Soft rock cliff retreat under changing climate drivers

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BLUE Coast — Physical and biological dynamic coastal processes and their role in coastal recovery

Introduction

Cliffs composed of glacial and pre-glacial sediments typify long stretches of the coastline of East Anglia, UK (Figure 1). Long-term average annual cliff retreat is typically 2 - 5 m a^{-1} where cliffs have no protection from storm impacts. 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 use shoreline change analysis for unprotected cliffs to identify storms that have had major cliff impacts. We then use recent meteorological and hydrodynamic data to characterise the forcing energetics. The winter of 2010-11 in the UK has been widely referred to as "The Big Freeze", involving a protracted period of easterly air flow from mid-November and into December, while the 5 December 2013 North Sea storm surge left a wake of devastation around the UK east coast. We can identify totally different underpinning regional scale meteorological scenarios generating these events. The associated cliff retreat has implications for patterns and magnitude of sediment delivery to the nearshore and this is important for future management planning for unstable cliffs.

Figure 1: Soft rock cliffs at Covehithe, Suffolk, UK in A) Summer (7 May 2018) and B) Winter (30th March 2018)

Objectives

The main objectives of the research are to:

- Assess available Earth Observation data for shoreline change analysis over centennial, decadal and annual scales
- Quantify centennial scale morphological change in the shoreline for unprotected/unmanaged soft rock cliffs
- Evaluate more recent decadal scale shoreline change
- Derive annual shoreline change to pair with specific events
- Use event-scale shoreline change to identify the forcing through elevated still water levels and high magnitude onshore waves
- Consider the findings in relation to regional synoptic meteorology

Location and Methodology: shoreline change analysis

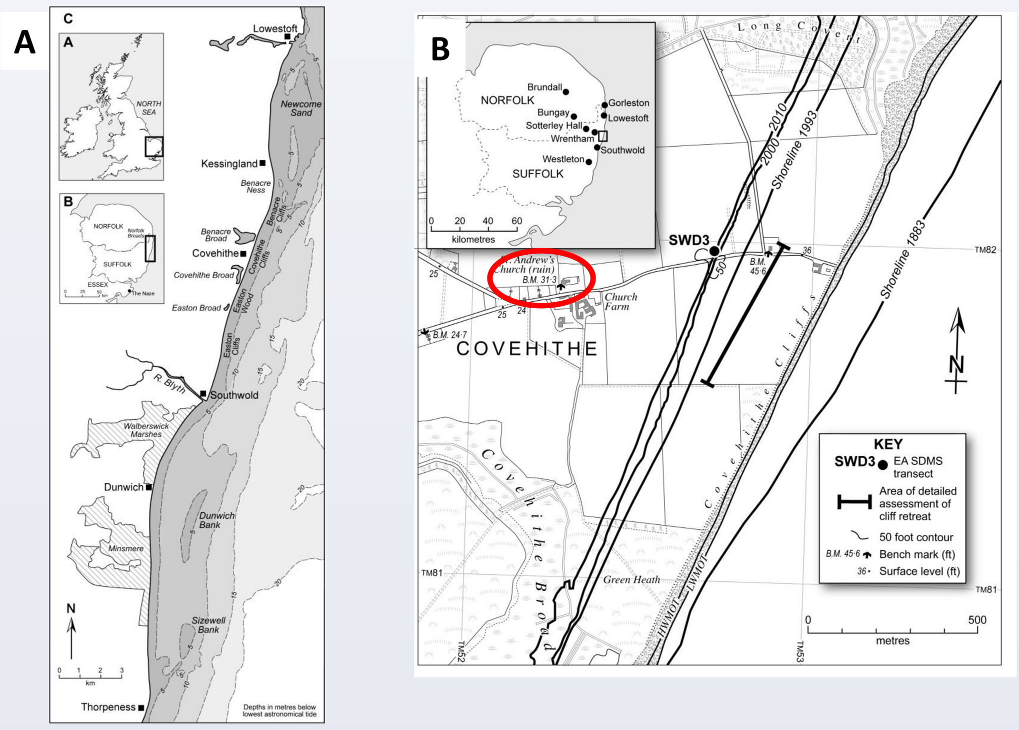

Figure 2: Location of the study site at Covehithe, Suffolk, UK. A) General setting within the UK and East Anglian Coast and B) detail of the Covehithe field site with historic shorelines (base map is from 1948) and the location of cross-shore profile SWD3 (SO14) from the UK Environment Agency database. Note St Andrew's church circled in red

