SITE GEOMORPHOLOGY OR INNER SHELF ADJUSTMENT CONTROLS COASTLINE RESPONSE TO CLIMATE CHANGE?

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Abstract

Regardless of regional uniformity in coastal climate-change effects, locally distinctive geomorphology may amplify uncertainties in the magnitude of coastal impacts including coastline retreat and increased storm erosion, at any particular site. Such variations in potential climate-change impacts were explored here within numerical experiments involving the manipulation of sediment and accommodation volumes. Two similar wave-dominated coastal barrier beaches located in close proximity (30 km apart) on the New South Wales Central Coast but fronting separate estuarine lakes (Lake Macquarie and Tuggerah Lake) were compared. Coupled shoreline migration and geomorphic evolution was simulated using a morphokinematic approach. Uncertainties surrounding realised magnitudes of climate-change effects were addressed through stochastic input sampling, by which environmental forcing and surface responses were randomly sampled from predefined distributions. Repeated iteration of the model thus yielded risk-based forecasts of coastline retreat for each site. Further experimentation using an alternative modelling approach was then used to constrain feasible rates of shelf adjustment for the forecast period.

Despite the close proximity of the two sites, similar coastal morphology and exposure, and uniform climate-change forcing, in the absence of mitigation measures, by 2100 forecast coastline retreat in the Lake Macquarie embayment was a factor 1.5 times greater than at Tuggerah at the 50% risk level and 1.3 times greater at the 0.01% risk level. Isolation of the individual contributions of each site's geomorphology (i.e. dune volumes, tidal inlets, submerged reefs, inner shelf shape and extent) to the between-sites difference indicated that forecasts were most sensitive to sand accommodation volumes generated across the inner shelf. This accounted for almost two-thirds of the difference in forecast coastline retreat between sites (i.e. three times greater than that attributed to variation in dune volume). Thus assuming comparable rates of shelf adjustment between sites, coastline retreat is moderated at Tuggerah by the lower accommodation volume generated across the deeper inner shelf there.

Introduction

Despite continual improvements to both the reliability and resolution of projections of climate-change effects (e.g. sea level rise, altered energy climate) over the coming century and beyond, progress on resolving the key influences on the coastal impacts of these effects has not kept pace. In particular, our understanding of surface response beyond the surf zone to sea level change remains largely inadequate at the timescales of interest [*Cowell et al.*, 1999]. This is problematic because adjustments of the inner continental shelf surface have the potential to generate large sediment accommodation volumes during rising sea level, to which sediments may be cumulatively lost from the coastline during successive erosion events [*Roy et al.*, 1994]. And as consequence, morphokinematic (i.e. surface behaviour) approaches to simulating coastal geomorphic evolution, which remain the most viable method of predicting the timing and magnitude of potentially devastating chronic coastline retreat at timescales beyond the reliable reach of process-based methods [*Wolinsky*, 2009], are particularly sensitive to shelf adjustment. Thus without an ability to constrain the feasible rates of shelf adjustment for the setting and timescale of interest, model forecasts of coastal impacts will continue to suffer from intractable uncertainties.

Here we examine the relative significance of distinctive site geomorphology and the rate of inner shelf surface adjustment to uncertainty in model forecasts of coastline response to projected climate change in the 21st century. First we compare future coastline retreat at two superficially similar and nearby embayed beaches located on the New South Wales Central Coast, where the potential for varying responses is examined. We then attempt to isolate the individual contributions of the various aspects of coastal geomorphology that differentiate the sites (e.g. dune volume, tidal inlets, inner shelf reefs and inner shelf shape), to the observed between-site difference in forecast coastline retreat by 2100. Lastly, the sensitivity of forecast coastline migration to the full range of potential inner-shelf adjustment rates is identified, and potential approaches to constraining uncertainty in the feasibility of different rates of adjustment are discussed in the context of the regional setting and forecast horizon.

Methods

Uncertainties in both projections of climate change effects for a given forecast horizon, and the response of modern coastal systems to these changes at the implied timescale, necessitates a risk-based approach to forecasting coastal impacts. Here we use a stochastic sampling technique and Monte Carlo simulations integrated within a coastal geomorphic model. In this approach uncertainties surrounding the responses of both the climate system and the coastal system of interest are quantified by defining the range of feasible responses for each parameter within a probability distribution [*Cowell et al.*, 2006]. This allows for the inclusion of a vastly wider body of information than is permissible using a deterministic approach based on best-estimate figures. Repeated model iterations then allows for the compilation of a probability distribution of potential coastline responses, and the magnitude of impacts can thus be determined for the range of risk levels considered.

The coastal geomorphic model applied here uses principles of sediment-mass balance to calculate shoreline migration and surface evolution in response to environmental influences such as sea level change and altered sedimentation regimes. Previously, the model has been applied successfully to reproduce the evolution of dated Holocene coastal sedimentary sequences observed in the field [*Cowell et al.*, 1995; *Stolper et al.*, 2005]. This type of model is commonly referred to as a morphokinematic or surface behaviour model, because the morphodynamic processes that contribute to surface evolution are parameterised within the surface behaviour itself. The advantages of this approach include that long-term geomorphic evolution can be simulated without a reliable means of deriving net sediment transport from physical processes at the timescale of interest – an enduring problem within coastal morphodynamics due to the temporal limitations of observations and non-linear system behaviour – and second, that a rapid computation time independent of forecast period allows for sufficient model iterations from which to build robust distributions of results for quantifying risk.

Field sites

The study area for this investigation spans the Lake Macquarie and Wyong LGAs on the NSW Central Coast. Specifically, two embayed beaches of similar alongshore extent and orientation that partially enclose the estuarine water bodies of Lake

Macquarie and Tuggerah Lake are compared. Here the sites are referred to as the Lake Macquarie and Tuggerah embayments, which enclose the uninterrupted stretches of oceanfront sandy coastline respectively known as Nine Mile Beach and Tuggerah Beach (Fig. 1). Separated by about 30 km of continuous rocky and embayed coastline, the Lake Macquarie and Tuggerah embayments extend approximately 9 and 7 km alongshore respectively and are both oriented more or less perpendicular to the predominant southeasterly energy regime [*Short and Trenaman*, 1992].

