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Simulating mesoscale coastal evolution for decadal coastal management: A new framework integrating multiple, complementary modelling approaches

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ABSTRACT

Coastal and shoreline management increasingly needs to consider morphological change occurring at decadal to centennial timescales, especially that related to climate change and sea-level rise. This requires the development of morphological models operating at a mesoscale, defined by time and length scales of the order 10^1 to 10^2 years and 10^1 to 10^2 km. So-called 'reduced complexity' models that represent critical processes at scales not much smaller than the primary scale of interest, and are regulated by capturing the critical feedbacks that govern landform behaviour, are proving effective as a means of exploring emergent coastal behaviour at a landscape scale. Such models tend to be computationally efficient and are thus easily applied within a probabilistic framework. At the same time, reductionist models, built upon a more detailed description of hydrodynamic and sediment transport processes, are capable of application at increasingly broad spatial and temporal scales. More qualitative modelling approaches are also emerging that can guide the development and deployment of quantitative models, and these can be supplemented by varied data-driven modelling approaches that can achieve new explanatory insights from observational datasets. Such disparate approaches have hitherto been pursued largely in isolation by mutually exclusive modelling communities. Brought together, they have the potential to facilitate a step change in our ability to simulate the evolution of coastal morphology at scales that are most relevant to managing erosion and flood risk. Here, we advocate and outline a new integrated modelling framework that deploys coupled mesoscale reduced complexity models, reductionist coastal area models, data-driven approaches, and qualitative conceptual models. Integration of these heterogeneous approaches gives rise to model compositions that can potentially resolve decadal- to centennial-scale behaviour of diverse coupled open coast, estuary and inner shelf settings. This vision is illustrated through an idealised composition of models for a ~70 km stretch of the Suffolk coast, eastern England. A key advantage of model linking is that it allows a wide range of real-world situations to be simulated from a small set of model components. However, this process involves more than just the development of software that allows for flexible model coupling. The compatibility of radically different modelling assumptions remains to be carefully assessed and testing as well as evaluating uncertainties of models in composition are areas that require further attention.

1. Introduction

The increasing concentration of human populations close to open coast and estuarine shores places great pressure on the living and

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non-living resources of these coastal environments (Vitousek et al., 1997; Turner, 2000). These resources serve multiple human needs including settlement, marine energy, recreation, transport, aquaculture, as well as safety. Managing such competing interests requires a thoughtful and considered approach. A key area of difficulty stems from the extent to which diverse functions and values are underpinned by complex geomorphological systems in which landforms evolve dynamically under the influence of both natural and anthropogenic forcing (Valiela, 2006; Nicholls et al., 2007). Climate change is widely accepted to be one of the main drivers of coastal change (Wong et al., 2014), not only through accelerated sea-level rise (Pilkey and Cooper, 2004) but also through changes in wave climate and the attendant modification to alongshore sediment transport regimes (Chini et al., 2010; Chini and Stansby, 2012; Bonaldo et al., 2015). Since it is the morphology that mediates the linkage between marine and coastal processes and the risks of erosion and flooding, there is a pressing need for coastal geomorphic science to rise to the challenge of delivering an important contribution to the overall management of coastal communities in the face of increasing variability and change (see also Lane (2013)).

As French and Burningham (2009) argue, one of the grand challenges facing coastal geomorphology today is to improve our ability to make quantitative predictions of morphological change at a scale that is relevant to longer-term strategic coastal management. Following French et al. (this issue — a), this scale is herein referred to as the mesoscale, and is characterised by time horizons of the order 10^1 to 10^2 years and less rigorously imposed spatial dimensions of the order 10^1 to 10^2 km. Such predictions of coastal change should be delivered within an uncertainty framework that is robust enough to inform management and policy thinking. An additional tier of complexity stems from the extent to which natural geomorphic systems have been influenced by human activities (Haff, 2002). This is a particular problem at the coast, given the extent to which many decades or even centuries of coastal protection, estuarine reclamation, dam construction and dredging have led to the depletion of natural sediment systems (Komar, 1999; Lotze et al., 2006) and now constrain the adjustment of landforms to changes in sea level, wave climate, and other drivers (Hapke et al., 2013).

The problematic nature of mesoscale coastal change prediction originates in several ways. This scale, for example, is awkwardly placed between more traditional areas of research that address either smaller scale processes, which have been investigated through detailed observational, experimental and modelling studies, or larger scale coastal evolution, which has been the subject of many geological studies based on the analysis of stratigraphy and resulting conceptual models (French and Burningham, 2009). As Woodroffe and Murray-Wallace (2012) note, whilst empirical investigations of past coastal evolution can readily draw upon techniques that transcend a broad spectrum of scales, the range of modelling approaches that can be deployed on the prediction of future changes is more limited (Fig. 1). Also, mesoscale coastal behaviour is driven by a large number of processes that include not only the more fundamental mechanics of fluid motion but also a multitude of sediment transfers, morphodynamic feedbacks and biological influences, the relative importance of which is usually difficult to determine a priori (Payo et al., this issue). From a modelling perspective, this implies a difficulty in defining what processes need to be incorporated and how they should be considered. This is a crucial task that requires considerable attention during model development.