Figure 2 shows the study site on the East Anglian coast of the UK, with this research primarily focusing on the unprotected cliffs of Covehithe. Cliffs reach elevations of up to 14 m and so as they retreat they concurrently release large volumes of sand and silt-sized sediment into the nearshore zone. This important ecosystem service helps to maintain the nearshore and offshore sand bars found in the shallow southern North Sea basin. Hence this role is important in the defense of unstable shorelines elsewhere in the region. In this study we develop and apply a methodology based on the full range of recent Earth Observation data that maximises the potential for detailed shoreline change analysis (full details of the methodological chain of analysis can be found in Pollard et al. 2019 and the application to soft rock cliffs is illustrated in figure 3). Most of the data are supplied by the Environment Agency of the UK.

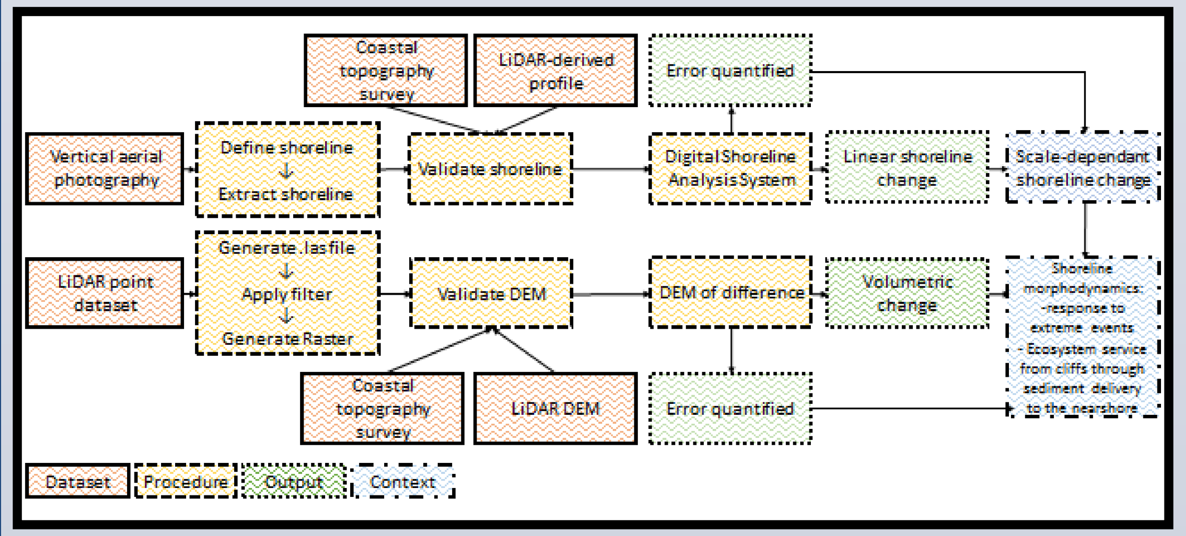

Figure 3: Methodological approach for using Earth Observation data (topographic survey, vertical aerial photographs and LiDAR) for linear and volumetric shoreline change analysis (see Pollard et al. 2019)

Results: scale dependent shoreline change analysis

Shorelines were digitised using the clifftop edge, marked clearly on the 1:10560 Ordnance Survey map (1883) and annual aerial photographs (1992 onwards). The Digital Shoreline Analysis System (DSAS) was configured to cast transects at 5 m alongshore spacing. Pairs of shorelines intersected by the transects enabled Net Shoreline Movement (NSM) and End Point Rate (EPR) to return total shoreline retreat (m) and annual retreat rate (m a^{-1}) respectively. Figure 4 shows transect casting, 2010, 2011 and 2018 shorelines and baseline, overlain on the 2010 and 2011 aerial photographs.

Figure 4: The DSAS methodology: St Andrew's church and clear shoreline retreat in 2010-11 (circled in red) in the vicinity of SWD3 (SO14)

Centennial, decadal and event scale shoreline change analyses were run for 1883-2018, 1992-2018, 2010-11 and 2013-14. Results (fig 5A) show highly consistent alongshore retreat from 1883 to 2018 averaging 3.74 m a^{-1}; a similarly consistent slightly higher retreat occurs 1992-2018 (average 4.45 m a^{-1}). NSM between 1883 and 2018 is 4-600 m. The striking observation is the shoreline change that occurs at the event scale, reaching over 20 m in 2010-11. This is 4 times the long-term average. Fig 5B demonstrates inter-annual pulsed nature of cliff retreat using EA summer cross-shore profile SWD3 (SO14).

