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# Coasts and climate: Insights from geomorphology

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**Abstract**

Geomorphology is increasingly engaged with the connections between coastal behaviour and climate variability and change. While impacts of climate change at the coast are often primarily viewed in terms of landform adjustments to accelerated sea-level rise, geomorphologists are also starting to unlock the subtleties of how coastal processes are forced by a broader suite of climate factors. This progress report highlights three main strands of recent geomorphological research in this vein: the search for a broader suite of climatic signatures in recent coastal deposits; empirical analyses of the linkages between climate variables and contemporary shoreline change; and enhancement of our capability to predictively model climate-driven changes in coastal morphology.

**Keywords**

climate change, coasts, geomorphology, modelling, sea level, storminess

## I Introduction

As in other earth science disciplines, the specific problems addressed by coastal geomorphology are increasingly framed by bigger questions of the kind that fall naturally from a prevailing paradigm of climate change science. In part, this provides a new framework for a continuation and extension of well-established lines of research. A multitude of studies thus explore coastal responses to changes in sea level and sediment supply at various timescales. These include work by Abbey et al. (2011) on the influence of repeated low-amplitude Pleistocene eustatic sea-level oscillations on the distribution and geomorphology of submerged shelf edge reefs in northeast Australia, and by Costas and Fitzgerald (2011) on the sedimentary architecture of the terminal zone of a barrier spit in Massachusetts, from which the imprints of both progressive sea-level rise and local inlet dynamics are inferred. Of the more contemporary analyses, that of Webb and Kench (2010) is of particular interest in that it challenges prevailing assumptions regarding the erosional vulnerability of reef islands to sea-level rise. Based upon a geographically extensive analysis of historic shoreline changes around 27 central Pacific atoll islands, the style of shoreline adjustments is seen to vary, and must thus be

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viewed in the context not only of sea level but also of other forcing factors and constraints.

While impacts of climate change at the coast are often primarily viewed in terms of adjustments to accelerated sea-level rise (e.g. Aagaard and Sørensen, 2012; Anderson et al., 2010; Ford, 2012; Jackson and McIlvenny, 2011; Kebede et al., 2012; Strauss et al., 2012), geomorphologists are also unlocking the subtleties of climatic forcing of coastal processes. This progress report highlights three main strands of recent research in this vein: the search for a broader suite of climatic signatures in recent coastal sedimentary archives; empirical analyses of the linkages between climate variables and historical shoreline change; and the enhancement of our capability to predictively model climate-driven changes in coastal morphology at the time and space scales that really matter.

## II Coastal signatures of Holocene climatic variability

Coastal landforms are arguably among the most sensitive to climate change on account of the strong linkage between atmospheric warming and sea level, and the fundamental role of the latter as a boundary condition determining the reach of wave and tidal processes (e.g. Tessier et al., 2012). Not surprisingly, there continues to be a plethora of studies that attempt to unpick the associations between sea-level rise and coastal change. Regard et al. (2012) present novel insights into late-Holocene cliff recession based on a new method of measuring and modelling $^{10}$Be concentrations across modern shore platforms. A forward numerical model predicts the form of $^{10}$Be concentration transects as a function of prescribed cliff recession and vertical platform downwearing rates in response to postglacial sea-level rise. Two independent features allow the recession rate model to be fitted to data: a sharp $^{10}$Be concentration drop predicted at the stationary location of the cliff during the last glacial period; and a mid-profile maximum with an amplitude related to the cliff retreat rate. Applied to chalk cliffs on the English Channel coast of France at Mesnil-Val, $^{10}$Be data yield a retreat rate since the mid-Holocene of 11–13 cm yr$^{-1}$, remarkably similar to measured retreat over a 30-year period. At a millennial timescale, Clemmensen et al. (2012) combine cartographic and photographic evidence with topographic and subsurface structure surveys to describe the 1000-year development of a beach-ridge foreland on an island in the Kattegat Sea (between Denmark and Sweden). Sedimentary and geomorphological evidence points to a fall in relative sea level, but that excess sediment supply was also a key factor in facilitating the growth of this system. In a rather different setting, Allen et al. (2012) use sophisticated lidar-based mapping and geospatial analysis to elucidate the late-Holocene evolution of a cuspate foreland, Cape Henry, in Virginia, USA. At this location, numerous beach ridges, swales and dune ridges provide a record of horizontal shoreline progradation as well as vertical sea-level rise that can be discerned from a landward trend in swale heights. Woodroffe and Murray-Wallace (2012) highlight the importance of investigations of past sea-level change, particularly in terms of their role in our quest for a better understanding of impacts of future sea-level change. They note the potential wealth of untapped geomorphological evidence within the stratigraphic record of coastal responses to different directions, magnitudes and rates of sea-level change. An archaeological perspective can extend these reconstructions to include anthropogenic responses to sea-level change as shown in Mourtzas' (2012) extensive palaeogeographic analysis of coastal Greece, which documents the intertwining histories of environmental change and human activity.

