MODELLING LONG TERM IMPLICATION OF CLIMATE CHANGE PROJECTION ON SHORE MORPHOLOGY OF NORTH NORFOLK, UK, COMBINING TOMAWAC AND SCAPE

Nicolas Chini[1], Peter Stansby[1], Mike Walkden[2], Jim Hall[3], Judith Wolf[4], Jason Lowe[5], and Robert Nicholls[6]

Assessment of nearshore response to climatic change is an important issue for coastal management. To predict potential effects of climate change, a framework of numerical models has been implemented which enables the downscaling of global projections to an eroding coastline, based on TOMAWAC for inshore wave propagation input into SCAPE for shoreline modelling. With this framework, components of which have already been calibrated and validated, a set of consistent global climate change projections is used to estimate the future evolution of an un-engineered coastline. The response of the shoreline is sensitive to the future scenarios, underlying the need for long term large scale offshore conditions to be included in the prediction of non-stationary processes.

Keywords: coastal morphology, climate change, numerical model downscaling

INTRODUCTION

Shoreline management requires both nearshore and regional hydrodynamic conditions at a large temporal scale in order to design schemes to protect socially, economically or environmentally valuable areas along a vulnerable coastline. The need for nearshore conditions, such as wave heights or water levels, is obvious since these parameters directly affect the area of interest. Information at a regional scale should also be taken into account as it provides details about longshore sediment transport, affecting beach volumes, and inshore wave transformation leading to modification in nearshore wave climate. Moreover, these local and regional data should cover a large temporal span in order to allow statistical analysis and assess extreme values. Including the variability induced by climate change, the temporal span should be enough large to incorporate the presence of non stationary processes, such as sea level rise or change in storminess or in storm tracks. Although forecasting future climate is a difficult task due to the level of uncertainties, the demand for quantified prediction is continuously increasing.

To tackle the issue of spatial and temporal scale, deterministic numerical models are necessary tools. Reliability of continental shelf models, solving the depth-averaged shallow-water equations, has increased over the years and hindcast models are in statistical agreement with observations along the UK coastline (Horsburgh and Wilson, 2007). These models were used to estimate the effect of sea level rise and climate change scenarios on water level residuals in the North Sea (Lowe and Gregory, 2005). Offshore wave parameters are now widely estimated using models solving the wave action conservation equation including the effects of wind-wave generation, white-capping and wave-wave interactions. Closer to the coast where water is shallower, other processes should be included to model inshore wave transformation such as bathymetric refraction, wave breaking, shoaling, bottom friction and variable water depths due to tides and/or surges. Development of numerical methods and increasing computer power have enabled reduction of computational time and increasing spatial resolution. The simulated water elevations and waves can be then used to drive morphological models and to assess therefore shoreline position in the future (Leake et al., 2008).

An integrated framework of numerical models has been developed by the Tyndall Centre for Climate Change Research (Nicholls et al., 2008a; Mokrech et al., 2009), in order to downscale global climate scenarios on to a coastline subjected both to erosion and flooding. The framework is applied to the coastline of East Anglia (UK) and it is used to study the effects of several shoreline management policies assuming different sea level rise and wave climate scenarios (Dawson et al., 2009). Dependence of flood risk on the erosive state of adjacent cliffs is described, highlighting the complex coastal management problem of mitigating at the same time erosion and coastal flooding risks. The framework is able to represent the dominant interactions that determine the long term evolution of this coastline, and translate numerical results into information for stakeholders. Dickson et al. (2007) show that sediment transport and coastline erosion off East Anglia are sensitive to wave directionality and

Tyndall Centre for Climate Change Research at [1]Manchester University, [2]Royal Haskoning, [3] Newcastle University, [4]National Oceanography Centre, [5]Hadley Centre, [6]Southampton University

rising sea levels. This latter analysis was performed using one wave climate estimated from 23 years of historical wind data (HR Wallingford, 2002). Sensitivity to wave directionality is performed by an arbitrary shift of offshore wave direction. The aim of the present paper is to revisit this sensitivity analysis, using the UKCP09 projections (Lowe et al., 2009) which predict the UK shelf seas response to three different green-house gas emission scenarios.

After introducing the area of interest in the first section, details about the downscaling procedure are provided. Offshore changes in wave conditions due climatic scenarios are then discussed in a third section and their implication for longshore sediment transport and coastal erosion are finally presented.