Unlike much of the NSW coast, both the land surface and submerged inner shelf within the Lake Macquarie and Tuggerah sites has been recently surveyed using high-resolution remote sensing techniques. In 2007 the NSW Department of Planning conducted a pilot study on the feasibility of high-resolution terrain data collection for the NSW coast, within which a LiDAR altimetry survey of the Central Coast and Hunter region land surface was commissioned [NSW Department of Planning, 2008]. Furthermore, the NSW Office of Environment and Heritage has collected marine LiDAR and high-resolution soundings across the Lake Macquarie and Tuggerah inner shelf surfaces to 40 m depth. In the context of this research, the availability of high-resolution terrain data ensures the precise mapping of site geomorphology, and thus the reliable quantification of sedimentary features and accommodation. This allows for a previously unattainable degree of integrity in model calculations.

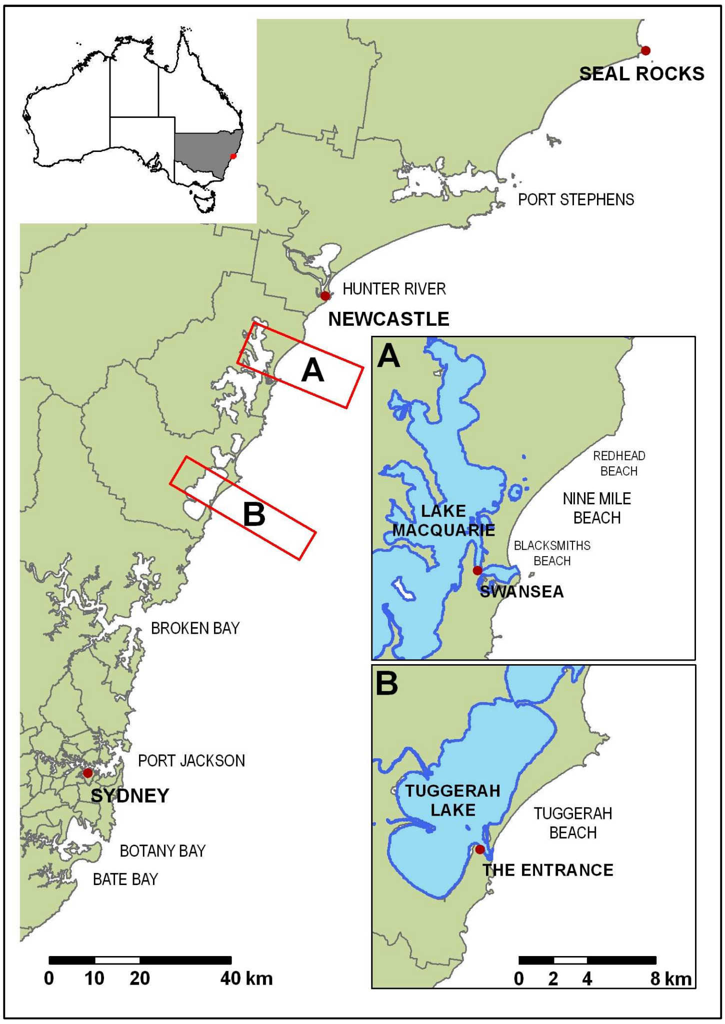

Figure 1. Map of Nine Mile Beach and Tuggerah Beach, located within the Lake Macquarie and Tuggerah embayments of the New South Wales Central Coast.

Aside from the abundance of high-resolution terrain data, the Lake Macquarie and Tuggerah sites present a unique opportunity to investigate the potential influence of differences in coastal and inner shelf geomorphology on future coastline response to climate change in otherwise comparable and nearby coastal systems. Common to all aspects of site geomorphology discussed below, the variation between sites implies a difference in the volumes of sedimentary features in key accommodation bins, which may contribute to varying shoreline behaviour in response to a given climate change scenario. Although both sites are similar in alongshore extent, sediment type and exposure to the predominant wind and wave climates, the following key differences, which are illustrated in Figure 2, are observed between the geomorphology of the two embayments:

- **Dune height & volume**
  Both Nine Mile Beach and Tuggerah Beach exhibit a progressive increase in dune height moving from the south end of each embayment to the north, which is consistent with the orientation of both coasts to the prevailing energy climate. However, average foredune height at Nine Mile Beach rises to 7 m at a distance 150 m landward of the shoreline, whilst in comparison this exceeds 10 m at Tuggerah Beach. Furthermore, although the dunes have historically been subject to mining and disturbance from development in parts, the modern dune system in the Tuggerah embayment remains substantially larger. This is demonstrated by comparison of the alongshore-averaged terrain data models for the sites (Fig. 3), which indicates an average volumetric difference of 650 m^3 per metre of beach for the dune systems to 500 m landward of the shoreline.

- **Tidal inlet morphodynamics**
  The southern limits of Nine Mile Beach and Tuggerah Beach are both defined by tidal inlets that connect the respective estuarine lakes with offshore waters. However, site differences in basin geometry and inlet constriction contribute to variation in inlet hydrodynamics [*Boothroyd*, 1985], which is evidenced by the shape and extent of the flood-tide deltas. Training walls located at Swansea Heads permanently maintain the Lake Macquarie tidal inlet, whereas the opening to Tuggerah Lake at The Entrance is typical of a more natural system. Periodic dredging takes place within both inlets to maintain navigability. As consequence of differences in the volume and shape of the basins, and the relative flow rates permitted by the inlets, the Lake Macquarie flood-tide delta is comparatively larger, measuring 4.25×10^6 m^2 compared to 2.90×10^6 m^2 at Tuggerah Lake.

- **Inner shelf reefs**
  With the exception of only the central portion of the embayment, the inner shelf fronting Tuggerah Beach is littered with outrcropping reefs between depths of 15-40 m. The inner shelf reefs protrude from the surrounding shelf surface to depths as shallow as -10 m and cause significant disruption to the otherwise consistent slope of the shelf surface away from the beach. In contrast, the inner shelf fronting Nine Mile Beach is void of any such outcropping reefs and thus takes a form described by the natural response of the seabed to the prevailing energy climate, shelf sediments and inherited geomorphology.

- **Inner shelf shape**
  Aside from outcropping reefs, the Lake Macquarie and Tuggerah inner shelf surfaces further vary in the shape and slope of the seabed beyond the surf zone. Figure 3 shows that the Lake Macquarie inner shelf is typically shallower, and thus if a uniform depth limit of significant shore-normal sediment transport is assumed for both sites, the active shelf area at Lake Macquarie is also much larger than at Tuggerah. That is, the Lake Macquarie shelf potentially affords a greater sediment accommodation volume under rising sea level conditions.