Whilst advances in computer technology have allowed researchers to apply models, based on reductionist process-knowledge, to larger-scale highly idealised problems (Hibma et al., 2003; van der Wegen et al., 2008; van Maanen et al., 2013a), up-scaling such models to issues involving mesoscale morphological change in more realistic case studies is far from straightforward (Huthnance et al., 2007; Murray, 2013). Within geomorphology more generally, there is considerable interest in so-called 'reduced complexity' models that focus more directly on the subset of processes and feedbacks that are essential to explain a particular phenomenon (e.g. Murray and Paola, 1994; Coulthard et al., 2002; Seybold et al., 2007; Nicholas, 2010; Walkden and Hall, 2011). Reduced complexity modelling entails a more synthesist approach to explanation (Paola, 2000) that contrasts with the tendency towards reductionism that underpins models that incorporate finer-scale aspects of hydrodynamics and sediment transport (Nicholas and Quine, 2007; French et al., this issue — a). Matters of terminology aside, the reduced complexity/synthesist modelling approach has proven effective in exploring the process of emergence and explaining poorly understood behaviour (Ashton et al., 2001). There is the question whether the simplifications involved in reduced complexity modelling can make such approaches less suitable for precise predictions (Murray, 2003). Indeed, there is debate in some quarters over the extent to which reduced complexity models can be made sufficiently robust to provide the quantitative insight required for effective management (Ziliani et al., 2013). Over recent years, however, studies have started to successfully apply this modelling approach to real coastal issues, including rapidly eroding cliffs and the related assessment of various management scenarios (Walkden and Hall, 2011; Walkden et al., 2015).

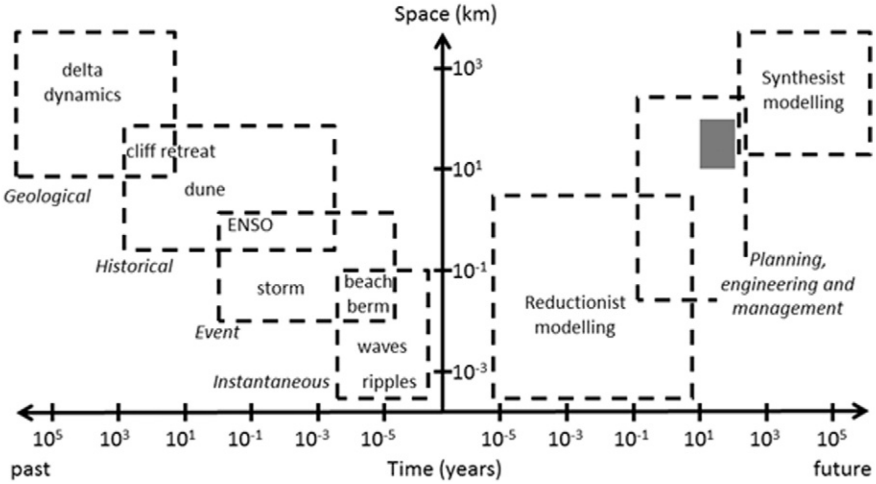

Fig. 1. A comparison of space and time scales relevant to the analysis of observed coastal processes and morphodynamic behaviour (left-hand axes; based on Cowell and Thom (1994) and Woodroffe (2002)), and indicative ranges for which reductionist and synthesist modelling approaches have traditionally been used (right-hand axes). The mesoscale (indicated by the grey region) lies within the 'Planning, engineering and management' scale, situated at the intersection of the more traditional approaches.
Adapted from Woodroffe and Murray-Wallace (2012).

At the same time, the capability of models based on more fundamental hydrodynamic and sediment transport processes has continued to evolve. A key development on this front is the harnessing of the power of distributed computing to allow numerical solution of the equations of fluid motion at much larger spatial scales whilst simultaneously increasing the spatial resolution (Cowles, 2008; Amoudry and Souza, 2011). In addition, a variety of data-driven approaches have been developed that utilise the expanding archive of observational data to reveal causal linkages from analyses of past morphological change and, potentially, generate quantitative predictions of future change (Reeve and Karunarathna, 2011). Finally, new qualitative modelling approaches have also emerged, which can inform the specification of model domains, component landforms and human influences (French et al., this issue — b), as well as identify the key feedbacks that need to be represented mechanistically in order to capture the essence of the overall system behaviour (Payo et al., this issue).