STUDY AREA

The study site is a 100km long coastal domain located off East Anglia, UK, within the Southern North Sea (Fig. 1). The coastline is mainly formed by soft cliffs, from Sheringham to Happisburgh. Further south of Happisburgh; low lying coast is protected by sandy dunes. This area has a complex tidal pattern: mesotidal at Cromer, and microtidal at Lowestoft. Tidal range for spring tides varies from 3m in the North to 1.6m in the South of the domain. The area is subjected to surges generated in the North Sea, with a 50-year return level of 2.36m±0.24 at Lowestoft (Flather et al., 1998). Wave data have been collected from 07/12/1985 to 30/06/1987 offshore of Cromer at a 31m mean water depth (Clayson and Ewing, 1988). Waves from the North are the most common. Average significant wave height is below 1m. The upper part of the continental shelf off the area of interest is also characterised by the presence of large-scale seabed features, including tidal sand banks. The complex pattern of tidal sand banks is taken into account since it acts as natural coastal defence by dissipating offshore wave energy propagating towards the shore (Stansby et al., 2006). Cliff recession is also dependent on the volume of sand available on the beach. The latter is modified by the longshore drift which is firstly assumed to be only driven by waves. The longshore sediment transport along this coastline is in a westerly direction North of Cromer and is directed towards the South, south of Cromer (Vincent, 1979). There is a significant exchange of sediment between the coast and the nearshore banks at Winterton Ness, although this process is not well understood.

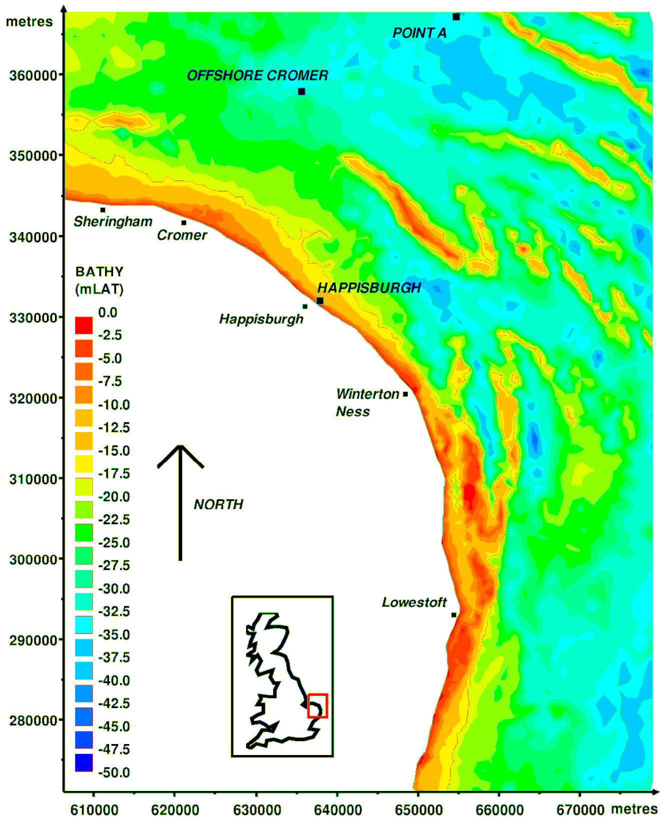

Figure 1. Map showing the bathymetry of the upper part of continental shelf off the study area, and its localisation on the UK coastline.

METHODOLOGY

Modelling strategy

Along the coastline from Sheringham to Winterton Ness, the morphological model SCAPE is used to investigate long-term longshore sediment transport and both cliff and platform recession (Walkden and Hall, 2005). The model is driven by nearshore wave parameters (significant wave height, mean wave period and mean wave direction) and water levels. Longshore sediment transport is computed using the CERC formulation (SPM, 1984). Linear wave theory is assumed for propagation and breaking is said to occur when the ratio of significant wave height to water depth is 0.6. An empirical cross shore sediment transport formulation is used, based on the results by Nairn and Southgate (1993). Cliff and platform erosion rate is computed using an erosion shape function. Beach grade eroded material settles on the beach, while silts and clays are lost to suspension. Eventually, the effect of shore parallel coastal structures and groynes can be included in the simulation. Calibration and validation of the model is presented by Dickson et al., 2007. In the present study, any human-designed structures are not considered, in order to analyse the behaviour of an un-engineered coastline to changes in sea level and in nearshore wave climate.

Nearshore wave climate provided to SCAPE is computed here using a methodology developed by Chini et al. (2010). This methodology, based on setting up of a look-up table using the wave model TOMAWAC (Benoit et al., 1996), permits fast estimation of wave transfer from deep to shallow waters including the effects of water depth variation, either due to tides, surges or sea level rise, wave refraction by bathymetry, wave shoaling, wave energy dissipation by bottom friction and bathymetric wave breaking. Nearshore wave measurements are available off Happisburgh, at 14m water depth, and are used to validate this methodology at a nearshore location. Offshore wave conditions are provided by the ANEMOC database (Benoit et al., 2008), hindcast using TOMAWAC with historical wind data from the ERA40 re-analyses. Water elevation are provided by National Oceanography Centre continental shelf model, CS3X (Horsburgh and Wilson, 2007). Results are presented in terms of a Q-Q plot in Fig. 2.

Greenhouse gas emission scenarios are transformed into wave and surge characteristics along the UK coasts using a set of numerical models (Lowe et al., 2009). Leake et al. (2007) show that climate models are in statistical agreement with hindcasts. The smaller model resolution is 12km along the UK coastline. Integrated wave parameters are provided to the TOMAWAC model. Because of the quality of the results provided by the continental shelf model in terms of water depth, a higher resolution along the coastline is not required and surge-tide levels are directly imposed on the SCAPE model.

