# LONG-TERM TRENDS, SHORT-TERM SHOCKS AND CLIFF RESPONSES FOR AREAS OF CRITICAL COASTAL INFRASTRUCTURE

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**Abstract:** Cliffs composed of glacial and pre-glacial sediments typify long stretches of the coastline of East Anglia, UK. This paper assesses both long-term and short term retreat as it can be extremely rapid. Long-term average annual cliff retreat is typically 2 - 5 m $a^{-1}$ where cliffs have no protection from storm energetics. However, in single events retreat can be 3 – 4 times this long-term average. Individual storms deliver short term shocks to both the cliff and the beach system which can have serious socio-economic consequences, particularly significant in areas of critical coastal infrastructure. In this paper we look at two such recent events, the 5 December 2013 North Sea storm surge and the February – March 2018 "beast from the east" and "mini beast". Each of these events left a large shoreline footprint, but each arose from different underpinning meteorological scenarios. Lessons can be learnt for future management planning.

## Introduction

Low frequency, high magnitude meteorological events present short-term shocks to coastal systems and can have serious socio-economic consequences in areas of critical coastal infrastructure. Sections of the UK East Coast are composed of easily eroded glacial and pre-glacial sediments (Ehlers and Gibbard 1991) with cliff-beach systems supporting critical infrastructure in several places. Where cliffs have no protection and exist in a natural state, they show long-term (1880s to 2000s) average retreat rates of 2 - 5 m $a^{-1}$, equivalent to an inland translation of the shoreline of 240 - 600 m (Brooks and Spencer 2010). However, these long-term trends mask a more complex, pulsed record of cliff recession. Rather, several cliff systems around the UK East Anglian coast have shown decadal-scale fluctuations in rates of retreat (Brooks and Spencer 2014); thus retreat rates in the 1990s were up to 7 times higher than in the 2000s. More recently, the impact of single high magnitude events has been evaluated, showing the importance of short term shocks to the cliff system, where up to 12 m can be taken laterally from the clifftop edge during a single event (Spencer et al. 2015). This rate is 3 - 4 times the long term average and suggests that cliff dynamics are likely to have involved periods of relative stability interspersed with periods of short term rapid change.

In the past decade alone there have been two newsworthy events that might be considered to fall into this category, each having a rather different meteorological context. Firstly, during the extreme winter of 2013/14, which has been widely reported as having extreme impacts across the shorelines of the whole of North West Europe (Castelle et al. 2015; Masselink et al. 2015), one of the westerly-originating extra tropical storms was able to develop into a classic SE tracking southern North Sea storm surge event (Muir Wood et al. 2005), associated with the presence of a blocking high pressure over Scandinavia. The effect of this storm, Storm Xaver on 5 December 2013, was to generate large and long-lived (>12 hour) storm surge residuals that coincided with high spring tides, with peak residuals occurring just 1 - 2 hours prior to high water (Spencer et al. 2015). A storm surge water level of 3.32 m ODN (ODN = Ordnance Datum Newlyn where 0.0 m ODN approximates to Mean Sea Level) was recorded at Great Yarmouth (Spencer et al. 2015). In addition, winds were onshore and persistent, able to generate onshore or obliquely onshore waves, more pronounced on the north-facing North Norfolk coast (peak Hs of 3.8 m at Blakeney Overfalls wave buoy (23m water depth)) than they were for the north-east and east-facing Suffolk coast (peak Hs of 2.9 m at Happisburgh (10 m water depth); peak Hs of 1.5 m at Sizewell (18 m water depth). A second extreme event was dominated by more severe wave activity which had its greatest impact on east-facing coasts. At the end of February / beginning of March 2018, a prolonged spell of bitterly cold weather accompanied by blizzards and significant snowfall, engulfed much of Northern Europe. In a large-scale meteorological event known as Sudden Stratospheric Warming (SSW), a weakened Polar Vortex resulted in extremely cold arctic air flooding out to lower latitudes (UK Met Office 2018). The UK east coast experienced near gale-force easterly winds from Siberia – 'the beast from the east' - accompanied by unusually high inshore waves. At the Southwold Approach WaveNet site (20 m water depth) peak Hs reached 4.4 m on 1 March 2018, the highest waves experienced since records began in 2010, and were sustained at > 3 m over 47 hours. This event was followed by a second, shorter duration event, the so-called "mini beast" where wave heights reached 4.0 m at Southwold Approach, and were sustained at > 3 m for 32 hours. Both events were on high spring tides and due to their longevity covered between them several high tides.

