NEW UNDERSTANDING OF A COASTAL EROSION HOTSPOT IN A BIMODEL WAVE CLIMATE

JON J. WILLIAMS[1], JOHN ATKINSON[2], DARREN M. PRICE[3], LUCIANA S. ESTEVES[2], SHIRIN S. COSTA[3]

1. *Mott MacDonald, Mott MacDonald House, 8-10 Sydenham Road, Croydon CRO 2EE, UK. jon.williams@mottmac.com.*
2. *University of Bournemouth, Talbot Campus, Fern Barrow, Poole, BH12 5BB, UK. lesteves@bournemouth.ac.uk and atkinsonj@bournemouth.ac.uk.*
3. *Mott MacDonald, Ground Floor, Royal Liver Building, Pier Head, Liverpool L3 1JH, UK. darren.price@mottmac.com and shirin.costa@mottmac.com.*

Abstract: In previous studies addressing coastal erosion *hotspots*, evidence is presented to demonstrate that geology and nearshore seabed features can exert control on local beach dynamics. In this study, an episodic coastal erosion *hotspot* at Thorpeness, UK is examined. Antecedent wave conditions and changes in incident wave characteristics resulting from interaction with the seabed geology and/or temporal changes in nearshore bathymetry are measured and modelled. Observations of changing sea bed features derived from radar measurements and results from numerical modelling demonstrate links between nearshore bathymetry and beach erosion events. The study examines also the conditions frequently experienced at the study site whereby persistent waves from a narrow sector reduce beach levels and modify the nearshore bathymetry in such a way that the impacts from storms from an opposing direction are larger than would normally be the case.

Introduction

In studies addressing coastal erosion *hotspots* (i.e. sections of coast that exhibit significantly higher rates of erosion than adjacent areas), McNinch (2004), List *et al*., (2006) and Noujas and Thomas (2015) present evidence to show that geology and nearshore features can exert control on local beach dynamics. Looking further at these controls, this study considers the coastline at Thorpeness, UK (Figure 1) where, episodic storm events result in an erosion *hotspot* spanning a 300m length of the shoreline. Historically, the location of the *hotspot* has varied alongshore, and available evidence indicates that the antecedent wave conditions and wave focus effects attributable to the local seabed geology and/or temporal changes in nearshore bathymetry play a role in determining both the location and the magnitude of erosion.

In this study, evidence of significant changes occurring in the nearshore bathymetry over relatively short periods has been obtained through the analysis of X-band radar images of waves on the sea surface. In addition, results from a numerical modelling study examining coastal responses to temporal changes in the dominant wave direction are used to show how bathymetric changes affect coastal morphology. Specifically, attention is given to the conditions frequently experienced at the site where persistent waves from a narrow sector reduce beach levels and modify the nearshore bathymetry in such a way that subsequent storm impacts from opposing wave directions are larger than would normally be the case.

Study area

The study area, characterised by a mixed sand and gravel beach (MSGB) is located on the coast of Suffolk, UK, and extends between Thorpeness village in the south and a cuspate shingle foreland approximately 2km north of the village and known locally as the *Ness* (Figure 1, 52.18°N, 1.61°E). The frontage is backed by 10m high Pleistocene cliffs composed of weakly cemented and poorly sorted coarse sands (Figure 1b). The offshore bathymetry shows several distinct features including the Sizewell bank to the north of the *Ness*, and underwater ridges of more resistant Coralline Crag that emerge in the nearshore and extend around 3km seaward with a SW to NE orientation (Figure 2a, b).

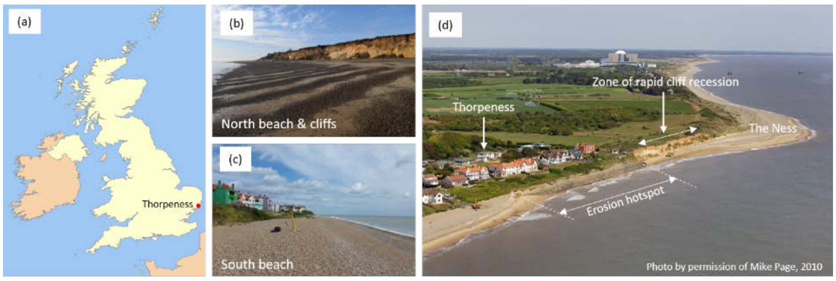

Figure 1. Location of the study area in the UK (a), illustrations of the beach settings at north (b) and south (c) and the erosion *hotspot* in 2010 (d).