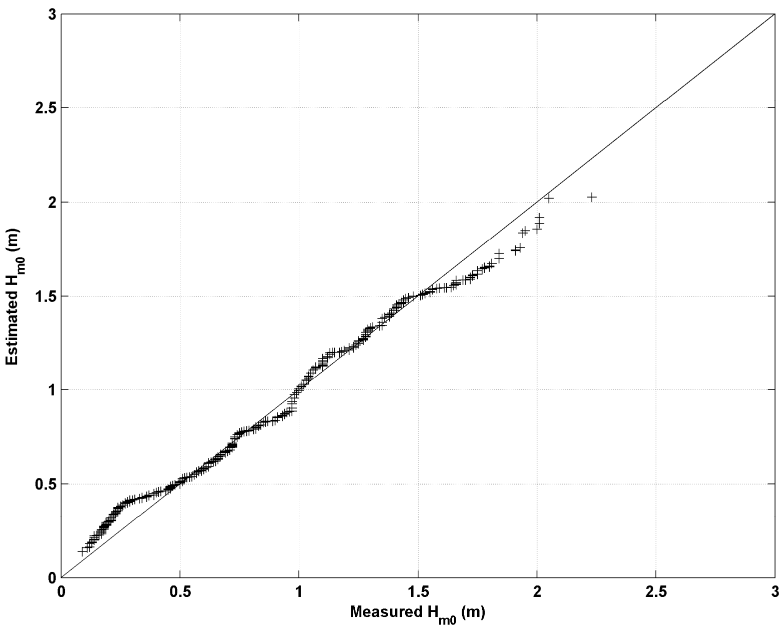

Figure 2. Q-Q plot of significant wave height at Happisburgh

Climate change scenarios

Three different climate change projections from the IPCC AR4 are considered here (Table 1). These projections are based on socio-economic futures leading to different greenhouse gas emission scenarios, representing anthropogenic climate change effects, as explained by Nicholls et al. (2008b).

Table 1. Emissions projections from the IPCC AR4.

	Emissions	Global temperature increase (C), best estimate and likely range	CO_2e by 2100 (ppm by volume)	Global SLR (m) by 2100
A2	High	3.4 (2.0-5.4)	1250	0.23 – 0.51
A1B	Medium	2.8 (1.7-4.4)	880	0.21 – 0.48
B2	Low	2.4 (1.4-3.8)	800	0.20 – 0.43

The global sea level rise (SLR) rates do not include potential ice sheet melting.

The two extreme projections are run for two time slices of 30 years: from 1960 to 1990, representing the baseline climate, and from 2070 to 2100, corresponding to the projected future climate. The intermediate scenario, A1B, is integrated for 140 years from 1960 to 2100.

Nearshore wave climate and SLR scenarios

Un-engineered coastline behaviour is only subjected to waves, tides, surges and SLR. Tides are not expected to be modified during the 21st century, and are thus considered stationary. Waves and surges are two dependant variables. They might change due to change in storminess or storm-tracks. To study the sensitivity of shore morphology to the modifications of loading induced by climate change, the following combinations are considered:

1. No change in SLR and no change in wave climate.
2. Change in SLR and no change in wave climate.
3. No change in SLR and change in wave climate.
4. Change in SLR and change in wave climate.
5. Change in SLR and change in wave climate and effect of SLR on inshore wave transformation.

The wave transformation from offshore to nearshore is performed for each climate change scenario. SLR modifies the water depth and is linearly added to the projected tide-surge elevations (Lowe and Gregory, 2005). The last scenario will show the sensitivity of shoreline evolution to the effect of SLR on the inshore propagation of waves, which might be significant for areas protected by offshore sandbanks. This latter seabed features are assumed fixed in time.

RESULTS

Changes in offshore wave conditions

Offshore waves are first analysed at point A where water depth is 35m (see Fig. 1).

Table 2 presents offshore 50-year return significant wave height computed for the baseline (present-day climate) conditions, the ANEMOC hindcast (Benoit et al., 2008), and for the projections (Leake et al., 2008).

Table 2. Offshore extreme wave heights.

Scenario name	Emissions scenario	50-year return wave height (m)	95% confidence intervals (m)
	Baseline	5.69	5.49 – 6.49
	ANEMOC hindcast	6.25	5.45 – 7.05
A2	High	5.21	4.82 – 5.64
A1B	Medium	6.36	5.72 – 7.07
B2	Low	5.54	5.12 – 6.02

The statistics are estimated fitting the GEV distribution to the annual maximum significant wave height. As mentioned by Leake et al. (2008), only small changes in extreme wave heights are projected. In detail, medium high and low medium scenarios lead to a small decrease in the 50-year return wave height, whereas the medium scenario induces an increase in this statistic. These variations seem to be related with a change in storm tracks (Leake et al., 2008).