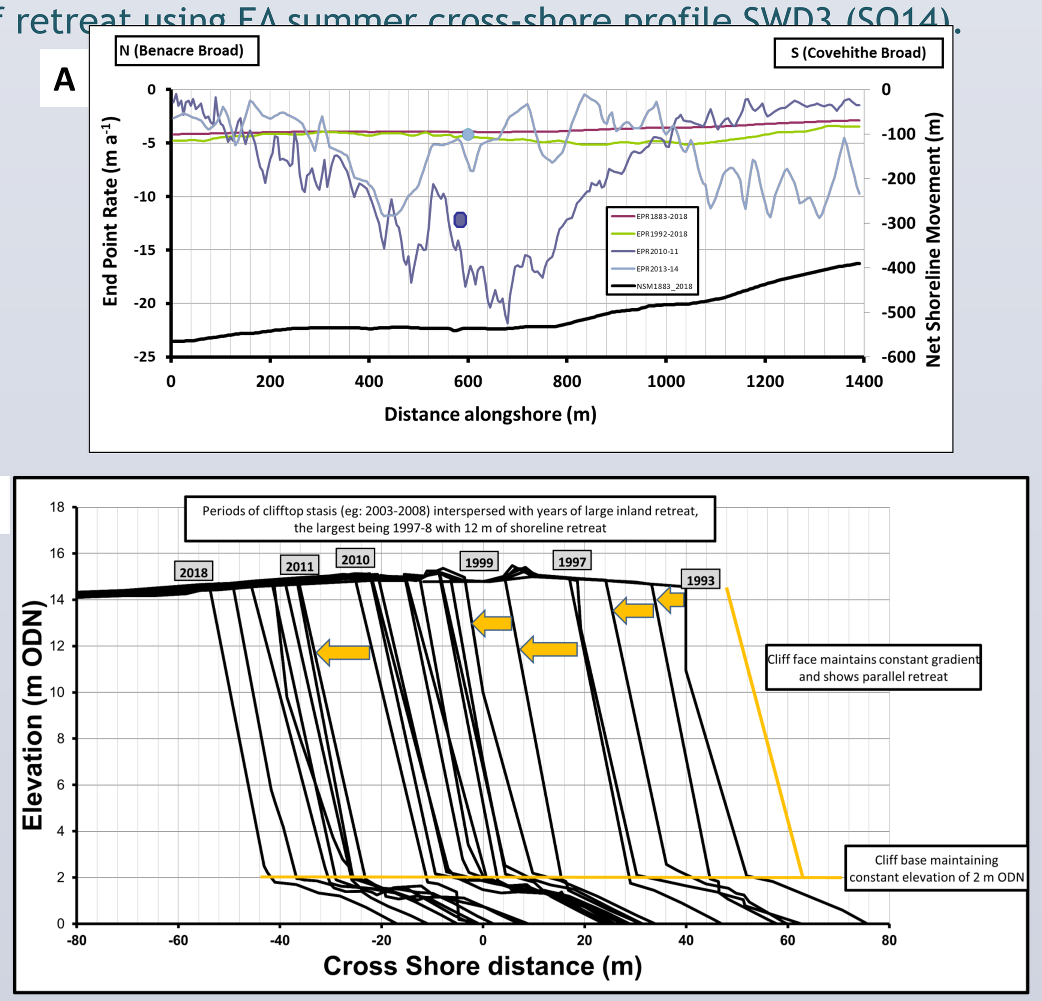

Figure 5: A) Timescale dependent EPR; B) Annual cliff retreat (summer – summer; 1993-2018) showing high shoreline retreat and clifftop stasis

Results: shoreline change and forcing events

From figure 5 we see the event-scale signal in the annual cross-shore profiles. The fact that there are years of stasis in the cliff retreat record suggests that large retreat signals are likely to be caused by single events or clusters of storms within a short period. Figure 6 shows that analysing a single cross-shore profile (SWD3) paints a broadly representative picture of change in the whole clifftop alongshore. Years of <4 m retreat can be separated from years having 4 – 7 m of retreat. But a category can also be defined where retreat is >7 m, as was the case in 2010-11.