Contributing to a comprehensive literature on mid- to late-Holocene coastal evolution, Reimann et al. (2011) further document the role of a mid-Holocene deceleration in sea-level rise in facilitating coastal progradation. An analysis of foredune ridge stratigraphies of coastal spits in the southern Baltic shows that subsequent phases of increased aeolian activity correlate with increased erosion and instability, commensurate with late-Holocene dune development elsewhere in northwest Europe (e.g. Costas et al., 2012). In the case of the Late Pleistocene dunes of the Tottori coastline, Japan, large-scale shifts in shoreline position have contributed to significant differences in the depositional setting and morphosedimentary character of dunes. This points to the importance of gross coastal configuration, as determined by sea level, on coastal dune development (Tamura et al., 2011b).

Coastal dunes offer abundant stratigraphic evidence for century- to millennial-scale climate forcing. Phases of enhanced or subdued wind-forced aeolian activity are recorded in stratigraphic transitions from large-scale cross-bedding to soil development. In western Europe, Holocene coastal dune history is marked by specific periods of increased storminess. At a site in southwest Portugal, these have been dated to 12.6, 5.6, 1.2, 0.4 and 0.3 ka (Costas et al., 2012) and aeolian activity and dune-building linked to enhanced phases of dominant westerlies. Tamura et al. (2011a) identify the winter monsoon as a primary control on aeolian processes and related phases of increased or declining dune activity in east Asia. They present evidence for major dune activity and development between the 15th and 17th centuries, which they compare with similar periods of dune migration and activity in northwest Europe during the Little Ice Age (e.g. Danielsen et al., 2012).

Troiani et al. (2011) argue that estuaries and coastal bays provide some of the best, yet least studied, archives of recent palaeoclimate. Extraction of unambiguous climate signals from these sedimentary environments is complicated by intermittency in the rate and continuity of sediment transport, deposition and erosion. As such, they pose challenges beyond those associated with more conventional archives such as lakes. However, multiproxy analyses open up new possibilities to reconstruct past wind and precipitation regimes. In shallow estuaries and bays, wind energy often exerts a dominant influence on sedimentation. Working in Copano Bay, Texas, in the context of a well-constrained model of Holocene morphological evolution, Troiani et al. (2011) analyse textural data from well-preserved mid-bay deposits to derive a proxy for wind strength over the last 9.6 ky. Early-Holocene low wind strengths were apparently followed by a windier period from 5.2 to 4.1 ka and by more tranquil conditions in the later Holocene. In a separate paper, Simkins et al. (2012) demonstrate the potential of magnetic susceptibility (MS) as a basis for correlating climate-driven variability in sedimentation. A larger set of bays along the northwest Gulf of Mexico show clear MS signals corresponding to the well-documented 8.2 ka climate event and stronger, more regionally coherent, responses at around 5.5 to 5.0 ka. However, use of MS as a direct palaeoclimate proxy is complicated by the fact that it may reflect the composition of the source rocks, weathering regime and grain size, each of which is associated with different climate factors. The authors are thus unable to exclude sea-level rise as a primary factor driving variability in sedimentation around the 8.2 ka event, and acknowledge that either increasing sediment flux due to intermittent rainfall under more arid conditions or an increase in background magnetic material could account for the more recent anomalies. Lessons from these studies include the importance of selecting a meaningful proxy and also the need for a robust conceptual model for the evolution of the wider coastal system before isolated cores are used to resolve specific controls on sediment accumulation. This is exemplified by the work of Dezileau et al. (2011), who note the potential of deposits preserved in the sediments of coastal lagoons as a basis for deciphering the links between climate and storm activity over longer timescales. They establish the historical context for the geomorphic evolution of lagoons in the French Mediterranean before attributing sedimentary and geochemical signatures of overwash events to more intense storm activity that is believed to have been driven by enhanced lower tropospheric baroclinicity over a large Central Atlantic and European domain during the latter half of the Little Ice Age.