The tide at Thorpeness is semi-diurnal with a peak astronomical range around 2.5m and maximum tide plus surge water levels reaching up to 3.8mOD during storms. It is thought that the bimodal wave climate, characterised offshore by waves from SSW and NNE sectors, gives rise to periodic and highly localised reversals in net alongshore sediment transport at Thorpeness (Burningham & French, 2016). It has been observed also that after refraction, persistent moderate waves from the SSW drive a northwards sediment drift resulting in beach narrowing and drawdown which subsequently makes the beach more vulnerable to storm waves from the NNE (e.g. Figure 1), particularly when the sea bed offshore from the *Ness* is also denuded.

Field observations

Figure 1d shows that in common with historical erosion events, the beaches adjacent to the *hotspot* in 2010 are much less eroded. It is considered that this evidence indicates that local coastal processes give rise to strong alongshore wave energy gradients and local wave focus. Evidence of widespread offshore bathymetric changes to support this view comes from multi-beam surveys conducted in 2014 and 2017 (Figure 2). Specifically, sediment accretion between the two survey dates of the order of 2m is observed offshore from the *Ness* as well as areas of erosion up to 1.5m north and south of the *Ness* (Figure 2c).

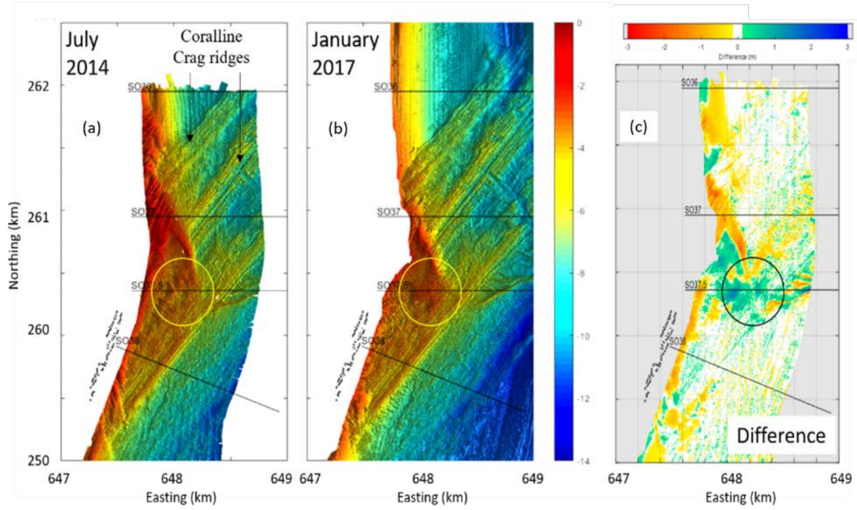

Fig. 2. Multi-beam bathymetric survey data: (a) July 2014; (b) January 2017; and (c) bathymetric changes between surveys (a) and (b).

Investigations of links between nearshore bathymetry and beach responses requires at a minimum bathymetric data on at least a monthly basis and/or pre- and post-storm surveys. As obtaining these data by conventional means is prohibitively expensive and impractical, this study used X-band radar to acquire hourly images of the wave field (Figure 3). These were subsequently processed after selecting the optimum wave conditions for the *wave-to-bathymetry* conversion algorithms (Young *et al*., 1985; Bell, 1999; Hessner *et al*., 2014; Atkinson *et al*., 2018) and bathymetric maps for an area of 3.3 km^2 for the period September 2015 to April 2017 were obtained. Validation of the radar-derived bathymetry using contemporaneous data from the January 2017 multi-beam survey (Figure 2b) confirmed for the first time that the radar-derived bathymetry in pixels approximately 40m by 40m was accurate to ± 0.5m in the vertical (Atkinson *et al*. 2018).