Longshore sediment transport is sensitive to change in wave direction. When comparing the different scenarios, some changes are noticeable in offshore wave directionality. Fig. 3 presents the directional occurrence of wave direction for the baseline and the projections. Medium low and medium projections induce small changes in wave direction occurrence. These two scenarios lead to more waves from the North. Projected changes are much more perceptible when considering the medium high scenario. A significant increase in the number of waves from the North and from the South is projected along with a decrease of waves coming from the North East.

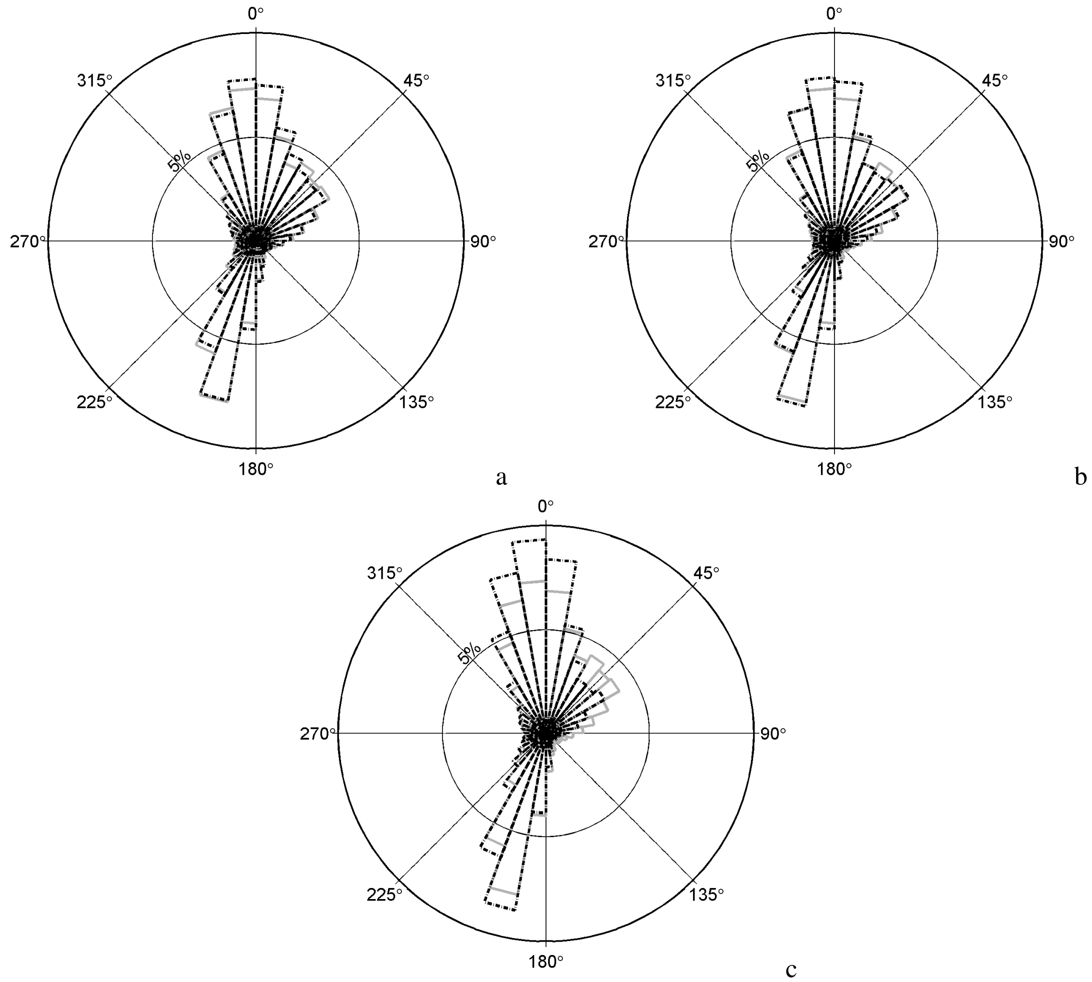

Figure 3. Offshore directional wave occurrence for (a) low medium, (b) medium and (c) high medium projections. Baseline (1960-1990) is represented in grey bars and projections are presented in black dotted bars.

Changes in inshore wave conditions

Fig 4 presents the spatial distribution of the 50-year return significant wave height over the upper part of the continental shelf for the baseline. As the wave propagates towards the shore, the magnitude is reduced. The effect of sandbanks is remarkable as this seabed feature generates a landward shadow area, where the 50-year return significant wave height is reduced. Fig. 5 presents the induced changes in the 50-year return wave heights for the different climate change projections. Low medium and high medium scenarios induce a decrease especially in the southern part of the domain. For the medium scenario, a significant increase in the northern part is noticeable. Along the coastline, only the medium scenario leads to an increase in the estimate of the 50-year return significant wave height.

