially longer-lasting effect, and likely also affected response to the 2013/14 storms. It is too soon to determine whether Rossbehy was undergone minor disturbance or is in a transitional phase, but if the latter the trigger is more likely to have been the smaller 2008 event rather the high magnitude storms of 2013/14. For these three locations, rapid resumption of pre-disturbance trends suggests the storm caused only 'minor disturbance' to the beach-dune system.

For the Lincolnshire coast, long-term progradation has been accompanied by an increase in sediment volume in the beach-dune system between Donna Nook and Mablethorpe (Montreuil and Bullard 2012). Although the December 2013 storm surge represents a large-scale disturbance event amplified by spring tides, its effects were mitigated ('filtered' - Phillips and Van Dyke 2016) by offshore winds up to 95 km hr^{-1}. Rebuilding of the incipient foredunes was instigated rapidly after the storm and within 12 months recovery was substantial with 180.1 m^3 of sediment added to dunes in the AOI. By normalising for survey area and time between surveys (Young and Asford 2006), previous seasonal sediment budget changes determined for 'embryo' dunes (described by Montreuil *et al* 2013) 0.6 km to the north can be compared to changes in the AOI. Rates of volume change for the embryo dunes in winter (2009/10) were $-0.000\,49\,\mathrm{m^3\,m^2\,day^{-1}}$ and $+0.000\,77\,\mathrm{m^3\,m^2\,day^{-1}}$ in summer 2010 (Montreuil *et al* 2013). By comparison, winter 2014 changes on the incipient foredunes following the 2013 storm were $-0.000\,30\,\mathrm{m^3\,m^2\,day^{-1}}$, summer 2014 showed a gain of $+0.000\,51\,\mathrm{m^3\,m^2\,day^{-1}}$ and winter 2014/15 was $-0.000\,023\,\mathrm{m^3\,m^2\,day^{-1}}$. The order of magnitude and trend of sediment budget changes immediately following the 2013 storm is comparable with pre-disturbance conditions, although winter 2014/15 shows a sediment loss likely due to erosion associated with high water levels immediately prior to the April 2015 survey (5.57 m ODN 07/04/15). The EA profiles indicate that by January 2018 the incipient dunes incorporated 73.25 m^3 m^{-1} of sediment, considerably more than the pre-storm incipient dunes (51.13 m^3 m^{-1}). This suggests behaviour similar to that identified by Morton *et al* (1994) where once post-storm recovery has started, a prograding system can undergo continuous gains that exceed the volume eroded by the storm.

Recovery of coastal foredunes is widely reported to take considerably longer than that of the adjacent beach following a storm, and this recovery period can be extended by the impact of subsequent storms (Houser *et al* 2015). Typically the time period is several years, occasionally extending to decades (Mathew *et al* 2010, McLean and Shen 2006) but evidence from this paper and elsewhere (e.g. Morton *et al* 1994) indicates recovery may occur more rapidly on prograding coastlines (<3 years). In cases where dune volume recovers rapidly, as reported here, by Morton *et al* (1994) and Castelle *et al* (2017), the post-storm geomorphic profile of the redeveloped incipient foredunes is different to the pre-storm profile and may undergo further change before reaching an equilibrium state.

4.3. Concluding remarks

Geomorphic resilience depends on the primary controlling factors of the system state, and the magnitude, frequency and intensity of disturbance. Where long-term coastline trends are controlled by strong morphological preconditioning, including local bathymetry, geomorphology and sediment supply, even high magnitude storm events cause only a minor disturbance to the system (Chaverot *et al* 2008, Pye and Blott 2016, Phillips *et al* 2017) which can be described as highly resilient. In other cases the occurrence of storm events themselves may be a primary control on coastal geomorphology due to their frequency, and resilience may hinge on the clustering of storms (Kish and Donoghue 2013, Houser and Hamilton 2009). Downes *et al* (2013)

highlight the importance of research on resilience being evidence-based and the need to apply methodologies that allow comparison of studies across time and space. Including this paper, recent studies focusing on coastal resilience in response to stormy periods have used repeat LiDAR surveys to determine changes in beach-dune sediment budget and the evolution and recovery of geomorphological features (Telling *et al* 2017). Insights in to the rapidity and persistence of geomorphic recovery are dependent on the time between surveys where closely-spaced surveys enable the detection of geomorphological change in response to specific forcing factors, whilst longer time periods between surveys (e.g. 6 months-years) indicate net changes and longer-term trends in coastline dynamics. Results reported here suggests that, as with the west coasts of England, Ireland and France, one of the stormiest periods on record triggered only a minor disturbance to the prograding beach-dune system on England's east coast.