Fig. 3. X-band radar: (a) deployed on 5m tower; and (b) the elevated location on the coast.

Examples of radar-derived bathymetry in Figure 4 show erosion in the nearshore region between October and December 2015, followed by subsequent periods of accretion in June 2016 and January 2017, when the nearshore was observed to be in its most accreted state over the monitoring period. The data show no strong seasonal signal (Atkinson & Esteves 2018), and the nearshore behavior appears to be controlled by changes in the dominant wave direction. There are inter and intra-annual variations in the direction of dominant waves, whereby southerly waves seem to favor deposition in the nearshore.

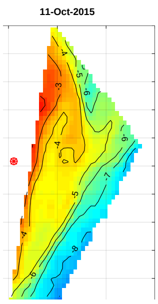

Fig. 4. X-band radar-derived bathymetry of the whole study area showing seasonal variability (red point indicates radar position). Note the changes in the *Ness* bar region.

At a higher temporal resolution, two examples of radar-derived bathymetry that demonstrate a relatively rapid temporal responses of the sea bed to waves are illustrated in Figure 5 and Figure 6. In Figure 5, the spit-like feature (hereafter termed the *Ness* bar) projecting offshore from the *Ness* in a southerly direction is subjected to a wave climate dominated by waves from the NNE between 6 and 28 February 2016. Over that period, the feature is shown to erode, thereby potentially exposing the adjacent shoreline to higher wave energy from the NNE. In contrast, Figure 6 shows sediment accretion on the *Ness* bar during a period of SSW waves between 12 and 23 February 2017. *Ness* bar accretion over 2 weeks has been shown using radar images to provide some shelter to the adjacent coastline from NNE waves.

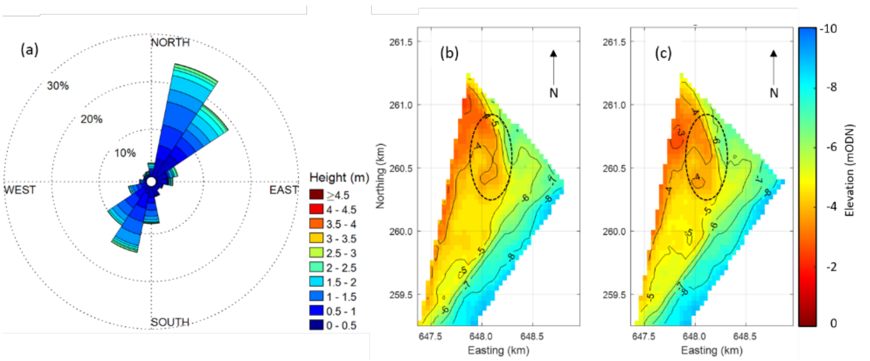

Fig. 5. Radar-derived bathymetric changes during a period of dominant NNE waves between 6 and 28 February 2016: (a) offshore wave rose (West Gabbard buoy); (b) radar-derived bathymetry, 6 February 2016; and (c) radar-derived bathymetry, 28 February 2016.

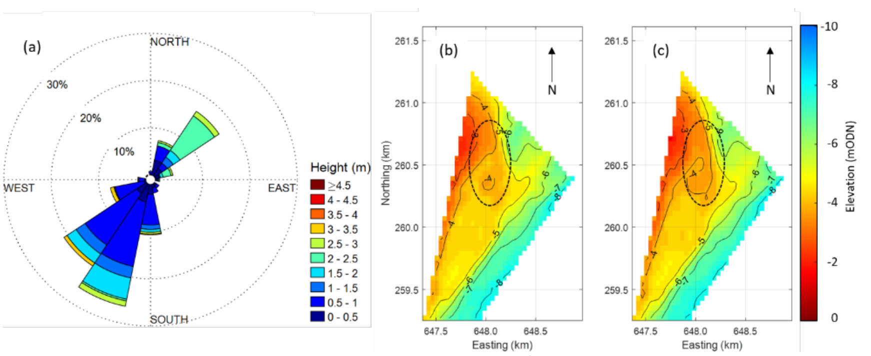

Fig. 6. Radar-derived bathymetric changes during a period of dominant SSW waves between 12 and 23 February 2017: (a) offshore wave rose (West Gabbard buoy); (b) radar-derived bathymetry, 12 February 2017; and (c) radar-derived bathymetry, 23 February 2017.