Broader climate impacts on Holocene coastal evolution are also explored by Van Soelen et al. (2012), who link large-scale changes in the hydrological cycle (forced by shifts in the ITCZ) to coastal sediment budgets. In their analysis of shallow marine (estuarine) cores from southwest Florida, increased mid-Holocene precipitation and runoff is seen to drive deposition of terrestrially derived organic matter. Evidence for storm activity is found in coarser sand and shell layers (in abundance between 3.2 and 2 ka), which implies enhanced tropical cyclone activity in the Gulf of Mexico in the late Holocene. In a cautionary account, Otvos (2011) unpicks previously published stratigraphic inferences of storm forcing and urges a more critical approach to the attribution of deposits to storm events. In particular, he argues that geomorphological interpretation is fundamental to stratigraphic analyses of this kind to ensure that inferred links to storm and hurricane provenance are justified. Costa et al. (2012) contribute an empirical microtexture approach that can increase the confidence with which deposits can be attributed to high-energy (tsunami or storm) events. In many systems, of course, complex imprints of sea-level change and discrete storm events are rendered ambiguous as a consequence of coeval morphodynamics, such as shifts in estuarine channel location (e.g. Fruergaard et al., 2011; Sorrel et al., 2012).

High temporal resolution studies offer compelling insights into past patterns of storminess that, in turn, provide important context for future predictions of how increasing storminess may drive coastal change as part of more widespread global change. Sorrel et al. (2010) combine very high-resolution seismics, mineral magnetics, sedimentology and accelerator mass spectrometry (AMS) $^{14}$C to interpret mid- to late-Holocene deposits in the Bay of Vilaine, western France. Proximal estuarine deposits provide the most complete late-Holocene archive, and analysis of their sequences implies a stronger fluvial influence during the Medieval Warm Period, including higher sediment yields attributable to anthropogenic forest clearances. Reduced storminess during this time is recognized by the dominant preservation of fine-grained sediment, but a subsequent shift to enhanced storminess under the deteriorating climate of the Little Ice Age is evidenced by an increase in marine-influenced sedimentation at that time. Sorrel et al. (2012) draw upon exceptionally large high-resolution seismic data sets from Mont Michel Bay and the Seine estuary, France. Located along the southern coast of the English Channel, these systems are exposed to the dynamics of the North Atlantic and its associated climate system, which makes them especially well suited to studies of variability in storminess. Their analysis reveals five clear phases of storminess over the last 6500 years that are ostensibly ‘phase-locked’ with North Atlantic Ocean variability and which exhibit a periodicity of about 1500 years. They also explore links with solar activity, but find no consistent correlation, suggesting that this is not a primary driver of millennial-scale variability in storminess.