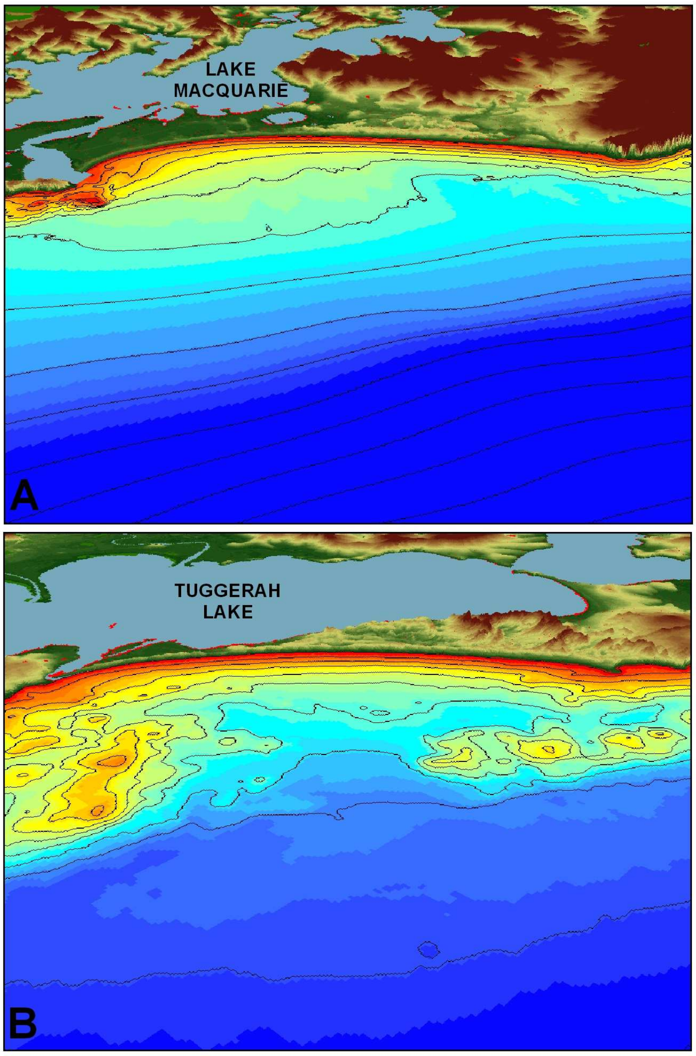

Figure 2. Digital terrain model of the Lake Macquarie and Tuggerah embayments illustrating the key differences in coastal and inner shelf morphology.

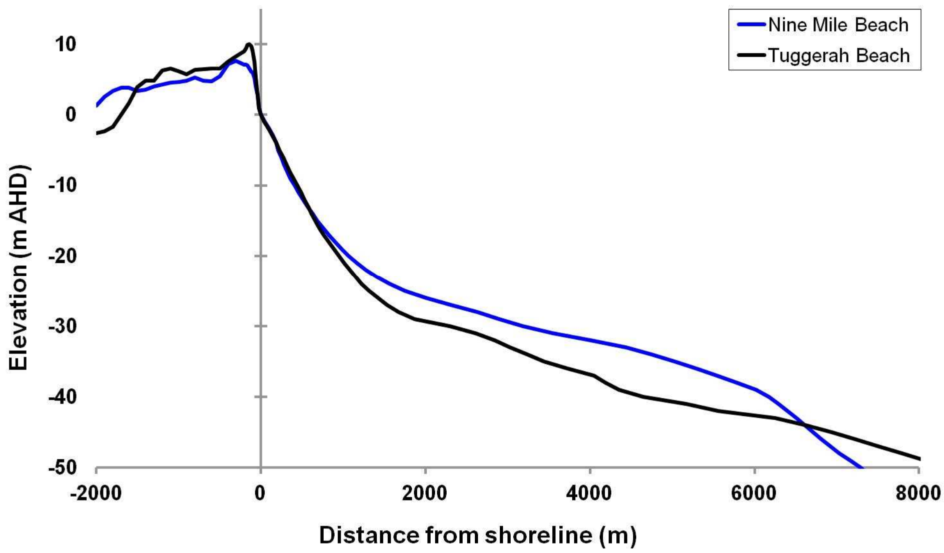

Figure 3. Averaged sections through the Lake Macquarie and Tuggerah coastal cells showing between-site differences in dune volume and the geometry of the inner shelf surface (note: inner shelf reefs are omitted here).

Forecasting coastline response to climate change

As mentioned above, this study overcomes uncertainties in the behaviour of physical systems by adopting a probabilistic approach to forecasting coastline response to climate change. Such approaches empower decision-makers through the expression of quantified model uncertainties in terms of risk, thereby effectively communicating both the reliability of forecasts and the likelihood of various impact scenarios. Equipped with this information, coastal managers can plan for those scenarios that correlate with a predefined acceptable level of risk, and adopt appropriate mitigation measures based on the quantified benefits defined by the reduction in exposure to such risk.

Here we consider the impacts of projected climate change for Nine Mile Beach and Tuggerah Beach by the year 2100. The range of projected climate change scenarios considered within model forecasts is summarised in Table 1. More specifically, the minimum, mode and maximum values define model input probability distributions for the key climate change effects that will dictate the future position of the coastline. First, raised sea levels will amplify the baseline impacts of inundation on exposed coasts through chronic shoreline retreat, due to cumulating permanent losses of coastal sediments to the lower inner shelf during storm events. The range of future sea level rise considered here acknowledges both present uncertainties in the most robust currently available global projections, and regional corrections for southeast Australian waters (Tab. 1). Furthermore, the range of sea level scenarios is inclusive of present planning guidelines in New South Wales [NSW Department of Planning 2010].

Second, a potential increase in the intensity and/or frequency of storm events may cause an increase in the volume of fluctuating storm-erosion demand, which refers to the periodic loss of coastal sediments to the inner shelf and subsequent replenishment during fair-weather conditions. Thus an altered storm-erosion demand that is consistent with projections of future variations in storm-wave climate [*McInnes et al.*, 2007] was also included in the model forecasts (Tab. 1). To ensure the comparability of forecasts between sites, the climate-change forcing scenarios described here were applied uniformly to both sites. Furthermore, at both sites coastline migration was measured from the base of the foredunes, approximately 40 m landward of the mean sea level shoreline defined by 0 m AHD.