Modelling

Evidence of relatively rapid bathymetric responses to waves from northern and southern sectors (Figure 5 and 6), and evidence of temporal and spatial changes in breaking wave locations in a zone up to 200m offshore (e.g. Royal Haskoning, 2010), indicate that the nearshore bathymetry along the Thorpeness frontage plays a role in determining the incident wave characteristics and associated beach responses. The evidence suggests also that location of the erosion *hotspot* is modulated by nearshore bathymetry. To investigate how changes in nearshore bathymetry affect the alongshore wave energy distribution and associated beach responses, a modelling study was undertaken using a Coastal Area Model (CAM) comprising the coupled MIKE21 flexible mesh (Figure 7) modelling components HD (hydrodynamics), SW (spectral waves) and ST (sand transport).

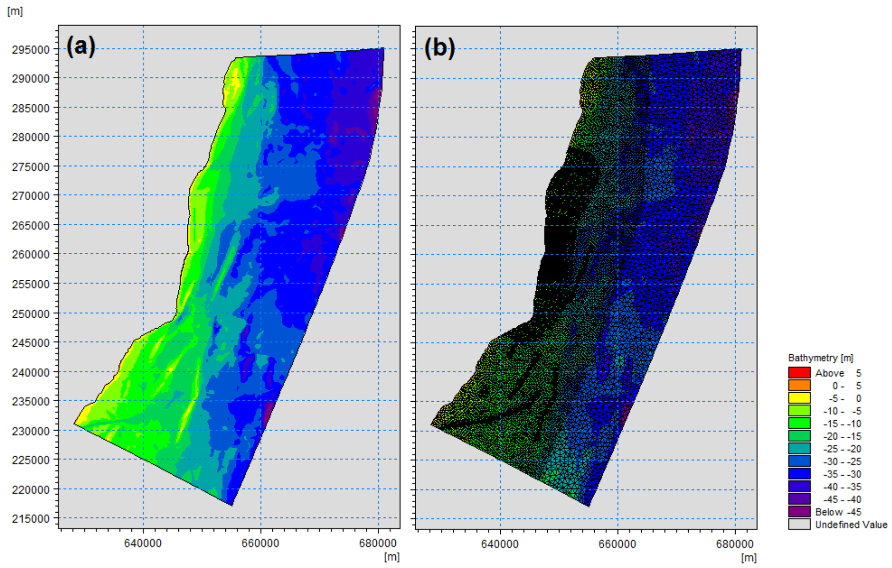

Fig. 7. MIKE21 CAM model setup showing: (a) composite bathymetry (2014); and (b) flexible mesh and boundaries.

Model setup

Bathymetry used to build the CAM was provided by Seazone, two detailed multibeam surveys in 2014 and 2017, beach transects and lidar (Figure 7a shows 2014 composite bathymetry). The model flexible mesh and boundaries are shown in Figure 7b. Tidal boundary conditions were defined by the DHI Global model and the model was forced using hindcast offshore waves and wind data from the NOAA WaveWatch III model. The model was calibrated for water level using data from the Class A gauges at Lowestoft and Harwich and was validated using data from a pressure sensor deployed close to the field site. The SW model was calibrated using data from the West Gabbard buoy and validated with data from the Sizewell wave buoy. In all cases, the MIKE21 CAM performance conformed with the key model performance metrics defined by

Williams and Esteves (2017).

The CAM was run for idealised wave conditions and several historical storm events. To investigate potential causes of the localised erosion, the model was run using 2014 and 2017 bathymetry for a northerly storm occurring on 13-14 January 2017 (Hs = 1.6m, Tp = 15s, direction = 45 deg. N at the Sizewell buoy) and southerly waves on 31 March 2010 (Hs = 2.1m, Tp = 7s, direction = 175 deg. N at the Sizewell buoy).