## III Contemporary coast-climate linkages

There is abundant evidence for sea-level forcing of coastal dynamics at decadal to century timescales. Brooks and Spencer (2012), for example, use historical observations of soft rock cliff erosion to show that the 20th-century acceleration in sea-level rise contributed to an order of magnitude increase in the volume of sediment released by erosion in Suffolk, eastern England. As noted above, however, sea-level rise is only one of several climate-related factors influencing coastal change. Coastal landform evolution is often considered to be event-driven, with storminess being a major factor driving both erosional (e.g. Gallop et al., 2011; Rangel-Buitrago and Anfuso, 2011) and depositional (e.g. Andersen et al., 2011; de Groot et al., 2011) responses. Various studies of historical shoreline change implicate storms in the perturbation of long-term behaviour (e.g. O'Connor et al., 2011, in northwest Ireland). Subaerial processes are also important, and Moses and Robinson (2011) provide an excellent synthesis of these in relation to chalk cliffs, pointing to the importance of rainfall variability and the frequency of frost action as controls on slope stability and cliff-facing weathering and retreat.

Establishing unambiguous empirical relationships between metocean parameters and coastal change is difficult. Esteves et al. (2011) draw attention not only to the issue of data availability but also to the high interannual and decadal variability in both forcing and response. In an analysis of coastal change along a 16 km portion of the eastern Irish Sea, UK, they find no clear correlation between metocean parameters and shoreline position for the period 1894–2005. Only an integrated climate measure, the North Atlantic Oscillation winter index (NAOw), showed any direct correspondence with erosional and accretional responses of this dune-backed beach system. Almeida et al. (2011) suggest that local factors are more important in controlling storm patterns in southern Portugal, where, despite intensive modelling in a data-rich context, variance in storm wave heights could only partially be explained by variations in the NAO.

The fact that NAOw correlates with observed coastal change invites comparison with ecosystem responses, which also tend to reflect multiple aspects of climate averaged over characteristic timescales as well as imparted through discrete events (e.g. Straile and Stenseth, 2007). That said, various studies in Europe point to associations between the NAOw and specific aspects of climate that then force particular coastal system responses (e.g. Dezileau et al., 2011; Silva et al., 2012). Brooks et al. (2012) point to the association between positive phases of the NAOw, storminess (including heavy precipitation) and episodes of more rapid soft rock cliff retreat in eastern England, while Vespremeanu-Stroe and Tatui (2011) argue for NAO-driven variability in storminess as a primary control on the decadal-scale behaviour of the Romanian Black Sea coast. However, Burningham and French (2013) show that NAOw is actually a poor proxy for storminess in northwest Europe. Analysis of various forms of NAOw (computed both from regional differences in normalized pressure anomalies and the principal component of an Empirical Orthogonal Function (EOF) analysis of sea-level pressure) and wind records for 53 ground stations in Great Britain and Ireland show that correlations with land station-based measures (extreme wind speeds, gale day frequencies, etc.) are almost invariably weak. What NAOw does capture, however, is the wind direction frequency, which is clearly a major driver of coastal wave climates (e.g. Le Cozannet et al., 2011; Zacharioudaki and Reeve, 2011).

This finding is consistent with studies of coasts that are subject to strong interannual variation in wave direction. On the Atlantic coast of Portugal, Dodet et al. (2010) showed winter-averaged wave direction and the NAOw to be significantly correlated for the period 1953–2009. Thomas et al. (2011a, 2011b) also demonstrate linkages between NAOw, wind speed and direction, and the rotation of bay beaches in south Wales, UK. While variation in wave height is a clearly significant influence on beach morphology, beach rotation is more closely linked to oscillations in the dominant wind and wave direction between southwest and southeast quadrants. Interestingly, beach behaviour lags NAO variation by up to 18 months.