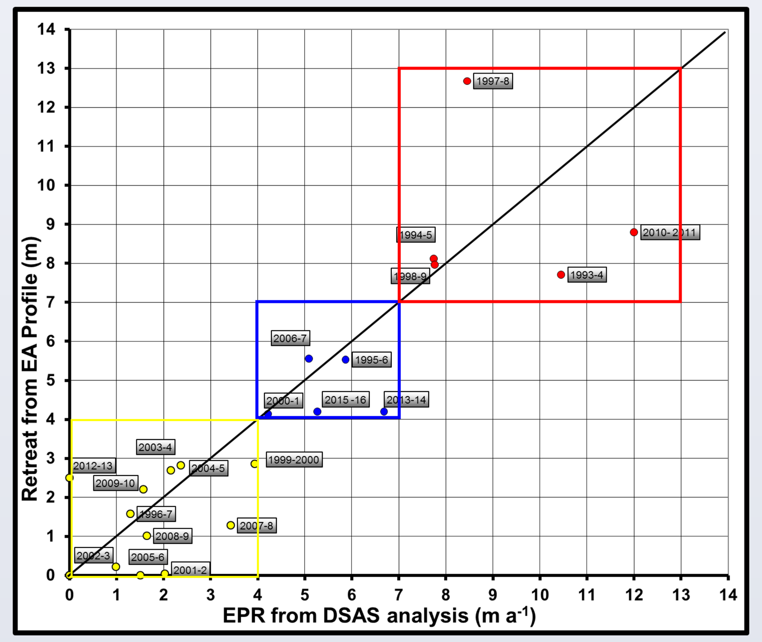

Figure 6: Clifftop retreat at cross-shore profile SWD3 and retreat of the whole cliffline found from DSAS analysis

Southwold Approaches waverider, operational from 6 October 2006, provides data for significant wave height and direction at 30 minute intervals. This enables some forcing context to be defined for 2010-11 which would not have been possible for previous years of high cliff retreat. Context for the 2013-14 event is provided in Spencer et al. (2015). Figure 7 is a timeseries covering the period for which we have annual cliff retreat records showing wind speeds >30 knots (15.4 m s-1) at Gorelston. Seasonality is clearly evident with clustering during winter months. By matching the wave record from 2006 the magnitude and persistence of a storm on 1 December 2010 is evident. The red dots represent onshore winds. Since wave records began (12 years) there have been just 36 hours of onshore waves >4 m, on 7 occasions. Other occurrences of waves peaking above 4 m have generally involved offshore/alongshore directions apart from 3 March 2009, where there is limited persistence compared with 1 December 2010.

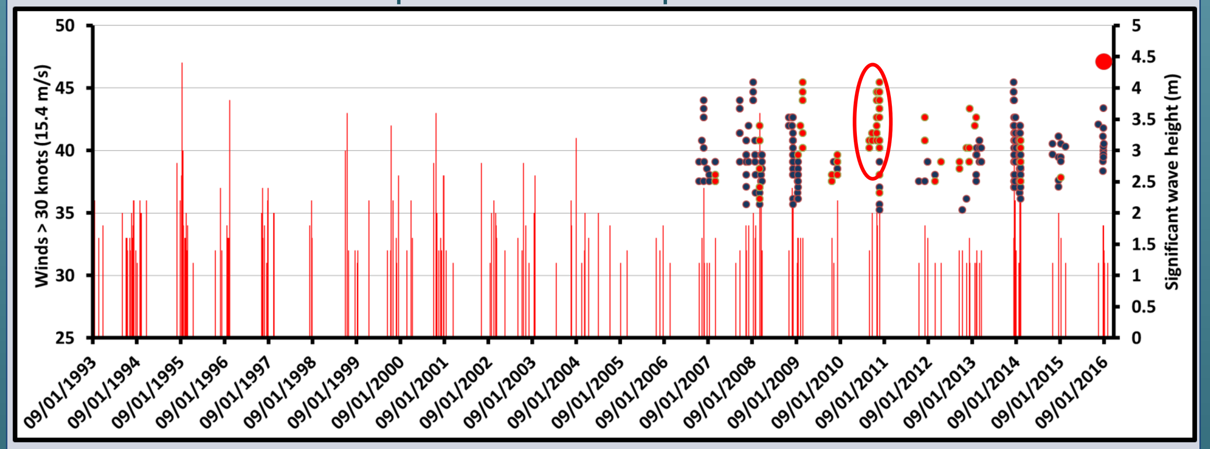

Figure 7: Gorleston wind record highlighting winds > 30 knots. Associated onshore (red dots) and offshore (blue dots) waves. Waves from 1 March 2018 are also shown as large red dot. 1 December 2010 is highlighted