From the preceding overview, it is evident that there continues to be significant progress in the rather separate fields of reduced complexity and reductionist modelling, as well as in data-driven and conceptual modelling. Viewed in isolation, all these developments have the scope to inform and improve our understanding of coastal evolution at the mesoscale. However, if we can integrate them into an overarching framework, where the approaches inform each other, we believe significant progress can be made (Nicholls et al., 2012). Previous studies that have combined conceptually different modelling approaches, such as Dawson et al. (2009) who adopted extensive reductionist wave modelling in combination with reduced complexity morphodynamic modelling, have proven the additional merit of model integration. Effectively integrating models that are based on different fundamental visions and assumptions and operate over different spatial and temporal scales is, however, not trivial (Voinov and Shugart, 2013; Sutherland et al., 2014) and this process would benefit from a more formal framework that highlights the potential links between the various approaches. Accordingly, in this paper we present an overall vision for a hierarchical modelling framework for mesoscale coastal change that is intended to help facilitate the overall integration process. It considers the open coast, estuaries and the inner shelf and their interactions as a coupled system, including all phases of sediment, from fine-grained transport of silts and clays potentially at the scale of shelf seas, to non-cohesive sediment transported at the scale of littoral cells and sub-cells.

The paper is structured as follows. Section 2 elaborates on the specific characteristics and relative strengths of reductionist and reduced complexity models. The framework to integrate the varying modelling approaches is presented in Section 3, and in Section 4 this modelling framework is illustrated with reference to the Suffolk coast, eastern England. Section 5 considers the practical difficulties of linking models, both conceptually and in software. Finally, Section 6 considers some issues associated with model evaluation and application within a probabilistic uncertainty framework.

2. Reductionist versus reduced complexity models

The possibility of easily adjusting both boundary and forcing conditions has made the application of models to study the geomorphological evolution of environmental systems increasingly popular. Different types of models are available, and equally diverse is the modelling typology. One class of models are built upon a detailed description of the faster and smaller scale processes. These models, commonly referred to as 'bottom-up' or reductionist models, are developed by attempting to include all the processes that can potentially affect the system's evolution as accurately as practical (Murray, 2003; Huthnance et al., 2007). The possibility of adopting this approach for simulating mesoscale morphological evolution has been questioned (De Vriend et al., 1993); debate exists whether the process representations adopted within reductionist models can ever be accurate enough and sufficiently complete to reproduce the non-linear and complex behaviour that drives coastal evolution, and whether they allow for all potential response pathways and system states (see also Phillips, 2007). Irrespective of the computing power available, error propagation when up-scaling from the faster and smaller scale processes to the scale of interest is likely to hinder the ability of reductionist models to deliver quantitatively accurate predictions for the mesoscale (Murray, 2013).

More synthesist models (Paola, 2000) represent an alternative and contrasting approach. Murray (2007) describes this class of models as those that are built upon the modelling strategy of explicitly representing only processes and interactions on scales not too much smaller than those of interest — and parameterizing (rather than explicitly simulating) the pertinent effects of the much faster and smaller scale processes. In geomorphology, this approach has given rise to a plethora of so-called reduced complexity models, chiefly related to aspects of river channel evolution and fluvial landscape evolution (Nicholas and Quine, 2007; van De Wiel et al., 2007). Theoretically, this approach rests on the 'emergent phenomena' perspective, in which the collective behaviours of many degrees of freedom can lead to the emergence of effectively new variables and interactions that operate on larger spatial and temporal scales (Werner, 1999). In this context it is worth mentioning that the concepts of eliminating unnecessary detail to focus on the scale of interest essentially apply to all scales and virtually all forms of environmental modelling involve choices in the level of complexity that is both tractable and appropriate for the problem being addressed (see also Nicholas and Quine (2007)).

There is clearly merit in addressing challenges of coastal management by defining the processes and variables that are most relevant at the mesoscale defined above. Following this approach, the pitfalls related to model imperfections cascading upward through the scales can be avoided (Murray, 2013). Of course, for such models to be quantitatively reliable, the parameterizations – which initially can even consist of poorly constrained 'rules' – must be honed by synthesising the results of observations and detailed modelling. The construction of more synthesist models can be challenging as reliable parameterizations might not be readily available and obtaining well-accepted parameterizations of the faster and smaller scale processes is not always straightforward.

Apart from the more philosophical questions of how to simulate multi-scale systems and whether or not it is possible to accurately predict large-scale morphodynamic behaviour starting from the faster and smaller scale processes, there are additional concerns when applying reductionist modelling techniques to the mesoscale. Reductionist models are computationally intensive and even though our ability to perform computationally demanding simulations is likely to keep on increasing (especially through various forms of parallel computing), using these models to perform regional- and decadal-scale simulations of morphological change becomes problematic from a practical point of view. In this context, however, it is worth noting that strategies have been developed that allow reductionist coastal area models to be used in the study of mesoscale coastal change (Coco et al., 2013). These strategies involve innovative morphodynamic updating techniques and are used to bridge the gap between short-term hydrodynamic and transport processes, varying over hours to days, and morphological changes, often taking place over much longer time periods (Roelvink, 2006). Modelling approaches adopting this technique have been particularly useful in exploring the formation and evolution of channel networks in highly idealised tidal settings (Hibma et al., 2003; Marciano et al., 2005; Dastgheib et al., 2008; van der Wegen et al., 2008; van Maanen et al., 2011). Recently, this development has also resulted in the successful application of reductionist coastal area models to simulate decadal morphological evolution of real estuarine systems (Ganju et al., 2009; van der Wegen et al., 2011; van der Wegen and Jaffe, 2013). A probable reason for this success lies in the fact that these studies address confined and highly constrained systems. In the morphodynamic prediction, the interaction of the major tidal movement with the initial bathymetry and the estuarine plan form likely dominates the variability from uncertain model inputs and process definitions (e.g. the applied sediment transport formulations or initial bed composition). Hence, despite these promising modelling efforts, it remains uncertain whether this approach can be easily extended to other coastal systems. Also, the computational demand is likely to remain an issue, especially given the need to predict future changes within a probabilistic uncertainty framework, which implies large ensembles of model runs.