Work in other parts of the world also points to decadal variability in metocean parameters as a driver of shoreline change at historical timescales. Of particular note is the analysis by Rankey (2011) of recent coastal change in the atolls of the Gilbert Island chain in the equatorial Pacific. Low-lying atolls and reef islands are frequently presented as among the most vulnerable coastal systems to climate change-driven sea-level rise. Yet, far from exhibiting a simple drowning response, the coral islands studied by Rankey show widespread changes (50% of shorelines showed measurable positional shifts between 2005 and 2009) that include both accretionary and erosional responses. He shows that shoreline variability is probably not influenced directly by sea-level change but that ENSO-related variation in wind direction and wave climate, together with local anthropogenic and autogenic shoreline processes, control much of the observed shoreline behaviour. Another study by Codignotto et al. (2012) attributes increasingly rapid shoreline erosion in the outer Río de la Plata estuary, Argentina, to an increase in the frequency and height of easterly and east-southeasterly waves acting in concert with an increase in the magnitude, duration and frequency of storm surges and background sea-level rise. Changing climate thus forces coastal morphological responses along multiple interacting pathways, both direct and indirect.

Although recent work on linkages between coastal change and climate variability has focused on beaches and soft rock cliffs, hard rock coasts and shore platforms are also sensitive to the frequency and intensity of storms. Boulder deposits have often been used to infer past tsunamis (e.g. Etienne et al., 2011) but in some locations they may be indicative of high-magnitude storms. Goto et al. (2011) present field evidence of boulder movement during specific storm events in the Okinawa Islands, Japan, where similar features would ordinarily be attributed to historical tsunamis. Etienne and Paris (2010) argue that storms are the dominant factor in the evolution of coasts in southwest Iceland, where storms in the North Atlantic may generate significant wave heights exceeding 15 m that can move individual boulders weighing 70 t or more. Unlike tsunamis, repeated storm-wave impacts rework boulders and rock debris into prominent ridge deposits. Such processes are clearly active on contemporary coasts – a finding supported by a detailed analysis of recent boulder generation and movement on exposed rock platforms in northwest Ireland in the context of computed transport thresholds by Knight and Burningham (2011) – and may become more so if storminess increases with global changes in atmospheric gradients between high and low latitudes. However, Stephenson and Naylor (2011) note the potentially confounding effects of complex geology, including time variation in rock strength and the distribution of discontinuities, as well as complex histories of detachment and breakage on the inference of wave energies from boulder deposits.

Styles of coastal behaviour vary with climatic context. Lantuit et al. (2011) present an intriguing study of a permafrost-dominated shoreline in northern Siberia. They find that erosion is spatially highly variable but seemingly controlled more by the complex cryostratigraphy of sediments exposed at the shoreline than by local variations in wave heights. Erosion rates for five epochs between 1951 and 2006 show surprisingly little correlation with the frequency of storms, and local factors account for much of the variability in the efficacy of storms as agents of morphological change. Haerens et al. (2012) go some way to determining specific threshold storm conditions (e.g. offshore wave height, storm duration) for location-specific coastal response. There is, of course, much ambiguity in the definition of storms, which might make links to geomorphic response more tenuous, particularly when measures of storminess are extracted from metocean time series (Burningham and French, 2012).

## IV Modelling coastal responses to climate change

Predictive modelling at meso-scales is key to the successful anticipation and adaption to climate change at the coast (French and Burningham, 2009; Nicholls et al., 2012). The major challenge is that the timescales that matter for climate change take us out of our 'comfort zone' in terms of our ability to translate our understanding of coastal processes into models that retain a sound physical basis while at the same time demonstrating useful predictive skill. As Lane (2012) notes, the challenges of predicting complex non-linear system behaviour beyond the short timescales at which we can tightly specify governing physics and boundary conditions are not unique to geomorphology but apply equally to climate prediction itself. In a coastal context, geomorphology is arguably well placed to take a lead on predicting the impacts of alternative climate futures given that it can already draw on a range of modelling approaches that allow us to tackle the problem on multiple fronts.

For studies of regional change at scales of the order $10^2$ km, reliance continues to be placed on one-line models of shoreline evolution. Hoan et al. (2011) integrate a one-line model with an extended inlet reservoir model that is better able to resolve the complex shoreline changes that typically occur downdrift of inlets. Application to Long Island (New York, USA) shows that this approach is able to simulate both regional and local aspects of coastal change, including the effects of varying styles of inlet dynamics and different types of structural and non-structural engineering interventions. A problem with this approach is its reliance on the Bruun (1962) conceptualization of coastal profile response to sea-level rise (embedded in the one-line model), which has been extensively critiqued on account of its weak physical basis and low quantitative accuracy.