Discussion

New methodologies using Earth Observation data to examine clifftop retreat have enabled us to isolate storm magnitude and direction for individual events that generate high retreat rates. Two events in particular can be discussed in the light of continental-scale synoptic conditions. The 1 December 2010 event saw a significantly developed high pressure system located over western Europe generating persistent strong easterly winds delivering large waves directly onto the cliff base (fig 8A). Such events can be linked to higher level Sudden Stratospheric Warming (SSW) which interferes with the jet stream and typically generates high pressure over Europe and Scandinavia. The second meteorological synopsis on 5 December 2013 involved a low pressure system propagating through the North Sea Basin, where elevated water levels (surges) resulted. These high water levels set the baseline for wave action higher up the cliff. So although waves were alongshore they still undermined the cliff base (fig 8B).

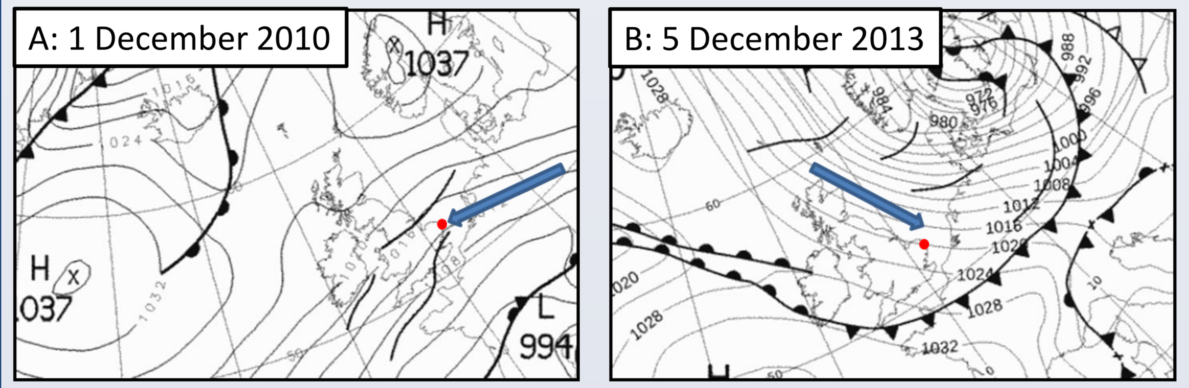

Figure 8: Synoptic meteorological charts from events with cliff top retreat showing prevailing wind directions and location of the study site (red dot)

Retreating soft rock cliffs perform a wider ecosystem service in being the engine-room of sediment delivery to the nearshore region. LiDAR data now available can quantify associated sediment volume release for individual events. Hence in 2010-11 and 2013 -14, 96 m m^{-3} and 48 m m^{-3} were released respectively. Previous assessments of sediment release have tended to focus on long-term averages, but studies of annual cliff retreat show the highly pulsed nature of this process.

Conclusions

Annual retreat in soft rock cliffs is highly variable and can be up to 20 m, compared to a long-term average of 2 - 5 m a^{-1}. Annual analyses for a single point profile as well as along the entire clifftop suggest that single profiles can provide reasonable estimates of average retreat in the cliff section, even if they cannot show alongshore variability in retreat. Clifftop stasis in some years suggests that large retreat is probably due to a single event or cluster of events. We identify two events that have generated recent large cliff retreat, in 2010 and 2013, and shown the former to be wave-limited and the latter to be water level limited (surge). Different regional-scale meteorological synoptic scenarios can lead to high cliff retreat; one is easterly dominated (waves) and the other westerly dominated (water levels). Both have high level impacts on sediment delivery to the nearshore region, important to take into consideration for future management planning under changing storminess and sea level rise.

Acknowledgements

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Met Office (2019): MIDAS Open: UK mean wind data, v201901.

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