In this paper we explore the effect of these different short-term shocks on the cliff systems of eastern England using spatially and temporally comprehensive

Earth Observation methodologies to detail and quantify their consequences for cliff retreat. We consider the associated effect of beach change which has important implications for cliff stability, and we discuss the wider implications for sediment delivery onto the beach and into the nearshore zone, a very important function of these short term shocks as sediment becomes released and therefore available for alongshore transport and subsequent deposition downdrift.

**Methods**

For the coast of Norfolk, UK between the settlements of Mundesley and Walcott (Figure 1), we established the change in shoreline position from historical maps (since 1880s) and more recent vertical aerial photographs (taken annually in late summer, 1992 - 2016). The clifftop edge can be clearly defined on both data types. The maps and photographs were georectified to be within the same co-ordinate system (OSGB36) and then digitized to generate shorelines for individual years (see Pollard et al. 2019 for a discussion of errors associated with digitisation). The ArcGIS add-on, the Digital Shoreline Analysis System (DSAS; Thieler et al. 2009), was then used to quantify long-term cliff retreat rates, with an alongshore shore-normal transect spacing of 5 m, over the 12 km cliff frontage between Mundesley and Walcott.

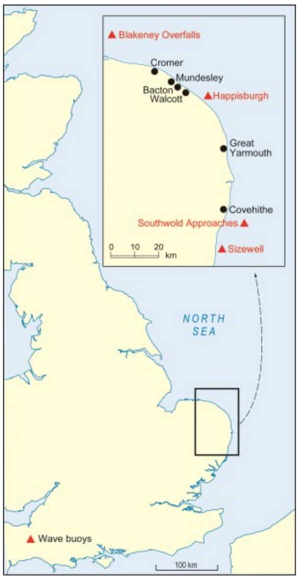


Fig. 1. Location of the sites in this paper showing the general setting of East Anglia and (inset) the specific locations in Norfolk and Suffolk.

To overcome shadowing effects in the aerial imagery and to better establish the link to sediment release from the cliffs, and the input of sediment to the coastal system, resulting from the 5 December 2013 storm surge, ground elevation change from LiDAR (Light Detection And Ranging) datasets (flown on 5 October 2013 and 24 November 2014) was used to generate Digital Elevation Models (DEMs) of cliff face morphology. This allowed the determination of cliff profile change, modes of cliff failure and the sediment volumes released by these processes. Beach change analysis was performed using the DEM of Difference (DoD) for the 2013 and 2014 LiDAR.

To assess the impact of "the beast from the east" and "mini-beast" events on beach morphology in late February / March 2018, high resolution cross-shore profiling (Leica Viva GS08 GNSS satellite survey (RTK) system; 3-D coordinate quality of < 50 mm, and typically of < 20 mm) was undertaken by the authors on 9 April 2018, supplementing the regular biannual cross-shore surveys of the UK Environment Agency recorded on 8 September 2017 and 14 February 2018.

## Results

Map evidence shows that the long-term retreat of the cliff frontage between Mundesley and Walcott averaged 0.52 m $a^{-1}$ in the period between 1885 and 1968. This long-term rate can be disaggregated into three phases of retreat: 0.56 m $a^{-1}$ (1885-1905); 0.75 m $a^{-1}$ (1905-1946) and 0.23 m $a^{-1}$ (1946-1968) (Figure 2).

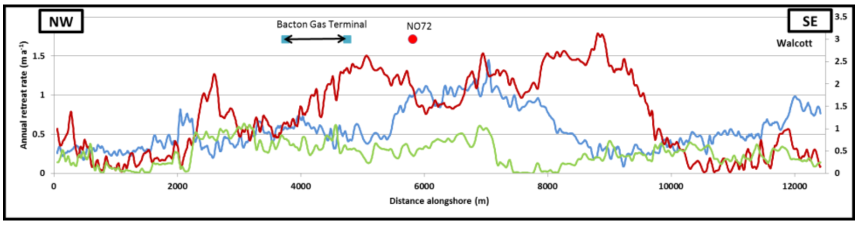


Fig. 2. Annual cliff retreat rate for the frontage between Mundesley and Walcott, Norfolk coast, UK for the time periods 1885-1905 (red), 1905-1946 (blue) and 1946-1968 (green).

The initial small increase in retreat rate from 0.56 m $a^{-1}$ (1885-1905) to 0.75 m $a^{-1}$ (1905-1946) might be attributable to regional sea level rise given the timescale involved (Pye and Blott 2009), or it could be due to the occurrence of more storms in the period 1905-1946. Since 1946 the cliffline has been defended in several places to protect critical coastal infrastructure (Clayton 1989); this explains the decrease in retreat rate to 0.23 m $a^{-1}$ (1946-1968).