Results

In both cases difference plots in Figure 8 show that among other differences, the wave power along the frontage between Thorpeness and the *Ness* is larger for NNE and southerly waves on the 2014 bathymetry. These results indicate that: (a) the nature of the offshore bathymetry influences the incident wave energy, and (b) changes in offshore bathymetry occurring in a relatively short period (2.5 years) can affect significantly wave energy along the shoreline.

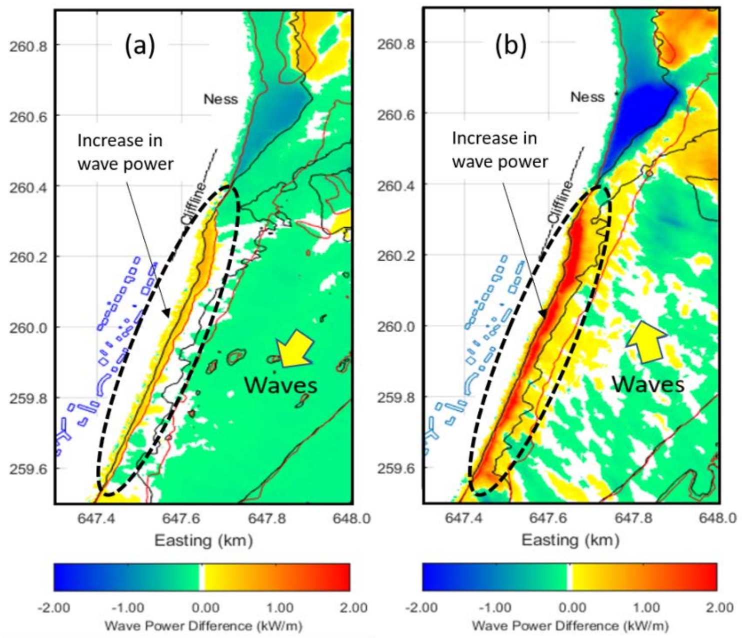

Fig. 8. MIKE21 CAM model results showing wave power differences between 2014 and 2017 bathymetry for: (a) NNE waves on 13-14 January 2017; and (b) southerly waves, 31 March 2010

The results shown in Figure 8 raise questions regarding the time and wave conditions necessary to modify the nearshore bathymetry in such a way that it influences the wave energy reaching the coast, and by implication, the beach behavior. While the data necessary to simulate actual short-term nearshore erosion are lacking, a relatively simple modelling exercise can provide insights on how the 2017 bathymetry and beach topography respond to different wave forcing conditions.

Taking the 2017 bathymetry as the starting point, the CAM was run for constant wave conditions typifying northerly and southerly directions for a 15-day spring-neap tidal period (Table 1). A 10X speed up factor was used for bed morphology to exaggerate and make easily quantifiable any bathymetric changes predicted by the model (Figure 9).

Table 1. Waves defined in CAM morphological runs for a neap-spring-neap tidal cycle

			Offshore wave and conditions				
Model run	**Start date**	**End date**	**Hs (m)**	**Tp (s)**	**Wave direction (deg. N)**	**Wind speed (m/s)**	**Wind direction (deg. N)**
1	1/4/2010	15/4/2010	2.38	7.88	7.4	15.0	7.4
2	1/4/2010	15/4/2010	1.45	4.67	195.4	15.0	195.4