Table 1. Range of climate change scenarios considered within model forecasts.

	Minimum	Mode	Maximum
Sea level rise (m)	0.50[1]	0.91[2]	1.40[3]
Storm-erosion demand [k] (m^3/m of coastline)	160 (k - 0.1k)	200 (k)	300 (k + 0.5k)

1. *CSIRO and BOM* [2007]; 2. *Meehl et al.* [2007] and *McInnes et al.* [2007]; 3. *Rahmstorf* [2007].

Each risk-based forecast of coastline response to climate change presented here was generated from 5000 iterations of the model, using stochastic input sampling (Fig. 4). That is, during each model run most input parameter values were selected at random in order to sample the full range of feasible geomorphic responses. Where appropriate however, the selection of particular parameters was correlated in order to preserve physical relationships and exclude unreasonable solutions. For example, the loss of coastal sediments to tidal-inlet sequestration was correlated with sea level rise, which dictates the generation of sediment accommodation in estuarine deltas [*Eysink*, 1990]. The Lake Macquarie and Tuggerah coastal compartments were assumed to be closed cells in regard to the littoral drift of coastal sediments given their embayed nature, adjacent rocky shores to north and south, and the absence of evidence to suggest significant contemporary headland bypassing of sediments.

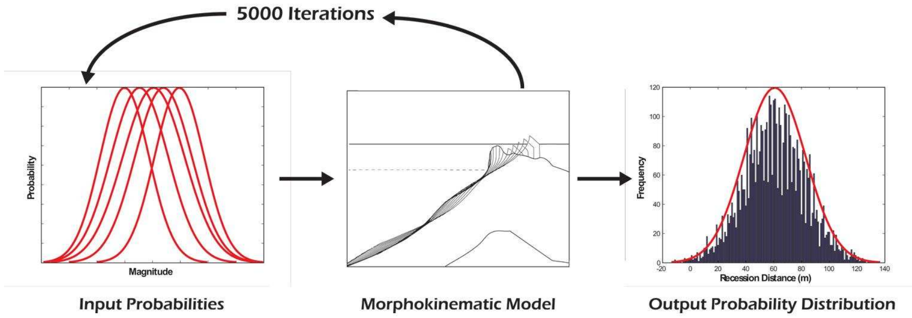

Figure 4. Illustration of the stochastic sampling procedure used in probabilistic forecasts of coastline response to climate change.

Quantifying the influence of site geomorphology on model forecasts

To examine the contribution of site differences in coastal and shelf geomorphology to variation in forecast coastline migration between sites, a series of further experiments were conducted in which the various differentiating features described above were systematically substituted between sites. Specifically, the model forecast for Tuggerah Beach was repeated four times, during which the dune profile, tidal inlet sequestration, inner shelf reef and inner shelf geometry data from the Tuggerah Beach site was substituted individually with data from Nine Mile Beach. The corresponding probability distribution of forecast coastline migration from each hybrid model was subsequently compiled and compared with risk curves previously prepared for the site models.

Exploring uncertainty in rates of inner shelf adjustment

Compounding uncertainties in climate change projections *per se*, the likely response of contemporary coastal systems to such environmental changes over the timescales of projections also remains poorly constrained. Most notably perhaps, the rate of inner shelf surface adjustment under rapid rates of sea level rise has the potential to cause significant sensitivity in model forecasts of coastline migration. This is because the rate of shelf adjustment is directly dictated by the rate of deposition of relocated coastal sediments over the shelf surface. Therefore, in cases where the active shelf comprises an extended and low-gradient surface, small variations in the rate of surface response equate to large variations in the volume of sediment exchanges between coast and shelf. Considering the typical geometry of the New South Wales inner shelf surface [*Boyd et al.*, 2004], and the estimated depth-limits of significant surface activity [*Cowell et al.*, 1999], the rate of shelf adjustment likely represents a significant source of uncertainty in model forecasts.

It is important to note that this problem differs from that of deriving a suitable definition for the depth limit of significant surface activity. Again, here model inputs are selected at random from predefined distributions and thus a range of feasible limits to shelf surface activity are sampled. Rather, the uncertainty in this instance relates to two common assumptions: first, that under conditions of rising sea level accommodation is generated across the inner shelf; and second, that coastal sediments instantaneously fill this accommodation at the timescale of interest. Here, a response that satisfies the collective assumptions is termed ‘full adjustment’. Alternatively where the assumptions are violated, the inner shelf becomes vertically dilated as the coastline migrates upward and landward and the shelf surface aggrades at a comparatively lower rate.

To explore the influence of different modes of shelf adjustment on coastline migration the model forecast for Nine Mile Beach was repeated twice more, although in this case with shelf response fixed at *full adjustment* and subsequently *full dilation* (i.e. minimal adjustment). In this way the bounds of uncertainty in rates of inner shelf adjustment could be defined. Figure 5 demonstrates the ranges of shelf adjustment considered under each of the scenarios.