The impact of changing climate on the magnitude and frequency of storms in NW Europe is difficult to predict. There is a consensus that storm tracks will shift poleward with concomitant changes to regional impacts, but it remains unclear whether storminess will intensify (Zappa *et al* 2013, Mölter *et al* 2016, Rasmijn *et al* 2016). This paper has focused on the post-storm response of a prograding coastal dune system and demonstrated the ability of that system to recover rapidly from the impacts of a high magnitude storm. It highlights geomorphological response to seasonal forcing factors and the importance of both offshore and onshore winds for incipient foredune recovery. Within four years dune advance has exceeded the position expected based on longer term coastal trends. One implication of this is that coastal protection offered by prograding coasts is likely to endure irrespective of future changes to storminess.

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References

Aagaard T, Davidson-Arnott R, Greenwood B and Nielsen J 2004 Sediment supply from shoreface to dunes: linking sediment transport measurements and long-term morphological evolution *Geomorphology* **60** 205–24

Ackerley D, Chandler J and Bullard J 2016 Monitoring dune response to the east coast storm surge of 2013 using laser scanning and SfM photogrammetry *Coastal Management: Changing Coast, Changing Climate, Changing Minds* ed A Baptiste (Amsterdam: ICE Publishing) http://icevirtuallibrary.com/doi/abs/10.1680/cm.61149.545 Full text: https://ice.org.uk/

Anthony E J, Ruz M-H and Vanhée S 2008 Aeolian sand transport over complex intertidal bar-trough beach topography *Geomorphology* **105** 95–105

Backstrom J, Jackson D, Cooper A and Loureiro C 2015 Contrasting geomorphological storm response from two adjacent shorefaces *Earth Surf. Process. Landf.* **40** 2112–20

Bauer B O, Davidson-Arnott R G D, Walker I J, Hesp P A and Ollerhead J 2012 Wind direction and complex sediment transport response across a beach-dune system *Earth Surf. Process. Landf.* **37** 1661–77

Bauer B O, Hesp P A, Walker I J and Davidson-Arnott R G D 2015 Sediment transport (dis)continuity across a beach-dune profile during an offshore wind event *Geomorphology* **245** 135–48

Brasington J, Langham J and Rumsby B 2003 Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport *Geomorphology* **53** 299–316

Brooks S M, Spencer T, McIvor A and Möller I 2016 Reconstructing and understanding the impacts of storms and surges, southern North Sea *Earth Surf. Process. Landf.* **41** 855–64

Brunsden D and Thornes J B 1979 Landscape sensitivity and change *Trans. Inst. Br. Geographers* **NS4** 463–84

Castelle B, Marieu V, Bujan S, Splinter K D, Robinet A, Sénéchal N and Ferreira S 2015 Impact of the winter 2013–2014 series of severe Western Europe storms on a double-barred sandy coast: beach and dune erosion and megacusp embayments *Geomorphology* **238** 135–48

Castelle B, Bujan S, Ferreira S and Dodet G 2017 Foredune morphological changes and beach recovery from the extreme 2013/2014 winter at a high-energy sandy coast *Mar. Geol.* **385** 41–55

Chaverot S, Héquette A and Cohen O 2008 Changes in storminess and shoreline evolution along the northern coast of France during the second half of the 20th century *Z. Geomorphologie* **52** 1–20

Coveney S and Fotheringham A S 2011 Terrestrial laser scan error in the presence of dense ground vegetation *Photogramm. Rec.* **26** 307–24

Crapoulet A, Héquette A, Marin D, Levoy F and Bretel P 2017 Variations in the response of the dune coast of northern France to major storms as a function of available beach sediment volume *Earth Surf. Process. Landf.* **27** 1603–22

Downes B J, Miller F, Barnett J, Glaister A and Ellemor H 2013 How do we know about resilience? An analysis of empirical research on resilience and implications for interdisciplinary praxis *Environ. Res. Lett.* **8** 1–8