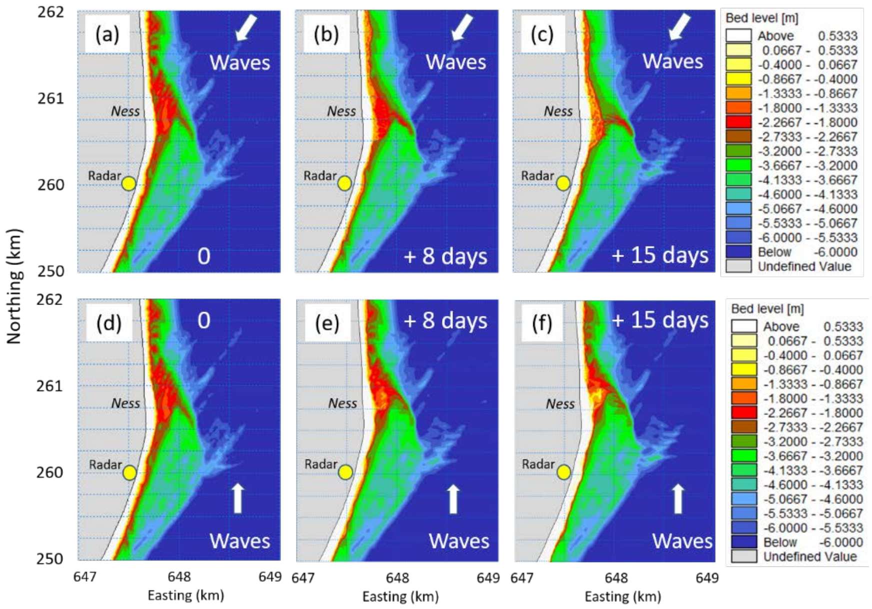

Fig. 9. Model predictions of coastal responses to northerly waves offshore (a-c) and southern waves (d-f) showing shoreline changes, the *Ness* bar and other subaerial feature after 8 and 15 days.

The northerly waves result in erosion of the northern face of the *Ness* bar (Figure 9c). At the same time, there is widespread modest accretion to the south of the *Ness* and beach drawdown north and south of the *Ness*. Despite the noticeable erosion, the southern extent of the *Ness* bar remains approximately the same. In the case of the southern waves, Figure 9f shows pronounced erosion of the *Ness* bar after 15 days along with more severe beach drawdown along the Thorpeness frontage. Although north of the *Ness* the shore line shows some evidence of accretion, beaches are largely unaffected by the wave action due to the shelter provided by this coastal feature.

Differences in patterns and magnitudes of erosion and accretion for northerly (Figure 9 a-c) and southerly wave (Figure 9 d-f) simulations are shown in Figure 10. For reference, the -3mOD contour at the start of the model simulation is shown by the dashed black line. For the northerly wave case (Figure 10a), erosion of around 1.5m is predicted immediately offshore from the northern face of the Ness with accretion on the Ness itself. There is also accretion on the *Ness* bar.

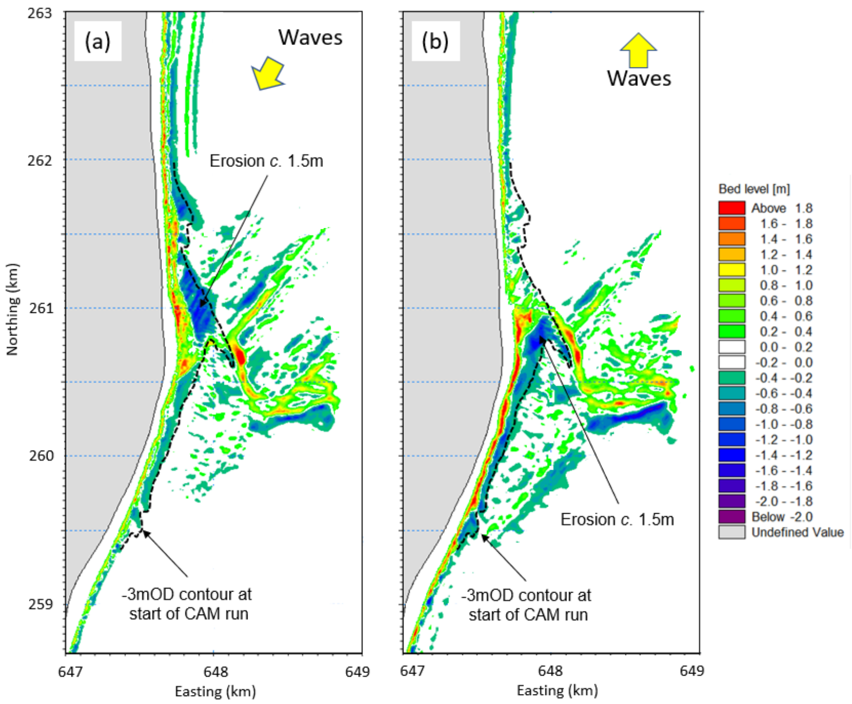

Fig. 10. Predicted bathymetric changes from the CAM for: (a) northerly waves; and (b) southerly waves after a 15-day simulation. Note: red and blue denote accretion and erosion, respectively.