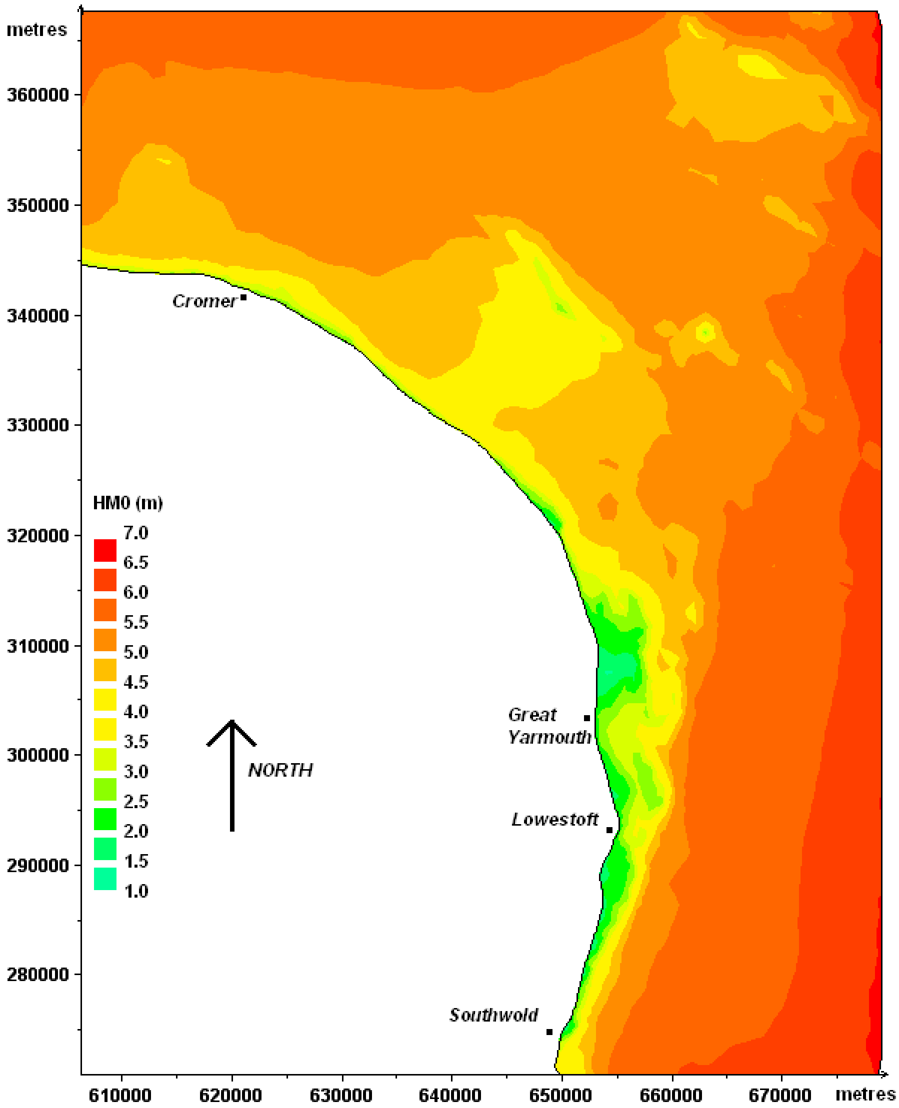

Figure 4. 50-year return significant wave height spatial distribution for the baseline a.