The degree to which physical processes can be parameterized varies widely, ranging from only subtle simplifications to highly abstracted representations of the smaller and faster scale processes. The latter type of model has been especially successful in discovering the essential processes responsible for the emergence of large-scale geomorphic patterns (e.g. Ashton et al., 2001). As pointed out by Murray (2007), however, those models that attempt to include only a minimum number of processes with the aim of gaining maximum insight are not necessarily capable of addressing more specific questions, such as management problems in real world settings. In this context, models can be too abstract for some purposes. This inevitably leads to challenges when simulating the mesoscale, as models should be computationally efficient, but also capable of resolving the dynamics that are of interest to coastal engineers and managers.

The modelling tool SCAPE (Soft Cliff And Platform Erosion; Walkden and Hall (2005)) is an example of a mesoscale reduced complexity model that has been used to answer real-world coastal management questions. Its applications have ranged from local studies of shore erosion to the simulation of large-scale coastal management strategies (Dickson et al., 2007; Appeaning Addo et al., 2008; Dawson et al., 2009). SCAPE is conceptually related to models like that of Ashton et al. (2001) in that dynamic behaviour emerges from the key real-world interactions that are simulated. The approach taken to develop this model was distinct, however, in that it was implemented for specific locations and was designed from the outset to also represent engineering interventions, such as seawalls and groynes. This led to the inclusion of a greater number of processes and a broader system of interactions. While this was necessary for the purposes of coastal management, it increased the need to rely more heavily on poorly constrained behavioural rules. Although the application of SCAPE and the comparison to field observations show that this approach has worked well, it is important to note that when the number of included processes needs to be increased, one must adhere to the underlying conceptual framework of the model. Also, increasing the number of processes modelled carries the danger that insights might be obscured due to the lack of clarity over which processes are governing the behaviour. Despite these dangers it will often be necessary, for the purposes of coastal management, to capture a broad set of processes and interactions.

3. Framework for model integration

3.1. Framework description

Since reduced complexity models have already been successfully applied to real coastal management issues, and this type of model has proven to be effective in simulating realistic emergent behaviours and geomorphic change over larger spatial and temporal scales (Walkden and Hall, 2005; Dawson et al., 2009), it is worth further exploring the full potential of this modelling strategy in generating quantitative predictions of mesoscale coastal evolution. The applicability of mesoscale reduced complexity models can potentially be enhanced by integrating them within a framework that is structured by overarching conceptual models and also includes more reductionist coastal area models and data-driven analyses. Such an approach, as schematised in Fig. 2, also brings the hitherto largely separate modelling communities in these four areas together to exploit the complementary insights that these diverse approaches have to offer. Reduced complexity models occupy a central position within the proposed framework as the primary means of simulating coastal geomorphic behaviour. It should be noted though that these models are closely linked to the other approaches and that information exchange is of key importance. To highlight the type of information that is being exchanged, we briefly outline the main capabilities of conceptual models, coastal area models and data-driven approaches to show how these can better inform the construction and application of the mesoscale reduced complexity models.

3.2. Conceptual models of coupled coastal, estuarine and inner shelf systems

Simulating mesoscale coastal evolution requires a system-level approach and appreciation of the interactions that occur between the open coast, estuaries, and the shallow sea bed. The process of conceptually analysing the coast highlights this interconnectivity, and this has recently been strengthened by the development of a formal Coastal and Estuarine System Mapping (CESM) approach (French et al., this issue — b) that re-engages with systems theory and builds on established conceptual frameworks such as the coastal tract concept of Cowell et al. (2003). CESM is founded on a hierarchical ontology of component landforms (e.g. spit, ebb delta, tidal flat, cliff, dune, inner shelf banks) that are organised into larger-scale open coast, estuary or inner shelf complexes. These natural features are supplemented by human interventions, which may be structural (e.g. seawalls, groynes) or non-structural (e.g. beach nourishment, dredging). System maps are configured with reference to sediment pathways as well as influences (such as the effect of a jetty on an inlet channel) that are not associated with a mass flux. Although CESM can be a pencil and paper exercise, it is supported by software that allows mapping to be undertaken within a geospatial context, aided by informative secondary datasets describing coastal geology, terrain, erosion and flood defence infrastructure and even modelled residual sediment transport vectors from coastal area models.