For the southerly wave case (Figure 10b), erosion is predicted on the southern side of the *Ness* and the *Ness* bar rotates anti-clockwise and shift northwards. Erosion of the nearshore region south of the *Ness* and corresponding accretion on the beach is clear.

To demonstrate how nearshore bathymetry plays a role in defining the distribution of wave energy along the shoreline, Figure 11 shows the predicted effect of the *Ness* bar on the alongshore wave power. In Case A, the *Ness* bar in the CAM is in the well-developed configuration measured in 2017 (Figure 2b; Figure 9a). In Case B, the *Ness* bar in the CAM is in an eroded condition (Figure 9f). In both cases, the shoreline is exposed to waves from the NNE (Hs = 2.5m, Tp = 8s). In the area between Thorpeness and the *Ness*, Case B shows higher wave power than case A. In Case B, the maximum wave power is located approximately 100m north of the radar site and decreases towards the *Ness* and towards Thorpeness to reach wave power values like those in Case A. The wave module of the CAM indicates that the *c*. 40% increase in wave power at this location is associated with wave refraction (focus) around the *Ness* bar and a reduction of wave energy dissipation in the deeper water between the *Ness* bar and the shoreline.

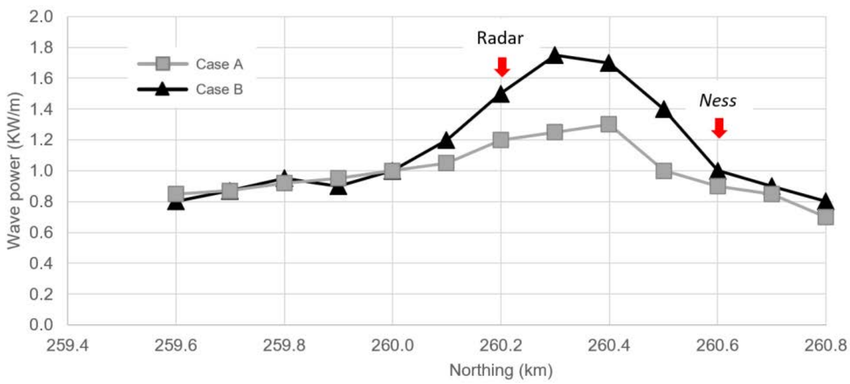

Fig. 11. Alongshore changes in wave power for Case A and B showing the wave focus effect attributable to the *Ness* bar.

Regular beach profile measurements along the frontage since the beginning of 2015 (e.g. Atkinson *et al.*, 2017) have shown higher rate of beach erosion between Thorpeness village and the *Ness*. Furthermore, erosion of the soft cliffs north of the radar site has exceeded 6m in the winters of 2016-2017 and 2017-2018, almost three times previous values. At the same time, erosion at the 2010 *hotspot* area has reduced suggesting that the focus of wave energy has shifted northwards since 2016 in the manner suggested by modelling results. This is entirely consistent with the historical record which shows regions of intense episodic erosion occurring at different locations along the frontage and confined to relatively short sections.

Conclusions

Although the present work offers an explanation for the shifting erosion *hotspot* at Thorpeness, it is considered likely that other coastal processes play a role in determining the shoreline morphodynamics. An analysis of the incident wave climate using wave persistence indices by Atkinson *et al.*, (2017) has highlighted the importance of antecedent conditions in conditioning the beach and increasing its susceptibility to storm impacts. As the modeling has shown, extended periods of moderate southerly waves erode the nearshore regions and build a berm on the beach south of the *Ness* and contributes to erosion and anticlockwise rotation of the *Ness* bar. Both these coastal responses contribute to making subsequent storm waves from the northern sector more effective with regards to erosion that would be the case if the *Ness* bar were better developed.

Atkinson and Esteves (2018) also show that Thorpeness beach responses to the same offshore wave conditions can differ significantly along different sections of the shoreline. This alongshore variability was attributed to exposure to bimodal wave directions, possible divergence of alongshore transport direction, and localised settings, such as variations in the sand to gravel ratio and the presence of coastal protection measures or, most likely, a combination of these factors.