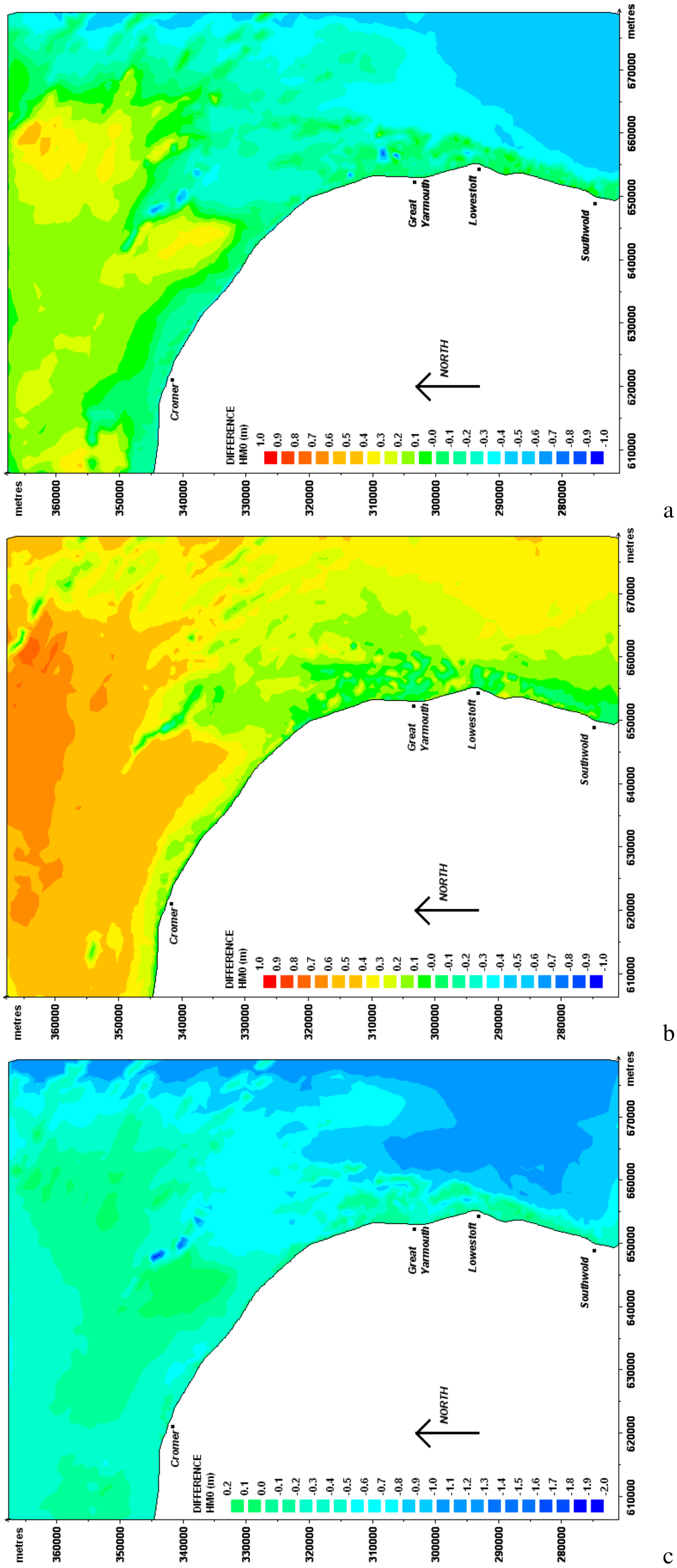

Figure 5. Change in the 50-year return significant wave height for the low medium (a), medium (b) and high medium (c) projections in 2100. Colour scale is modified for panel (c).

Induced changes in shoreline processes due to climatic scenarios

Outputs from SCAPE for the natural behaviour of the shoreline are now discussed. Fig. 6 and Fig. 7 present the results in terms of longshore sediment transport and cliff recession. The sign of the sediment transport rate indicates the direction of the transport. A positive rate means a northward transport. Zero chainage corresponds to Winterton Ness (see Fig. 1).

From the baseline wave climate, the model represents a shift in the sediment transport direction between 40km and 45km. Southward of this shift, the sediment transport increases and reaches a value of 400,000m^3/year around 20km. Cliff recession varies along the coastline. Highest retreat values reach 1.3m/year. Two differences are observable with previous results (Dickson et al., 2007). The highest rate of cliff recession is shifted southward and an increase in cliff recession appears at 10km. Despite these two differences, the new baseline wave climate generated from the climatic model produces similar results to the one presented by Dickson et al. (2007), where historical wave data were used.

Fig. 6 presents the results when modifying the offshore conditions according to climate change projections. The medium low scenario does not change the baseline nearshore processes. Model response to the two other climate projections is different. The high medium scenario shows a significant decrease in the longshore drift in the South and an increase of northward transport; the shape of the cliff recession shows significant change. On the other hand, the medium emission scenario leads to an increase of the longshore sediment transport south 35km, and an increase of 15% in the cliff recession.

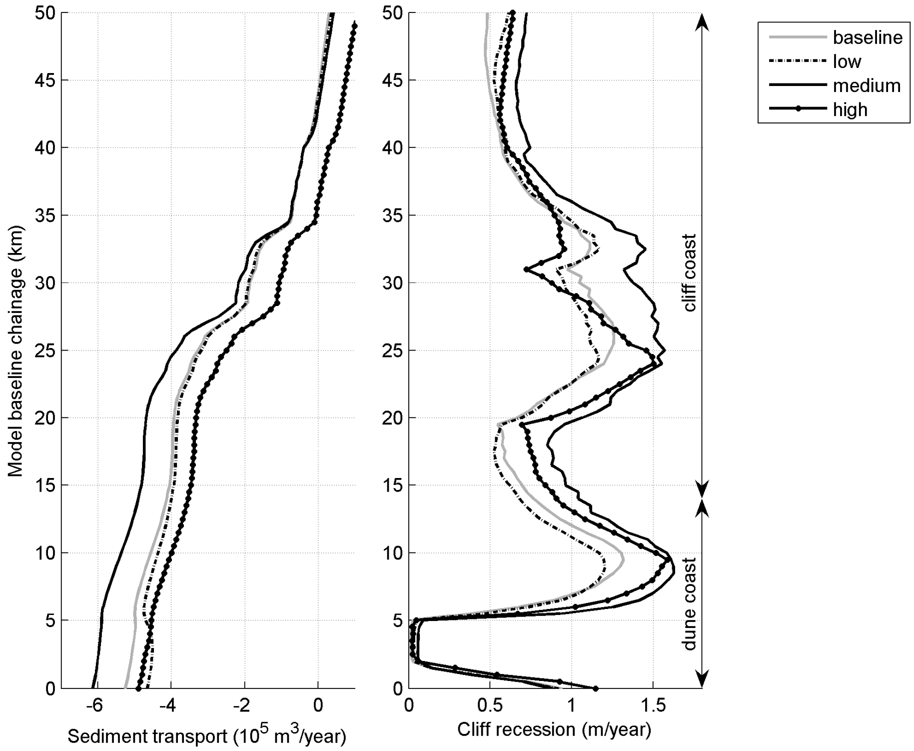

Figure 6. Sediment transport and cliff recession rates induced by the offshore climate scenarios.