CESM captures a system state averaged over a time interval that is long enough to exclude extraneous variability (e.g. seasonal beach rotation), but short enough to exclude trends that lead to gross changes in configuration (though localised state changes, such as barrier breakdown, can be included if these are persistent and relevant to the mesoscale; French et al. (this issue — b)). As such, it is useful for specifying the specific landform systems that need to be modelled. An additional stage of conceptual modelling that can further guide not only the selection but also the evaluation of more mechanistic models involves the application of causal loop analysis (Lane, 2000). This uses causal loop diagrams to indicate the positive and negative feedbacks between state and flow variables and determine, ahead of more quantitative modelling, whether processes are likely to have a reinforcing or a balancing effect. As such, a more detailed overview of the structure and functioning of geomorphic systems can be attained. Payo et al. (this issue) show how causal loop analysis can be applied to the coastal system at different scales, ranging from the active layer, through landforms, to landform complexes. The role of causal loop diagrams becomes particularly evident when assessing the importance of individual processes in driving overall system behaviour.

Within the integrated modelling framework (Fig. 2), system maps and causal loop diagrams can be used jointly to define the extent of the model domain and the landforms and landform complexes that need to be simulated by the mesoscale reduced complexity models. They also guide the construction of the latter (arrow 1 in Fig. 2). In essence, the conceptual models inform the decision making of what processes, interactions and human influences should be included within the geomorphic models and what can be excluded without neglecting relevant geomorphic behaviour. This is of particular importance when considering the mesoscale as it can be a daunting task to identify the key governing processes over these larger temporal and spatial scales. As such, the conceptual analysis of the coast provides a platform that

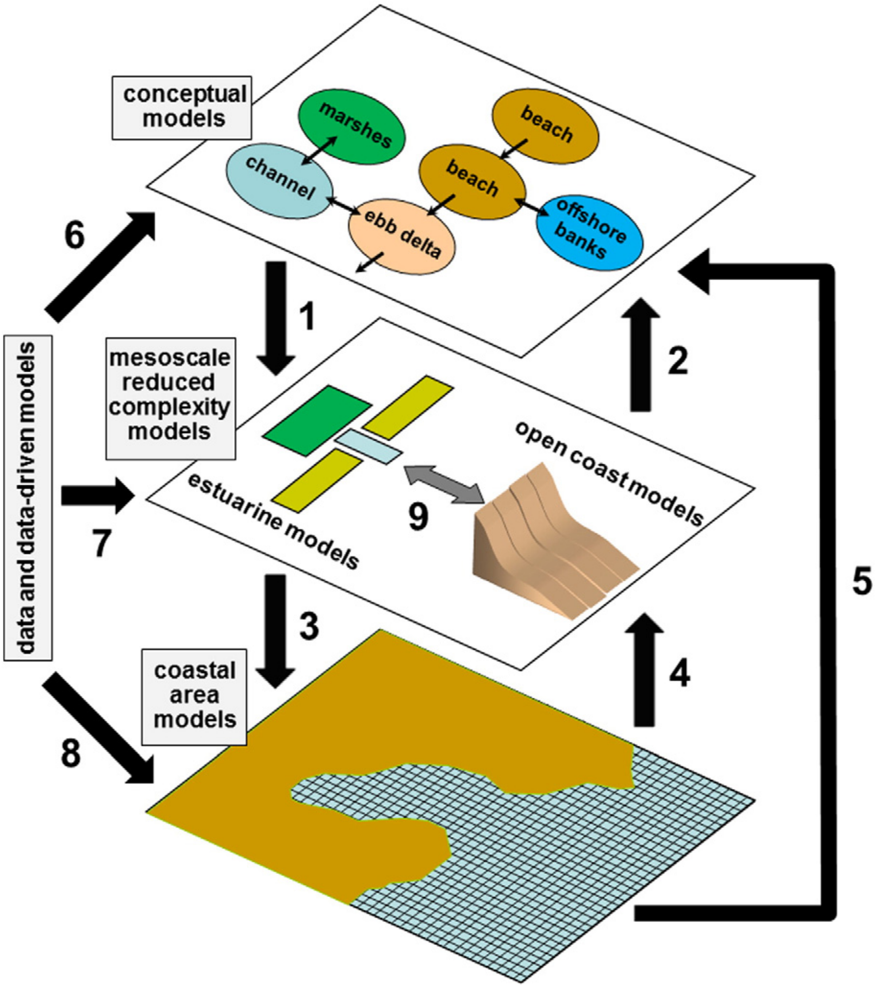

Fig. 2. Proposed modelling framework to simulate coastal evolution at the mesoscale, defined by length scales of the order 10^1 to 10^2 km and timescales of the order 10^1 to 10^2 year. The framework integrates mesoscale 'reduced complexity' models with conceptual models and reductionist coastal area models, supported by data and data-driven techniques. The arrows highlight the links between the various approaches. The numbers are only used as reference in the main text, and do not indicate a sequence of interconnections.

facilitates the development and deployment of quantitative models and is thus a key aspect within the integrated framework. Reduced complexity models can, in turn, play a potential role in the testing of the conceptualisations represented by the system maps by revealing key interactions between geomorphic subsystems at the landform scale (arrow 2 in Fig. 2).