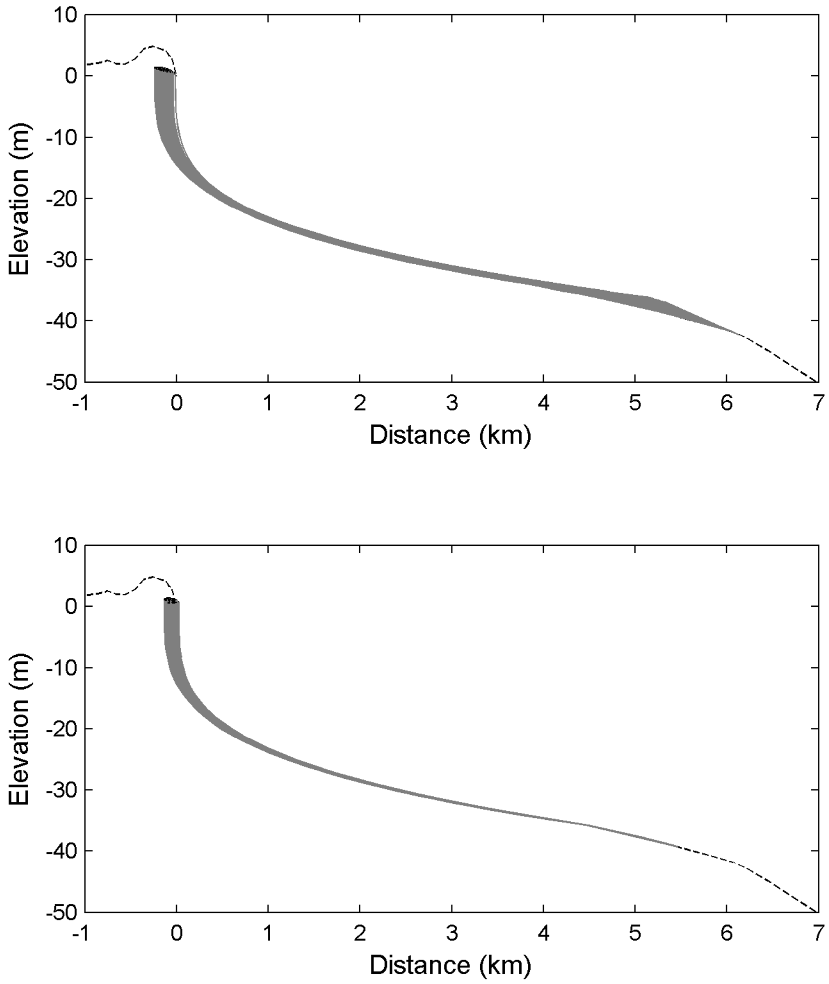

Figure 5. Comparison of profile envelopes from Nine Mile Beach model forecasts based on full adjustment (top) and full dilation (bottom) shelf responses.

Results

Despite the documented similarities and close proximity of the Nine Mile Beach and Tuggerah Beach sites, model forecasts indicate a considerable difference in climate-change induced coastline migration by 2100. Although both sites are expected to experience a landward retreat of the coastline throughout the next century and beyond, the magnitude of these impacts may be comparatively moderated at Tuggerah Beach. This appears to result from a combination of favourable geomorphic traits at that site, which contribute to a relatively low generation of shelf sediment accommodation under rising sea level conditions.

Risk-based forecast of coastline response to climate change

The findings from probabilistic forecasts of coastline response to climate change for Nine Mile Beach and Tuggerah Beach are presented in Figure 6, which is interpreted as the probability of exceeding a given magnitude of coastline retreat, or, the forecast impact of coastline migration for a predetermined acceptable level of risk. The range of risk thresholds highlighted in Figure 6 corresponds to 50, 10, 1, 0.1 and 0.01 % probability levels. In response to the uniform climate change scenario applied at both sites, the model forecasted a 1/2 risk of coastline retreat exceeding 84 m Nine Mile Beach by the year 2100, compared with 61 m at Tuggerah Beach. That is, the best estimate model (i.e. based on modal input values) predicts that coastline retreat due to climate change will be 1.38 times greater at Nine Mile Beach than at nearby Tuggerah Beach by 2100.

At increasingly vigilant risk thresholds, the impacts of the climate change scenario increased steadily, and at the 1/10,000 risk level coastline retreat at Nine Mile Beach exceeded 204 m, compared with 143 m at Tuggerah Beach (Fig. 6). For that risk level therefore, the forecast impact on coastline position was 1.43 times greater at Nine Mile Beach, reflecting a steady increasing trend in the between-site difference in coastline retreat for progressively more prudent thresholds of acceptable risk. That is, for lower levels of risk the between-site disparity in forecast coastline response widens.

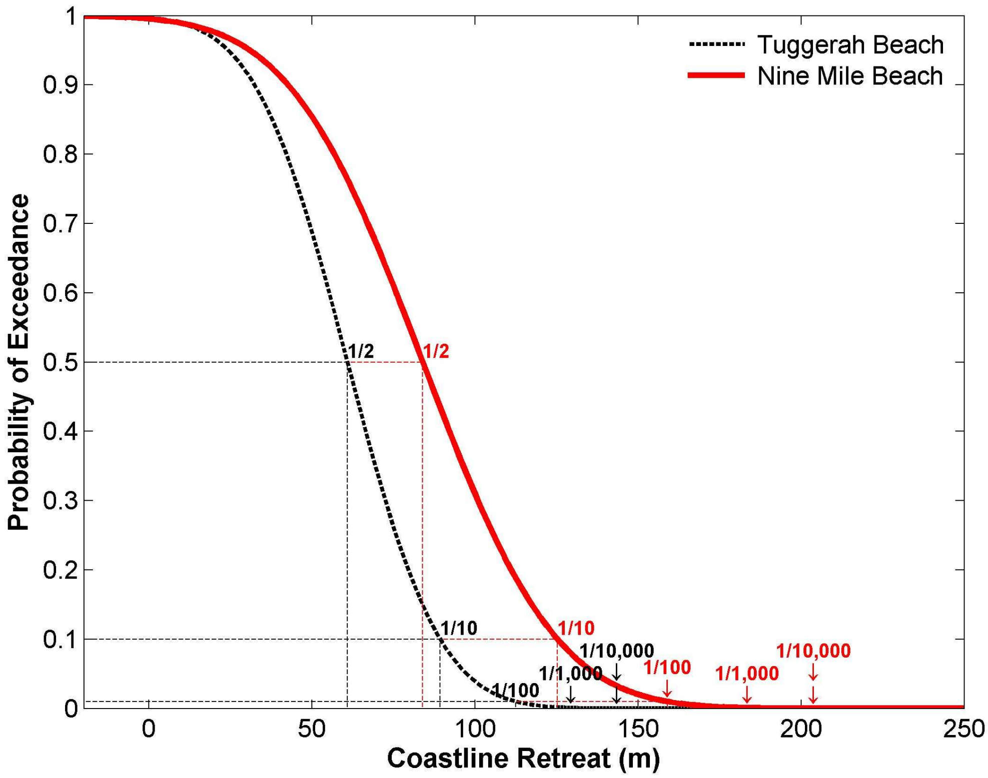

Figure 6. Model forecasts of coastline retreat due to climate change at Nine Mile Beach and Tuggerah Beach by 2100.