Fig. 7 shows the results of the shoreline sensitivity to changes in SLR and wave conditions. We present here the results obtained for the medium emission scenario (see table 1). This SLR rate has a small impact on the sediment transport and shore retreat rates. These rates are more sensitive to a change in the offshore conditions. Adding SLR on the inshore wave transformation does not modify the longshore sediment transport and the cliff recession. However this latter result can be modified if the SLR rate is higher than considered here, since waves will experience higher water depth when propagating towards the shore (Chini et al., 2010).

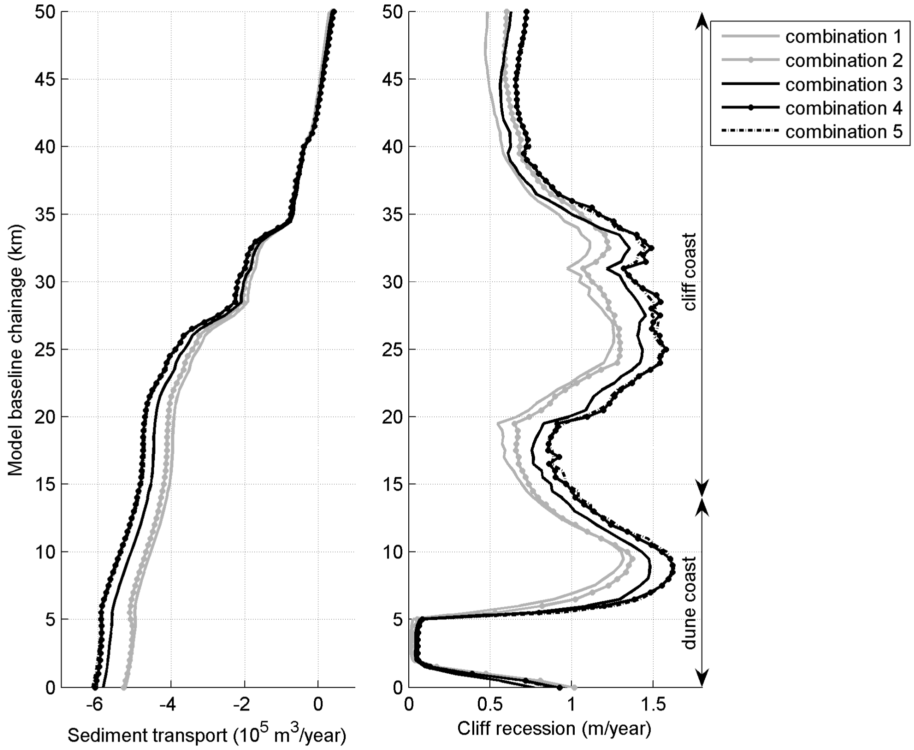

Figure 7. Sediment transport and cliff recession rates induced for combined scenarios of SLR and change in wave climate.

CONCLUSIONS

To transfer the effect of global climatic scenarios on an eroding coastline, a framework of models has been implemented by the Tyndall Centre for Climate Change Research (Nicholls et al., 2008a; Mokrech et al., 2009), based on TOMAWAC for inshore wave propagation input into SCAPE for shoreline modelling. Previous work has calibrated and validated each components of the framework. Here three emissions scenarios are applied on an un-engineered coast. It was shown previously that these scenarios will lead to no significant trend in storm surge increase and to some small changes in wave height and directionality off East Anglia. This result was used to justify stationary wave conditions along the coast. However with these small changes to inputs, application of the modeling framework demonstrates that the shoreline behaves differently from one scenario to another. It is also shown that the system is sensitive to the combination of sea level rise and future wave climate. This latter point deserves further investigation, ideally with a greater number of realisations of future wave climate.

ACKNOWLEDGMENTS

This work was originally funded through the Tyndall Centre for Climate Change Research and contributes to the Coastal Simulator programme led by Professor Robert Nicholls (Southampton University). It now contributes to the Flood Risk Management Research Consortium. The FRMRC is supported by grant EP/F020511/1 from the Engineering and Physical Sciences Research Council, in partnership with the DEFRA/EA Joint Research Programme on Flood and Coastal Defence, UKWIR, OPW (Ireland) and the Rivers Agency (Northern Ireland). Jason Lowe was supported by the Joint DECC and MoD Integrated Climate Programme — (DECC) GA01101, (MoD) CBC/2B/0417_Annex C5 and Defra. Their financial support is gratefully acknowledged. We would also like to acknowledge Gerard Goasguen (CETMEF) for making the ANEMOC dataset available, Kevin Horsburgh (POL) for providing the results from CS3X model driven with ERA-40 reanalysis, and the British Oceanographic Data Centre for field wave records.