3.3. Reductionist coastal area models

Reductionist coastal area models describe hydraulic and sediment transport processes on a high resolution grid (of the order 10^0 to 10^2 m) with small time steps (typically seconds to minutes). They are capable of resolving flow circulation patterns and sediment transports over spatial scales ranging from large parts of the continental shelf (Souza et al., 2007) down to the scales of morphological features typically found in coastal environments (e.g. channel-shoal patterns, mudflats and salt marshes) (Brown et al., 2015). Many commercial and research coastal area model codes are available. Examples are Delft3D (Lesser et al., 2004), ROMS (Warner et al., 2008), POLCOMS (Souza et al., 2007), the MIKE suite of models (Jacobsen and Rasmussen, 1997), TELEMAC (Le Normant, 2000), and FVCOM (Chen et al., 2003). Most of these packages may be run in 2D or 3D mode and include coupling to short wave generation and propagation models like SWAN (http://www.swan.tudelft.nl/) to account for wave-current interactions and the combined effect of waves and currents on bed shear stresses (e.g. Warner et al., 2010). Density currents triggered by temperature and salinity gradients in shelf seas or salt-fresh water interaction in estuaries are examples of complex and turbulent hydrodynamic processes that are covered by these coastal area models. Sediment transport modules describe the pathways of sand and mud movement due to tides, waves and residual circulation currents. Hydrodynamic and sediment transport computations can be conducted as part of stand-alone modules, or in combination with a final module that includes morphodynamic calculations by updating the bed level based on divergence of the sediment transport field and feeding back the updated bathymetry in a subsequent time step (Latteux, 1995; Roelvink, 2006).

The interactions between the shelf, open coast and estuaries have often been ignored, being placed in the 'too difficult' category. With regard to the model integration framework in Fig. 2, an obvious role for coastal area models lies in the provision of the boundary conditions for the mesoscale reduced complexity models (arrow 4 in Fig. 2). Information in terms of hydrodynamic forcing such as tidal elevations and wave conditions can be provided, as well as sediment availability by simulating continental shelf-scale sediment budgets and pathways. These types of boundary conditions are likely to be affected by climate change and coastal area models are therefore expected to provide a range of plausible scenarios. Also, these more reductionist models can potentially play a role in testing some of the hypotheses applied in the reduced complexity models. In turn, an exchange of information exists in the opposite direction: simulating mesoscale behaviour of landforms and landform complexes involves quantification of sediment sources and sinks, and this type of information can be fed back into the coastal area models (arrow 3 in Fig. 2). In addition to this two-way coupling, the large-scale sediment pathways simulated by the coastal area models can be used further to inform and validate the conceptualisation of mesoscale open coast-estuary-shelf interactions derived from CESM (arrow 5 in Fig. 2). Hence the models can be applied in qualitative and quantitative modes.

Although coastal area models in the framework proposed here are not directly used for morphological predictions, they do play a crucial role in informing the morphodynamic modelling. As with all models, it thus remains necessary to be fully aware of their limitations. Sediment transport modelling, in particular, is still mainly based on empirical expressions (Amoudry and Souza, 2011). Sediment diffusivities, settling velocities, and cohesive processes like flocculation all have an impact on the dynamics of sediment. The performance of reductionist models is clearly dependant on how well these aspects are represented and parameterized. In addition, the proper implementation of closure models for turbulence and mixing is challenging but nevertheless essential to quantitatively predict sediment dynamics and resulting net fluxes (Wang et al., 2012). Fortunately, the level of description and the accuracy of coastal area models have greatly improved over the last few decades and ongoing developments will almost certainly continue to improve their predictive abilities.

3.4. Data and data-driven approaches

The increasing pressure on coastal geomorphic systems and the growing awareness that these systems are highly dynamic have resulted in the implementation of systematic coastal monitoring programmes (Bradbury et al., 2002; van Koningsveld and Mulder, 2004; Nicholls et al., 2013). The extensive datasets that are being obtained by these programmes provide a major source of scientific insights. Some of these datasets are now also sufficiently extensive to be used for a range of different data-driven methods. For example, advanced statistical analysis techniques such as wavelet analysis can be used to identify certain patterns of behaviour within a dataset (Short and Trembanis, 2004). These behaviours can then be used to make predictions of future change based on appropriate extrapolation. Additionally, techniques are available to reveal links between datasets of two or more different variables. An example is canonical correlation analysis and Horrillo-Caraballo and Reeve (2008) showed how such a method can be used to make predictions of an unknown variable, such as beach morphology, based on another variable for which projections into the future do exist, such as wave height.