Influence of site geomorphology on forecast coastline retreat

Considering that the climate change scenario and sedimentary regime were maintained uniform between sites, the variation in forecast shoreline retreat by 2100 for Nine Mile Beach and Tuggerah Beach observed in Figure 6 must manifest from the combined effects of the four differentiating aspects of site geomorphology identified above. The isolated contribution of each geomorphic feature to the total between-site difference is presented in Figure 7, which was computed from sensitivity tests in which features from the Tuggerah geomorphology were substituted with the corresponding features at Lake Macquarie.

For the range of risk discussed here (1/2 - 1/10,000), the comparatively lower foredune and reduced volume of the dune system at Nine Mile Beach accounted for 4-12 m more (17-20 %) coastline retreat there by 2100. Similarly, the greater loss of coastal sediments to the Lake Macquarie flood-tide delta accounted for some of difference between site responses, although this was near negligible, contributing just 1 m to the difference in forecast shoreline retreat across all risk levels. The prevalence of submerged reef outcrops across the inner shelf fronting Tuggerah Beach had the effect of moderating forecast coastline retreat there by 2-9 m (9-15 %). By far the greatest contributor to the 23-61 m difference in model forecasts between sites was variation in inner shelf surface shape, which accounted for 17-45 m (74 %) of the difference.

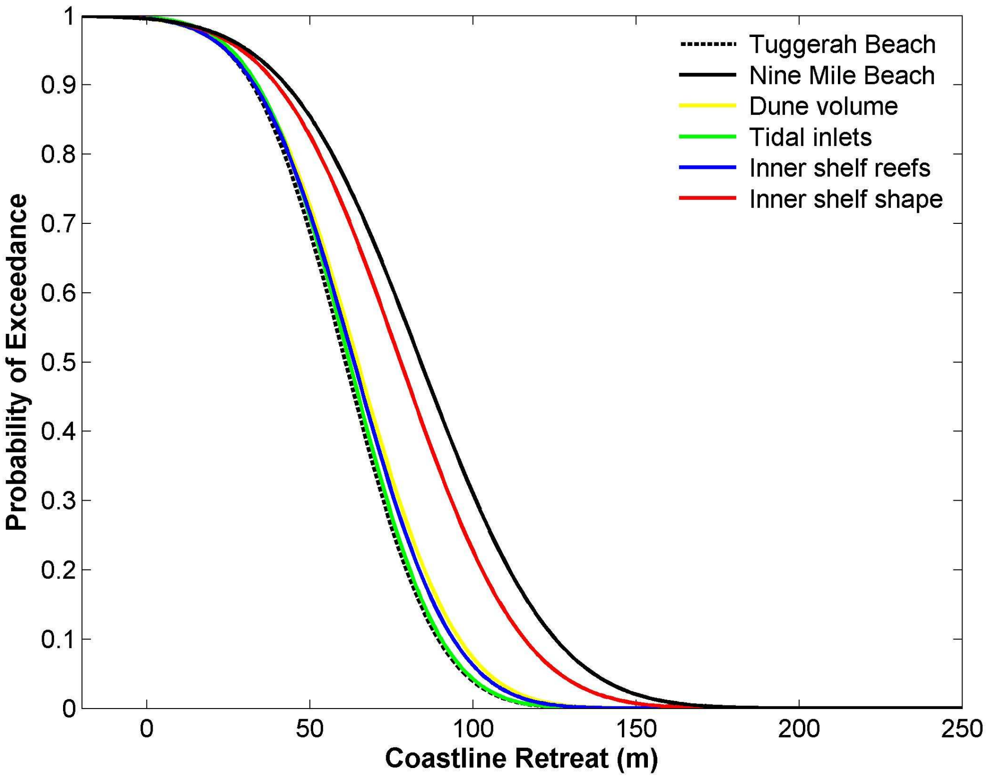

Figure 7. Contribution of various aspects of distinctive site geomorphology to the between-site difference in forecast shoreline retreat shown in Figure 4.

Effect of inner shelf adjustment on model forecasts

As expected, variation in the rate of shelf adjustment over the forecast period had a pronounced effect on model forecasts of coastline response to climate change (Fig. 8). For the case of a 'full adjustment' shelf response, the model forecast of future coastline migration at Nine Mile Beach increased to 134-251 m retreat for the 1/2 to 1/10,000 risk level range. This represents 160 and 123 % increases at the 1/2 and 1/10,000 risk levels respectively. Conversely, if a 'full dilation' response of the shelf is assumed, forecast coastline migration for Nine Mile Beach by 2100 becomes comparable to that at Tuggerah Beach (*c.f.* 61-143 m), with the coast retreating only 59-155 m for the same range of risk levels (i.e. 30 and 24 % reductions on the Nine Mile Beach site model forecast for the 1/2 and 1/10,000 risk levels). Figure 8 also demonstrates that the site models were calibrated on the conservative side of the range of uncertainty in rates of shelf adjustment, thereby acknowledging the low probability of full adjustment across the entire inner shelf given the forecast timescale.