Fan L, Powrie W, Smethurst J, Atkinson P M and Einstein H 2014 The effect of short ground vegetation on terrestrial laser scans at a local scale *ISPRS J. Photogramm. Remote Sens.* **95** 42–52

Goldstein E B, Moore L J and Vinent O D 2017 Lateral vegetation growth rates exert control on coastal foredune 'hummockiness' and coalescing time *Earth Surf. Dyn.* **5** 417–27

Guarnieri A, Vettore A, Pirotti F, Menenti M and Marani M 2009 Retrieval of small-relief Marsh morphology from Terrestrial Laser Scanner, optimal spatial filtering, and laser return intensity *Geomorphology* **113** 12–20

Hesp P 2002 Foredunes and blowouts: initiation, geomorphology and dynamics *Geomorphology* **48** 245–68

Hesp P A, Walker I J, Namikas S L, Davidson-Arnott R, Bauer B O and Ollerhead J 2009 Storm wind flow over a foredune, Prince Edward Island, Canada *J. Coast. Res.* SI **56** 312–6

Hesp P A 2013 Conceptual models of the evolution of transgressive dune field systems *Geomorphology* **199** 138–149

Houser C and Hamilton S 2009 Sensitivity of post-hurricane beach and dune recovery to event frequency *Earth Surf. Process. Landf.* **34** 613–28

Houser C, Wernette P, Rentschlar E, Jones H, Hammond B and Trimble S 2015 Post-storm beach and dune recovery: implications for barrier island resilience *Geomorphology* **234** 54–63

Kandrot S, Farrell E and Devoy R 2016 The morphological response of foredunes at a breached barrier system to winter 2013/2014 storms on the southwest coast of Ireland *Earth Surf. Process. Landf.* **41** 2123–36

Kish S A and Donoghue J F 2013 Coastal response to storms and sea-level rise: Santa Rosa Island, Northwest Florida, USA *J. Coast. Res.* **SI63** 131–40

Labuz T A 2016 A review of field methods to survey coastal dunes—experience based on research from South Baltic coast *Journal of Coastal Conservation* **20** 175–90

Le Mauff B, Juigner M, Ba A, Robin M, Launeau P and Fattal P 2018 Coastal monitoring solutions of the geomorphological response of beach-dune system using multi-temporal LiDAR datasets (Vendée coast, France) *Geomorphology* **304** 121–40

Lloyd M G, Peel D and Duck R W 2013 Towards a social-ecological resilience framework for coastal planning *Lane Use Policy* **30** 925–33

Lynch K, Jackson D W T and Cooper J A G 2010 Coastal foredune topography as a control on secondary airflow regimes under offshore winds *Earth Surf. Process. Landf.* **35** 344–53

Maspataud A, Ruz M-H and Hequette A 2009 Spatial variability in post-storm beach recovery along a macrotidal barred beach, southern North Sea *J. Coast. Res.* SI **56** 88–92

Masselink G, Castelle B, Scott T, Dodet G, Suanez S, Jackson D and Floc'h F 2016 Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe *Geophys. Res. Lett.* **43** 2135–43

Mathew S, Davidson-Arnott R G D and Ollerhead J 2010 Evolution of a beach-dune system following a catastrophic storm overwash event: Greenwich Dunes, Prince Edward Island, 1936–2005 *Can. J. Earth Sci.* **47** 273–90

Matthews T, Murphy C, Wilby R L and Harrigan S 2014 Stormiest winter on record for Ireland and UK *Nat. Clim. Change* **4** 738–40

McLean R and Shen J-S 2006 From foreshore to foredune: foredune development over the last 30 years at Moruya Beach, New South Wales, Australia *J. Coast. Res.* **22** 28–36

Mölter T, Schindler D, Albrecht A T and Kohnle U 2016 Review on the projections of future storminess over the North Atlantic European region *Atmosphere* **7** 60

Montreuil A-L and Bullard J E 2012 A 150-year record of coastline dynamics within a sediment cell: Eastern England *Geomorphology* **179** 168–85

Montreuil A-L, Bullard J E, Chandler J H and Millett J 2013 Decadal and seasonal development of embryo dunes on an accreting macrotidal beach: North Lincolnshire, UK *Earth Surf. Process. Landf.* **38** 1851–68