Apart from using data time-series to make direct predictions based on the extrapolation of trends and behaviours, the knowledge and insights obtained by analysing coastal measurements can also be used to inform and construct the reduced complexity models (arrow 7 in Fig. 2). A simple example is the inclusion of an equilibrium beach profile, derived by extensive empirical studies (Bruun, 1954; Dean, 1977), within a model such as SCAPE (Walkden and Hall, 2005). A large number of equilibrium models are also available for tidal inlet systems, including the well-known relationship between tidal prism and the cross-sectional area of the channel (O'Brien, 1931, 1969; Jarrett, 1976). Similar types of empirical relationships exist between tidal prism and ebb-tidal delta volume (Walton and Adams, 1976), and basin area, tidal range and flat volume (Eysink and Biegel, 1992). ASMITA is an example of a reduced complexity model that adopts these empirical relationships to simulate the mesoscale evolution of tidal embayments and estuaries (Stive et al., 1998; Rossington et al., 2011).

Another class of data-driven approaches is based on machine learning techniques. Their applicability in a variety of coastal disciplines has rapidly increased over the past few years. Examples of machine learning techniques include artificial neural networks, boosted regression trees and genetic programming. These techniques are highly effective in linking input and output vectors and have been used to develop powerful predictors in the field of hydrodynamics (Tsai and Lee, 1999; Sztobryn, 2003; Browne et al., 2007), sediment dynamics (van Maanen et al., 2010; Oehler et al., 2012; Yoon et al., 2013; Goldstein and Coco, 2014), and morphodynamics, as shown by Tsai et al. (2000) who used neural networks to study beach profile evolution. Recently, Goldstein et al. (2014) extended the use of machine learning techniques by incorporating the generated predictors (in this case of near-bed reference concentration and ripple geometry) into a numerical model of inner-shelf sorted bedforms. The new hybrid model was reported to be capable of generating novel autogenic behaviour. This demonstration of successfully adding machine learning components to a process-based numerical model suggests that a similar strategy could be adopted when constructing mesoscale reduced complexity models, as these models could also benefit from including predictors gained through machine learning applications.

It should be noted that regardless of whether data-driven methods are applied to make direct predictions or used to construct and inform reduced complexity models, the applicability of these methods is limited by the range of conditions which are covered by the dataset from which they are derived. An additional concern is that data-driven approaches can provide only limited physical insights, although they do allow the formalised exploration of large data sets. Data-driven approaches are often seen as black-boxes with little, if any, capacity to enhance understanding of the dataset from which they have been derived (Cunge, 2003). Although interpreting the knowledge gained by black-box type models is not straightforward, a variety of methods is available that can help to overcome this disadvantage and which can be used to analyse the dataset and the physical processes involved (e.g. Gevrey et al., 2003).

Fig. 2 also depicts an exchange of information from observational data to the conceptual models (arrow 6 in Fig. 2) and to the coastal area models (arrow 8 in Fig. 2). In the former case, this link represents the feed of quantitative information into the system maps. With respect to the latter, coastal measurements are vital in testing the ability of the coastal area models to provide realistic large-scale sediment pathways and hydrodynamic forcing conditions for the reduced complexity models.

4. Example of an integrated modelling approach — the Suffolk coast

4.1. Description Suffolk coast and problem definition

The idealised framework set out above can be illustrated with reference to the Suffolk coastal system, on the east coast of the United Kingdom (Fig. 3). This system hosts numerous human developments (towns, villages and a nuclear power station) and important nature designations (e.g. Minsmere) situated on a variety of soft landforms including sedimentary cliffs and low lying land fronted by beach ridges. Previous modelling studies have investigated decadal morphological evolution of the coast in northeast Norfolk, which is situated near Suffolk. However, that study site is relatively uniform with an almost continuous line of cliffs. In Suffolk, the coastal system is more complex, being characterised by the presence of controlling soft headlands and forelands, several estuaries, a more-or-less continuous sand and gravel littoral drift system (Pontee, 2005; Burningham and French, 2015a), and links between the nearshore and offshore sandbank systems. Sea cliff retreat can reach several metres per year (Brooks and Spencer, 2010), posing a direct threat to coastal communities (Fig. 4).

Certain aspects of coastal processes and geomorphic behaviour in Suffolk have been previously explored. Detailed tidal modelling of the Blyth estuary (Fig. 3), for example, has been conducted to study potential effects of sea-level rise on peak currents and discharges (French, 2008), while regional wave modelling, on the other hand, has helped to appreciate the complexity of the littoral drift system (French and Burningham, 2015). In addition to these modelling efforts, the analysis