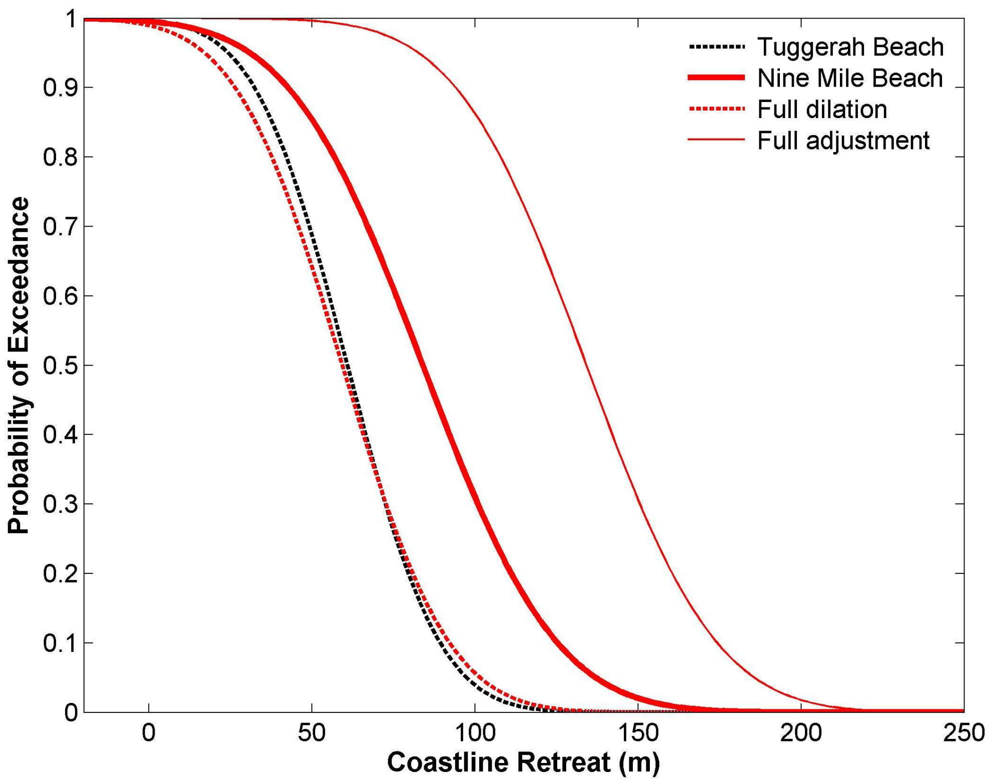

Figure 8. Effects of full adjustment and full dilation modes of shelf response on forecast coastline response to climate change for Nine Mile Beach.

Discussion

Although recent science has begun to inform coastal managers and planners on the expected effects of climate change over the coming century at a resolution sufficient for regionally-tailored actions [*CSIRO and BOM*, 2007; *McInnes et al.*, 2007], there remains a persisting inadequacy in awareness of the potential for site amplification or attenuation of the coastal impacts of climate change. Considering the pronounced regional gradient in coastal geology characteristic of the New South Wales coastline [*Roy and Thom*, 1981], and superimposed distinctive site geomorphology as illustrated by the Central Coast examples here, it would be naïve to expect regionally uniform migration of the coastline in response to forecast climatic forcing. Rather, as supported by the findings here, site idiosyncrasies that influence the volume and distribution of coastal sediments and accommodation may drive considerably different responses at a given site. In the absence of sufficiently detailed quantifications of site geomorphology to constrain uncertainties in site responses therefore, mitigating or adapting to the expected impacts of climate change presents a formidable challenge to coastal managers and planners. Compounding this problem is the need to constrain probable rates of inner shelf response to rapid sea level rise at management timescales (10 – 10^2 years), which typically fall between the resolutions of sufficiently detailed historical observations and geological records of past events.

Potential for site variation in coastline migration

It is clear from the findings in Figure 6 that model forecasts of coastline retreat due to climate-change driven sea-level rise and altered storm-erosion volumes are sensitive to the geomorphic features of each site. For the comparison between Tuggerah Beach and Nine Mile Beach, sediment characteristics and all environmental processes were maintained uniform between sites, with variation in the models limited only to differences in site geomorphology (i.e. dune height & volume, tidal inlet sequestration, inner shelf reefs, and inner shelf shape). Ultimately, the substitution experiments indicated that the nature of all such features at Tuggerah Beach have the effect of moderating coastline retreat in response to the range of climate change scenarios considered. That is, substitution with the corresponding features from Nine Mile Beach resulted in increased coastline retreat at all risk thresholds (Fig. 7). The attenuation of impacts at Tuggerah Beach arose from both the provision of greater resistance to erosion at the coastline, and the comparatively lower generation of accommodation in adjacent and interdependent sedimentary environments.

First, the larger dune system backing Tuggerah Beach that comprises both a taller foredune and altogether higher dune volume (Fig. 3) affords greater resistance to coastal erosion, necessitating the removal of more sediment per metre of shoreline to achieve comparable coastline retreat as at Nine Mile Beach. Aside from this larger dune defence, three other aspects of the Tuggerah site geomorphology contributed to relatively lower generation of sediment accommodation in the system by rising sea level, thus reducing opportunities for eroded sediments to be permanently lost from the coastline. After accounting for the longer coastline of the Lake Macquarie embayment, the greater efficiency in tidal inlet hydrodynamics that contribute to the larger flood tide delta at that site had negligible influence on coastline retreat when implemented as a comparable rate of inlet sequestration at Tuggerah (Fig. 7). Thus the major contributors to lower accommodation generation at Tuggerah Beach are the presence of inner shelf reefs and overall shape of the inner shelf surface.

During sea level rise, the drowning of the inner shelf under progressively deeper waters is expected to create new accommodation space, where the seabed exceeds the reach of significant wave disturbance, and where eroded sediments from the coastline may be deposited. Localised disruptions to the prevailing slope of the seabed, such as the reef outcrops of the Tuggerah inner shelf, have the effect of reducing the potential for accommodation generation by occupying volume in the water column. That is, the shelf has less capacity to store sediments eroded from the coastline. Furthermore, lithified surfaces at the seabed indicate areas in which sediments cannot settle from transport in the long term, without the creation of substantial accommodation above. Thus the inner shelf reefs at Tuggerah Beach have the effect of reducing forecast coastline retreat (Fig. 7).

Similarly, the total potential volume of accommodation generated across the shelf depends on the shape and seaward extent of the ‘active’ shelf surface – the limit of which is defined by the depth limit of significant wave-induced sediment mobility [*Cowell et al.*, 1999; *Hallermeier*, 1981]. That is, a wide inner shelf has the potential to generate far greater accommodation during rising sea level than a narrow or steeply sloping shelf, because a wide shelf offers a greater surface area at or near the active shelf limiting depth. Figure 7 demonstrates that the shallower inner shelf of the Lake Macquarie embayment had the greatest influence on variation in model forecasts of coastline migration, generating a larger accommodation volume in response to the range of climate change scenarios.

Constraining uncertainty in rates of shelf adjustment

Of course the sensitivity of model forecasts to inner shelf dimensions varies with the assumed rate of shelf adjustment for the forecast period – that is, the higher the rate of shelf adjustment, the greater the accommodation generated across the shelf and the greater the potential coastline retreat. Figure 8 indicates that for the site comparison and substitution experiments, a relatively conservative rate of shelf adjustment was adopted, which although accounting for the entire range of potential responses between full dilation and full adjustment (Fig. 5), acknowledged the low probability of full response with increasing proximity to the depth limit of the active inner shelf. More specifically, given the relatively rapid sea level rise and short timescales of the climate change scenarios considered (*c.f.* Holocene rates of change), it is unlikely that eroded coastal sediments will fill accommodation across lower parts of the inner shelf within the forecast period. It is most likely the case therefore, that the inner shelf response rate for forecasts should fall somewhere between full dilation and full adjustment, initially favouring a dilation response and tending closer toward full adjustment as the forecast period is extended farther into the future.