Within this long-term context, it is possible to assess the cliff retreat linked to the 5 December 2013 storm event. Figure 3 shows the clifftop edge in 2013 (Figure 3A) and cleaned post-surge cliff faces in 2014 (Figure 3B). Using LiDAR data to extract heights from cross-shore point shapefiles (Figure 4), we quantified the retreat of the clifftop edge at this locality at 8 m (figure 4A), 16 times the long-term average.

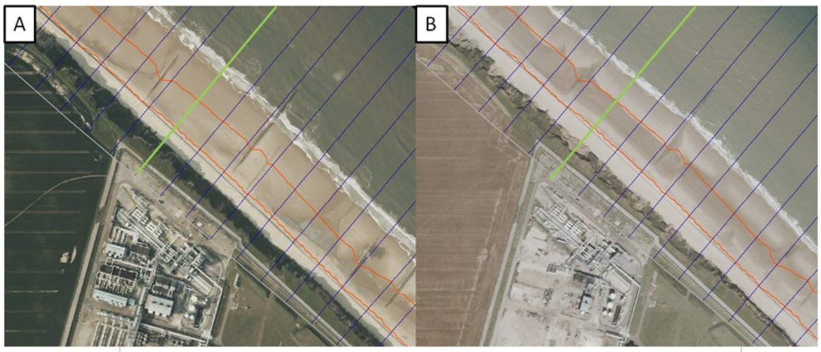


Fig. 3. Aerial photographs for 2013 (A) and 2014 (B). Red lines = Mean High Water Springs (MHWS) and Mean Sea Level (MSL). Green cross-shore profile is the profile shown in Fig 4A.

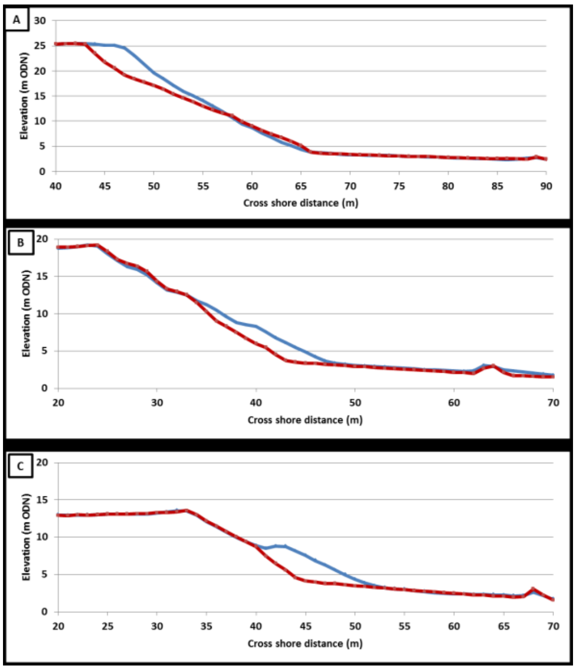


Fig. 4. Modes of cliff failure, 5 December 2013 storm (blue= pre-storm; red=post-storm). A) retreat of 8m; B) cliff base undercutting; and C) volumetric loss and over-steepening in the lower cliff.

Additional LiDAR analysis shows that an average of 20 $m^3/m$ of sediment was released from the cliffed frontage shown in Figure 3. Less than 50 % of this sediment was retained on the beach between Mean High Water Springs (MHWS) and Mean Sea Level (MSL). Along the 1 km frontage of the Bacton Gas Terminal itself, a structure of critical national significance, there was a total loss of 10,000 $m^3$ of sediment from the cliff (about half the total annual loss of beach sediment along the entire 20 km shore frontage from Cromer to Walcott (EACG 2012)). The beach lowering associated with such sediment volumes was explored using LiDAR, by developing a DEM of Difference (DoD) for the 2013 and 2014 datasets. Beach lowering was found to be up to 0.6 m (between MHWS and MSL) in front of the gas terminal (green cross-shore profile in Figure 3A and B). With a cliff base at 4.0 m ODN, wave action on top of the still water level during the surge (3.32 m ODN at Great Yarmouth, 40 km SE of the study site) would have reached the cliff base, causing the observed cliff collapse, clifftop retreat and sediment release.

Our final analysis involved investigating the short term shock from the “beast from the east” and “mini beast” by re-occupying a UK Environment Agency cross-shore profile located at NO72 (see Figure 2). At the end of summer 2017, prior to these two events, the upper beach was at a maximum elevation of 1.043 m ODN and the position of Mean Sea Level was located at 55 m from the seawall. By 14 February 2018 the upper beach elevation had reduced to 0.313 m ODN (a loss of 0.73 m), and the position of Mean Sea Level had shifted 5 m to landward. Beach erosion associated with "the beast from the east" and the "mini beast" reduced the upper beach level to -0.53 m ODN, with a landward translation of the position of Mean Sea Level of 39 m, placing it just 16 m from the sea wall. At its maximum, the beach lowering associated with these two events was just short of 1 m, almost double the lowering associated with the 5 December 2013 storm surge impact.