Moore L J, Vinent O D and Ruggiero P 2016 Vegetation control allows autocyclic formation of multiple dunes on prograding coasts *Geology* **44** 5590562

Morton R A, Paine J G and Gibeaut J C 1994 Stages and durations of post-storm beach recovery, southeastern Texas coast *J. Coast. Res.* **10** 884–908

Nield J M, Wiggs G F S and Squirrell R S 2011 Aeolian sand strip mobility and protodune development on a drying beach: examining surface moisture and surface roughness patterns measured by terrestrial laser scanning *Earth Surf. Process. Landf.* **36** 513–22

Phillips J D and Van Dyke C 2016 Principles of geomorphic disturbance and recovery in response to storms *Earth Surf. Process. Landf.* **41** 971–9

Phillips M S, Harley M D, Turner I L, Splinter K D and Cox R J 2017 Shoreline recovery on wave-dominated sandy coastlines: the role of sandbar morphodynamics and nearshore wave parameters *Mar. Geol.* **385** 146–59

Pye K and Blott S J 2016 Assessment of beach and dune erosion and accretion using LiDAR: impact of the stormy 2013–14 winter and longer term trends on the Sefton Coast, UK *Geomorphology* **266** 146–67

Rasmijn L M, van der Schrier G, Barkmeijer J, Sterl A and Hazeleger W 2016 Simulating the extreme 2013/2014 winter in a future climate *J. Geophys. Res.: Atmos.* **121** 5680–98

Ruggiero P, Kaminsky G M, Gelfenbaum G and Cohn M 2016 Morphodynamics of prograding beaches: a synthesis of seasonal- to century-scale observations of the Columbia River littoral cell *Mar. Geol.* **376** 51–68

Soudarissanane S, Lindenbergh R, Menenti M and Teunissen P 2011 Scanning geometry: Influencing factors on the quality of terrestrial scanning points *ISPRS J. Photogramm. Remote Sens.* **66** 389–99

Spencer T, Brooks S M, Evans B R, Tempest J A and Möller I 2015 Southern North Sea storm surge event of 5 december 2013: water levels, waves and coastal impacts *Earth-Sci. Rev.* **146** 120–45

Stallins J A and Corenblit D 2018 Interdependence of geomorphic and ecologic resilience properties in a geographic context *Geomorphology* **305** 76–93

Telling J, Lyda A, Hartzell P and Glennie C 2017 Review of Earth science research using terrestrial laser scanning *Earth-Sci. Rev.* **169** 35–68

Thom B G and Hall W 1991 Behavior of beach profiles during accretion and erosion dominated periods *Earth Surface Processes and Landforms* **16** 113–127

UK Meteorological Office 2014 Winter storms, December 2013 to January 2014 http://metoffice.gov.uk/climate/uk/interesting/2013-decwind

Usher M B 2001 Landscape sensitivity: from theory to practice *Catena* **42** 375–83

van Houwelingen S, Masselink G and Bullard J 2006 Characteristics and dynamics of multiple intertidal bars, north Lincolnshire, England *Earth Surf. Process. Landf.* **31** 428–43

van Houwelingen S, Masselink G and Bullard J 2008 Dynamics of multiple intertidal bars over semi-diurnal and lunar tidal cycles, North Lincolnshire, England *Earth Surf. Process. Landf.* **33** 1473–90

Vanhée S, Anthony E J and Ruz M H 2002 Aeolian sand transport on a ridge and runnel beach: preliminary results from Leffrinckoucke beach, northern France *J. Coast. Res.* SI **36** 732–40

Walters D C and Kirwan M L 2016 Optimal hurricane overwash thickness for maximising resilience to sea level rise *Ecology and Evolution* **6** 2948–56

Wang C, Menenti M, Stoll M-P, Feola A, Belluco E and Marani M 2009 Separation of ground and low vegetation signatures in LiDAR measurements of salt-marsh environments *IEEE Trans. Geosci. Remote Sens.* **47** 2014–23

Young A P and Asford S A 2006 Application of airborne LIDAR for seacliff volumetric change and beach-sediment budget contributions *J. Coast. Res.* **22** 307–18

Zappa G, Shaffrey L C, Hodges K I, Sansom P G and Stephenson D B 2013 A multi-model assessment of future projections of north Atlantic and European extratropical cyclines in the CMIPS climate models *J. Clim.* **26** 5846–62