REFERENCES

Benoit, M., F. Marcos and F. Becq. 1996. Development of a third generation shallow-water wave model with unstructured spatial meshing, *Proceedings of 25th International Conference on Coastal Engineering*, ASCE, 465–478.

Benoit, M., F. Lafon and G. Goasguen. 2008. Constitution et exploitation d'une base de données d'états de mer le long des côtes françaises par simulation numérique sur 23 ans. Base ANEMOC en Atlantique-Manche-mer du Nord, *European Journal of Environmental and Civil Engineering*, 12, 35–50.

Chini, N., P. Stansby, J. Leake, J. Wolf, J. Roberts-Jones and J. Lowe. 2010. The impact of sea level rise and climate change on inshore wave climate: A case study for East Anglia (UK), *Coastal Engineering*, 57, 973–984.

Clayson, C.H. and J.A. Ewing. 1988. Directional wave data recorded in the Southern North Sea, Report 258, Institute of Oceanographic Sciences, Deacon Laboratory, 72p.

Dawson, R.J., M.E Dickson, R.J. Nicholls, J.W. Hall, M.J.A. Walkden, P.K. Stansby, M. Mokrech, J. Richards, J. Zhou, J. Milligan, A. Jordan, S. Pearson, J. Rees, P.D. Bates, S. Koukoulas and A.R. Watkinson. 2009. Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change, *Climatic Change*, 95, 249–288.

Dickson, M., M.J.A. Walkden and J.W. Hall. 2007. Systemic impacts of climate change on an eroding coastal region over the twenty-first century, *Climatic Change*, 84, 141–166.

Flather, R.A., J.A. Smith, J.D. Richards, C. Bell and D.L. Blackman. 1998. Direct estimates of extreme storm surge elevations from a 40-year numerical model simulation and from observations, *Global Atmosphere and Ocean System*, 6, 165–176.

Horsburgh, K.J., and C. Wilson. 2007. Tide–surge interaction and its role in the distribution of surge residuals in the North Sea, *J. Geophys. Res.*, C4 (112), C08003.

HR Wallingford. 2002. Overstand to Mundesley strategy study: hydrodynamics, HR Wallingford Ltd, Report.

Leake, J., J. Wolf, J.A. Lowe, P.K. Stansby, G. Jacoub, R. Nicholls, M. Mokrech, S. Nicholson-Cole, M.J.A. Walkden, A. Watkinson and S. Hanson. 2007. Integrated modeling for coastal impacts, *Proceedings of 10th International Conference on Estuarine and Coastal Modelling*, Newport. ASCE, NewYork.

Leake, J., J. Wolf, J. Lowe, J. Hall and R. Nicholls. 2008. Response of marine climate to future climate change: application to coastal regions, *Proceedings of 31st International Conference on Coastal Engineering*, ASCE.

Lowe, J.A., and J.M. Gregory. 2005. The effects of climate change on storm surges around the United Kingdom, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 363, 1313–1328.

Lowe, J.A., T.P., Howard, A. Pardaens, J. Tinker, J. Holt, S. Wakelin, G. Milne, J. Leake, J. Wolf, K. Horsburgh, T. Reeder, G. Jenkins, J. Ridley, S. Dye and S. Bradley. 2009. UK Climate Projections Science Report: Marine and Coastal Projections. Met Office Hadley Centre, Exeter, UK.

Mokrech, M., S. Hanson, R. Nicholls, J. Wolf, M. Walkden, C. Fontaine, S. Nicholson-Cole, S. Jude, et al. 2009. The Tyndall coastal simulator, *Journal of Coastal Conservation*, in press.

Nairn, R.B. and H.N. Southgate. 1993. Deterministic profile modelling of nearshore processes. Part 2. Sediment transport and beach profile development, *Coastal Engineering*, 19, 57–96.

Nicholls, R., S. Hanson, M. Mokrech, P. Stansby, N. Chini, M. Walkden, R. Dawson, N. Roche, J. Hall, S. Nicholson-Cole, A. Watkinson, S. Jude, J. Lowe, J. Wolf, J. Leake, M. Rounsevell, C. Fontaine and L. Acosta-Michlik. 2008a. The Tyndall coastal simulator and interface, *Proceedings of 31st International Conference on Coastal Engineering*, ASCE.

Nicholls, R., P. Wong, V. Burckett, C. Woodroffe and J. Hay. 2008b. Climate change and coastal vulnerability assessment: scenarios for integrated assessment, *Sustainability Science*, 3, 89–102.

Shore Protection Manual. 1984. US Army Coastal Engineering Research Centre.

Stansby, P.K., C. Kuang, D. Laurence and B. Launder. 2006. Sandbanks for coastal protection: implications of sea-level rise, Part 1: application to East Anglia, Working Paper 86, Tyndall Centre for Climate Change Research.

Vincent, C.E. 1979. Longshore sand transport rates — A simple model for the East Anglian coastline, *Coastal Engineering*, 3, 113–136.

Walkden, M.J.A. and J.W. Hall. 2005. A predictive mesoscale model of the erosion and profile development of soft rock shores, *Coastal Engineering*, 52, 535–563.