Surface adjustment across the lower inner shelf for the modal climate change scenario and system response at Nine Mile Beach varied between 0.05 m and 0.5 m for full dilation and full adjustment responses respectively (Fig. 5). That is, the range of adjustment rates that contributed to the margin of uncertainty in forecast coastline retreat at Nine Mile Beach for the 1/2 risk level (Fig. 8) was 0.5-5 mm per year at 30 m depth. Historically, logistical barriers to accurately resolving minute surface change at such depths have precluded the empirical identification of depth limits of shelf activity and the collection of high-resolution time series of shelf adjustment [*Cowell et al.*, 1999] thereby hindering efforts to quantitatively understand inner shelf morphodynamics.

One approach to constraining uncertainty regarding feasible rates of inner shelf adjustment uses an alternative modelling approach to calculate surface behaviour in response to environmental forcing, without the explicit quantification of site processes. Specifically, BarSim is a ‘process-response’ model that uses experimentally validated system behaviour rules to simplify relationships between the complex array of physical processes active in coastal systems and depth-dependent erosion and deposition rates [*Storms et al.*, 2002]. Previously the approach has proven successful in reproducing the coastal geomorphic evolution resulting from rapid sea level change that has been preserved in documented sedimentary sequences [*Storms and Hampson*, 2005; *Storms et al.*, 2008]. By calibrating BarSim with the well-studied Tuncurry sequence [e.g. *Roy et al.*, 1997] located 30 km north of Seal Rocks (Fig. 9), some idea of feasible rates of inner shelf adjustment for the NSW coast may be gained. During the period 6 ka to present, the model indicates that rates of shelf adjustment between 20-30 m depth averaged 0.5-1 mm per year. Although the Tuncurry case involves shelf lowering rather than aggradation, this preliminary application provides an indication of potential depth-dependent rates of cumulative sediment transport across the inner shelf.

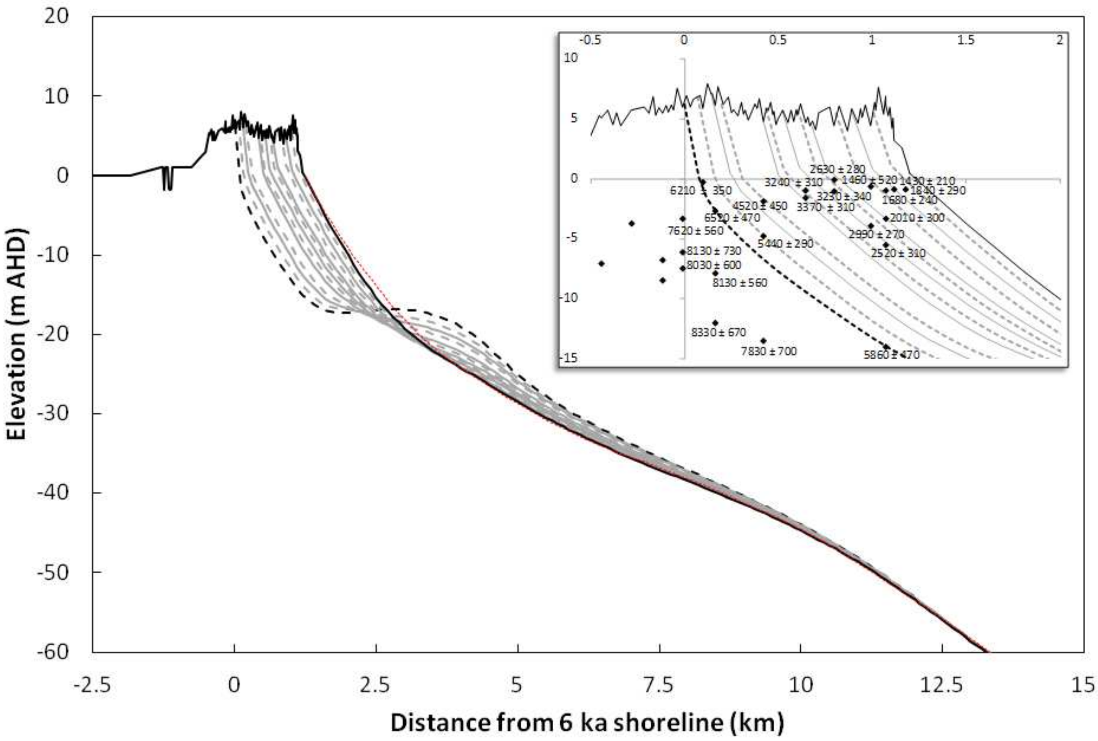

Figure 9. Simulated evolution of the Tuncurry coastal barrier from 6 ka – present. Coupled shelf lowering and coastline progradation is shown in 500-year steps that are consistent with both the contemporary surface (red) and dated core samples retrieved from the strandplain (inset).

Conclusions

The variation in forecast coastline retreat between the NSW Central Coast examples considered here imply that the potential for significant attenuation or amplification of coastal climate change impacts should be considered even within a localised setting, in which processes and morphology may be perceived to be relatively uniform. Due to the typically order-of-magnitude difference between the surface areas of coastal dunes and the inner continental shelf of the NSW coast, and the implications of this for sediment volume exchanges during sea level rise, slight differences in the shape and extent of the inner shelf can result in substantially greater site variation in forecast coastline migration than somewhat more obvious differences in dune volume. The findings thus highlight the significance of reliable bathymetric and surface texture datasets for the inner shelf seabed to reducing uncertainty in model forecasts of coastline response to climate change.

Compounding uncertainties that arise from the insufficient resolution or unreliability of existing shelf bathymetry data in many places, the influence of inner shelf geometry on cumulative sediment losses from the coast to the shelf during sea level rise remains dependent on the rate at which the inner shelf surface adjusts. Considering projections of sea level rise and the timescales of managing climate change adaptation, the effects of uncertainty in feasible rates of shelf adjustment on forecast coastline migration are comparable to those associated with uncertainties regarding site attenuation of impacts. Along with the widespread collection of high-resolution seabed data therefore, constraining rates of inner shelf adjustment to rapidly rising sea level represents the most effective means of minimising uncertainty in forecasts of future coastline response to climate change.

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