Local areas of intense erosion continue to present coastal management problems at Thorpeness. Temporary buried geo-bag sea defenses currently protecting properties from erosion at the site of the 2010 erosion *hotspot*, remain vulnerable to damage should the *hotspot* again shift southwards from its present location. A combination of modelling and monitoring of the nearshore bathymetry may provide an early warning of conditions that precede episodic erosion events and buy some time for pro-active interventions aimed at minimising future storm impacts.

Acknowledgements

The generous support for the project by Mott MacDonald Ltd (MML) and Suffolk Coastal District Council (SCDC) is gratefully acknowledged. The PhD studentship of John Atkinson is provided by Bournemouth University with additional contributions from MML and SCDC.

References

Atkinson J., Esteves L.S., Williams J.J., Bell P.S., McCann, D., (2017). "Monitoring nearshore processes and understanding significant coastal change using X-band radar". In: Aagaard, T., Deigaard, R. & Fuhrman, D., (Eds.), Coastal Dynamics, 12-16 June 2017, Helsingør, Denmark, 1506-1517.

Atkinson, J., Esteves, L.S., Williams, J.J., McCann, D. & Bell, P.S., (2018). "The Application of X-band radar for characterisation of nearshore dynamics on a mixed sand and gravel beach". *Journal of Coastal Research*, SI 85, 281–285

Atkinson, J. and Esteves, L., (2018). "Alongshore Variability in the Response of a Mixed Sand and Gravel Beach to Bimodal Wave Direction". *Geosciences*, 8 (12).

Atkinson, J.; Esteves, L.S.; Williams, J.W.; McCann D.L., and Bell, P.S., (2018). "The application of X-band radar for characterisation of nearshore dynamics on a mixed sand and gravel beach". *Journal of Coastal Research*, Special Issue 85, 281-285.

Bell, P. S., (1999). "Shallow water bathymetry derived from an analysis of X-band marine radar images of waves". *Coastal Engineering*, 37 (3–4), 513–527.

Burningham, H., and French, J. (2016). "*Shoreline – Shoreface Dynamics on the Suffolk Coast*". The Crown Estate, 117 pages. ISBN: 978-1-906410-76-6.

Esteves, L. S, Williams, J. J. & Bell, P.S., (2016). "X-Com, a tool to support coastal management decisions using X-band radar data". International Coastal Symposium 2016, 6 – 11 March 2016, Sydney, Australia, *Journal of Coastal Research*, Special Issue, 8pp.

Hessner, K., Reichert, K., Nieto Borge, J. C., Stevens, C. & Smith, M., (2014). "High-resolution X-band radar measurements of currents, bathymetry and sea state in highly inhomogeneous coastal areas". *Ocean Dynamics*, 64, 989-998.

List, J. H., Farris, A. S. & Sullivan, C. (2006). "Reversing storm hotspots on sandy beaches: Spatial and temporal characteristics". *Marine Geology*, 226, 261-279.

McNinch, J. E. (2004). "Geologic control in the nearshore: shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA". *Marine Geology*, 211, 121-141.

Noujas, V. and Thomas, K. V. (2015) "Erosion hotspots along southwest coast of India", *Aquatic Procedia*, 4, 548-555, doi:10.1016/j.aqpro.2015.02.071

Royal Haskoning (2010). *Thorpeness Erosion Response Works*. Stage 1 Report for Suffolk Coastal District Council, 9W2244/R/303906/PBor, 84pp.

Williams, J. J. and Esteves, L. S. (2017) "Guidance on Setup, Calibration, and Validation of Hydrodynamic, Wave, and Sediment Models for Shelf Seas and Estuaries". *Advances in Civil Engineering*, Article ID 5251902, 25 pages, https://doi.org/10.1155/2017/5251902.

Williams J.J., Esteves L.S. & Atkinson J., (2017). "X-band radar system to support coastal management decisions. In: *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, 2017: 1179-1185.

Young, I.R., Rosenthal, W., Ziemer, F., (1985). "A three-dimensional analysis of marine radar images for the determination of ocean wave directionality and surface currents". *Journal Geophysical Research*. (90), 1049–1059.