Physically based morphodynamic modelling continues to advance in ambition, aided by better data and the computational resources to explore a larger range of potential outcomes in a probabilistic manner. Typically, this involves sequential computation of hydrodynamics, sediment transport and the evolution of bed morphology within a morphodynamic feedback loop that operates at some multiple of the hydrodynamic time step. A variation on this theme is the use of a 'morphological acceleration factor' to upscale bed evolution at each hydrodynamic step in order to simulate change at longer timescales (Ranasinghe et al., 2011). Zhang et al. (2011) use this approach to hindcast the evolution of sandy beaches and cliffs of the Darss-Zingst Peninsula in the southern Baltic over the last 300 years. On this coast, past behaviour is primarily driven by the long-term effects of waves and longshore currents, with winter storms being a significant factor in certain areas. When their validated model is used to forecast change over the next 300 years with the addition of accelerated sea-level rise, most parts of the peninsula erode at a significantly faster rate. However, the upscaling factor is necessarily informed by a variety of factors, including the magnitude and non-stationarity in the hydrodynamic forcing, and the spatial discretization. Systems forced by a combination of tide and wave processes are particularly challenging to model at decadal scales and above. Brunneau et al. (2011) use a process-based morphodynamic model to investigate the morphological evolution of the Óbidos lagoon inlet, Portugal. A novel aspect of their work is the generation of synthetic wave climate spectra based on analysis of hindcast waves for a 57-year period, including seasonal and random interannual variability. Their results show that this system evolves towards one of two alternative stable states (with a third intermediate end point possible in the short term), a process that is ultimately more sensitive to progressive lagoon sedimentation under the influence of sea-level rise than to variation in wave direction.

In other contexts, longshore sediment transport may be much more sensitive to subtle changes in wind and wave direction that are poorly resolved by coarse climate model output. Various studies tackle the issue of appropriate downscaling of regional climate model outputs for use in simulating coastal wave climates. Charles et al. (2012) show that shifts in the wind systems both at the scale of the North Atlantic and within the Bay of Biscay drive offshore rotation of wave direction that has implications for nearshore processes. With reference to the Adriatic, Bellafiore et al. (2012) compare the ability of different regional climate models of the Mediterranean to resolve small-scale wind forcings that are significant drivers of coastal processes. They argue that, while an increase in spatial resolution yields more realistic forcing, an ensemble of downscaled climate models is most appropriate for coastal modelling purposes. A similar point is made by Zacharioudaki and Reeve (2011) in their analysis of beach response to changes in wave climate.

Simulation of coastal morphodynamics in a probabilistic framework remains prohibitively expensive using detailed process models. More promising are simplified ‘reduced complexity’ (RC) models that retain a mechanistic foundation but parameterize fine-scale processes that can be considered subgrid at a meso-scale. Ranasinghe et al. (2012) present a probabilistic coastline erosion model for beach-dune systems based on generation of synthetic storm series, IPCC predictions of sea-level rise, and a simplified model for dune erosion under the impact of waves (Larson et al., 2004). Run in a Monte Carlo framework, an application to Narrabeen beach (Sydney, Australia) yields probabilistic estimates of coastal recession that, unlike the widely used Bruun rule, are governed by physical processes. Results indicate a 50% probability that erosion will exceed 30 m by 2100, and 1% that it will exceed 45 m. By comparison, the Bruun model is very sensitive to assumptions regarding the offshore closure depth and, depending on the closure depth used, predicts erosion with an equivalent probability of exceedance from 8% to less than 1%.