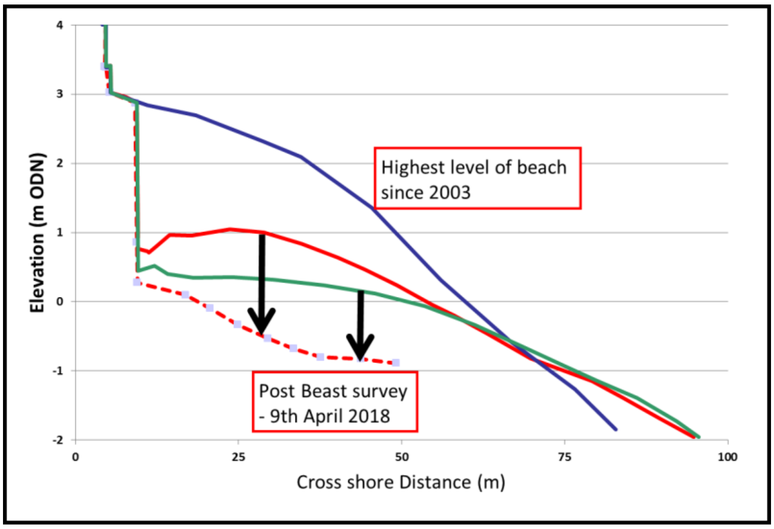


Fig. 5. Cross-shore profiles at NO72. September 2017 = thick red line; 14 February 2018 (green line; April 2018 (dotted red line) and the highest level of the beach since 2003 (blue line).

## Conclusions

Long-term cliff retreat in the glacial sediments of the cliffs of East Anglia can be up to 5 m $a^{-1}$ where they are not protected from storm impacts (as at Covehithe, Suffolk) but are around 0.2 m $a^{-1}$ where protection is available (as at Bacton, Norfolk). Two recent high magnitude, low frequency events have delivered short term shocks to both of these cliff systems as well as to the beaches that protect them. We have been able to quantify the cliff and beach changes associated with these events using the latest Earth Observation data. Although the two events involved very different underpinning meteorological contexts, one associated with an Atlantic weather system storm approaching from the west and the other from a severe outbreak of cold continental air from the east, they both had significant impacts on the cliffs and beaches of East Anglia. In unprotected cliffs, events such as these can remove up to 12 m from the clifftop edge due to high onshore waves coinciding with high spring tides, sometimes made more energetic through the development of a large surge residual. Since 1946 the cliffs at Bacton have been artificially protected from the worst storm impacts, and this is reflected in a decrease in mean cliff retreat rates from 0.75 m $a^{-1}$ to 0.23 m $a^{-1}$. However, even here the cliffs can retreat by up to 8 m during high magnitude events, due to ongoing beach lowering and the overtopping of hard defences. Specific beach lowering was up to 1 m during "the beast from the east" and "mini beast", enhancing cliff vulnerability to failure.

The lessons to be learned from these short term shocks are important for future management of the cliffs and beaches on the coast of eastern England. Firstly, if storm energetics increase in future on top of ongoing accelerated sea level rise, the short term shocks may well have even greater impacts and play a more significant role in determining long-term cliff retreat rates. Secondly, if beach lowering is also taken into account this could encourage the same impact on the cliff base as an additional 1 m of sea level rise. Thirdly, the sequencing of storms is a very important part of the story (Castelle et al. 2015). The 2013-14 winter saw sequences of westerly storms crossing northwest Europe (Masselink et al. 2015). The fact that only one of these developed into a surge that stripped up to 0.6 m off the beaches was fortunate. Had a second event delivered similar energetics, directed onshore and with a large surge residual the short term impacts could have been even greater. We can gain some insight into the potential importance of such sequencing from quantifying the combined effect of "the beast from the east" and the "mini beast". These two events occurred just 2 weeks apart. Our analysis shows that, taken together, these two events caused a greater degree of beach lowering than the single surge event of December 2013. Fourthly, there needs to be attention paid to the recovery phase from these shocks. We need to know the timescale for beaches to reoccupy pre-storm levels. If storms become more frequent in future, delivering cumulative short term shocks, we will need to be prepared for enhanced cliff retreat and the consequences for critical coastal infrastructure.

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