One of the most successful hybrid RC models to date has been the Soft Cliff and Platform Erosion (SCAPE) model (Walkden and Hall, 2011). This combines a conventional one-line model with a model of the erosional adjustment of a cliff backshore and shore platform and changes in beach volume. It is a hybrid approach in that the one-line model assumes an equilibrium profile whereas the cliff and platform model does not. Applied at broad spatial and temporal scales (centennial- to millennial-scale simulations of 30 km of the Norfolk coast, eastern England), the form of the coast emerges from the dynamic interaction between profiles, longshore flux rates, and changes in imposed process forcing and engineered constraints. Ashton et al. (2011) investigate further one of the key emergent behaviours of the SCAPE model, namely that the equilibrium recession rate for soft rock cliffs can be approximated as the square root of the change in the rate of sea-level rise. They develop a more general theoretical framework from which it is implied that cliff coasts subject to different rates of sea-level rise can respond in qualitatively different ways. As one of the more promising coastal behaviour models, SCAPE is being extended to cover a wider range of backshore types as part of the UK Integrating Coastal Sediment Systems (iCOASST) project (Nicholls et al., 2012).

A rather different form of mathematical modelling has been used by Trenhaile (2011) to explore the relative sensitivity of both hard and soft rock cliffs to changes in sea level and storminess. His profile model incorporates the effect of wave impact and bottom stress across the intertidal and shallow subtidal zone, and was run for a 3100-year period that included various sea-level and wave climate scenarios for both the 20th and 21st centuries. Interestingly, the results show cliff erosion rate to be relatively insensitive to an increase in storminess (represented by an arbitrary 10% increase in deep water wave heights for waves >7 m). This is attributed to the fact that higher waves break in deeper water and dissipate their energy across wide, turbulent surf zones such that their erosional efficacy may actually be less than that of waves of more moderate height (see also Trenhaile, 2010).

Another area of emerging interest concerns the application of data-driven models in an effort to understand the structure of coastal behaviour and, importantly, to determine the reasons why prediction of meso-scale change is so difficult. This approach is exemplified at a landform scale by Pape and Reussink's (2011) use of a neural network model to hindcast cross-shore sandbar behaviour over timescales of months. Despite the non-linear relation between wave conditions and sandbar dynamics, reasonable hindcasting skill is achieved, although this breaks down during periods of lower wave energy. At longer timescales, Karunarathna et al. (2012) combine a behavioural model of beach profile evolution based on a 1-D diffusion formulation with a data-driven inverse scheme that resolves the unknown parameters in the model governing equation. In an application to the beach of Christchurch Bay, southern England, where measurements of cross-shore beach profiles and incident waves extends over two decades, their model shows good predictive skill. Reeve and Karunarathna (2011) use a broadly similar approach to predict decadal morphological evolution of the Humber Estuary, UK. This type of model can potentially be used to forecast future response to changes in wave climate and sea level, although the results are invariably site-specific and fundamentally constrained by the extent and quality of historical data. If the nature of the forcing changes, model predictions are likely to diverge markedly from observations. As such, their applicability remains limited, but this kind of modelling is likely to yield important insights into the coupling of climate and coastal dynamics as the duration of high-resolution monitoring data sets is extended.

## V Concluding remarks

Geomorphologists have long been concerned with deciphering and quantifying landscape responses to environmental change over a broad range of scales. Despite concern in some quarters over the apparent lack of impact of geomorphology on the work of the International Panel for Climate Change (see, for example, Lane, 2012), the endeavours of geomorphologists are clearly pivotal to understanding how coasts and their associated populations and infrastructures will be impacted by climate change in its various guises. Recent geomorphological work reveals the subtleties of coastal change and the need to go beyond the more obvious associations of climate change, sea-level rise and erosion to uncover the styles of landform change applicable to particular settings. Climate change at the coast is not a crudely global phenomenon but widespread changes in the globally connected climate-ocean system drive landform responses that are regionally and locally mediated by the contingencies of geography and geology. Integrated climate measures correlate with integrated responses, though not always for reasons commonly supposed, and wind directions and frequencies may be just as important as extreme magnitudes in driving coastal system change.

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