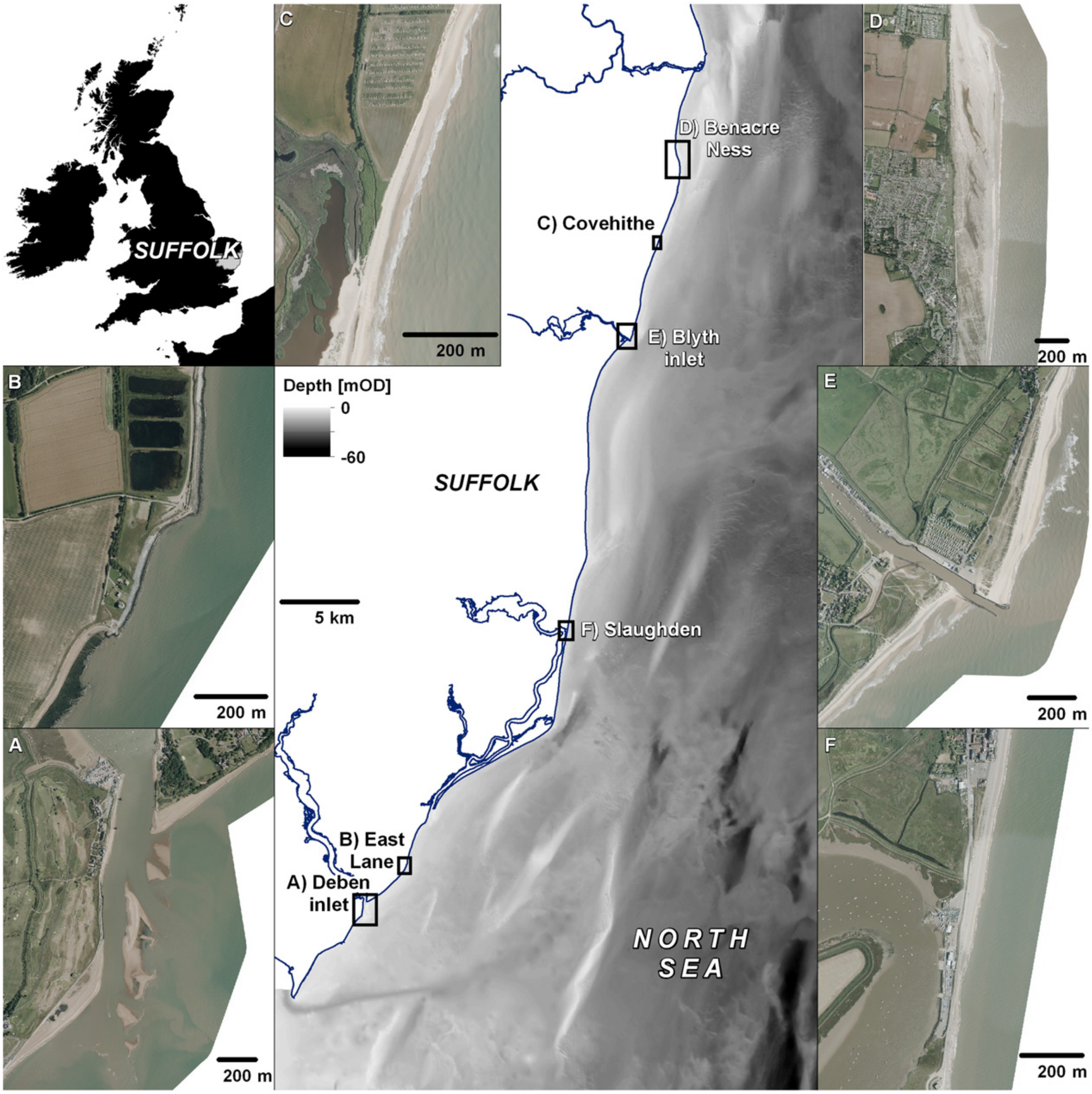

Fig. 3. Location and offshore bathymetry of the Suffolk coast. Aerial photos highlight the morphological variability and human interventions that need to be represented within the modelling approach.
Photo courtesy of the Environment Agency.

of historical maps, charts and photographs has provided key insights into long-term coastal erosion and the complex behaviour of the ebb-tidal shoal systems at the estuarine mouths (Burningham and French, 2006, 2007, 2015b; Pye and Blott, 2006; Brooks and Spencer, 2010). These studies have significantly advanced our understanding of individual elements of the Suffolk coastal system. However, they do not address how the morphology of such a highly interlinked system will evolve under future conditions, and an integrated approach that fully appreciates the interconnectivity between the estuaries, open coast, and offshore topography is still missing. This is needed not only because sea-level rise and a changing wave climate are likely to have a dominant effect on coastal behaviour, but also to assess the effects of existing sea defences in the future and the suitability of proposed interventions. For example, the East Lane defences constructed north of the Deben estuary (Fig. 3) interrupt the transport of beach-grade sediment, which is considered to deny supply to the Deben and the Felixstowe frontage further south (Environment Agency, 2010). The present Shoreline Management Plan (Suffolk Coastal District Council, 2010) prescribes to 'Hold the Line' and maintain the hard structures, but that continuation of this policy over the long term at East Lane is subject to on-going monitoring. The cliffs immediately south of the defences are currently retreating faster than elsewhere in Suffolk, but closer towards the Deben inlet, the cliffs are relatively stable (Burningham and French, 2015b). The alongshore, potentially cascading connection, and the linkages between sediment transport, supply and landform behaviour are poorly understood, especially in the context of changing forcing conditions.

4.2. Modelling mesoscale evolution of the Suffolk coast

4.2.1. Composition of open coast and estuary models

The sequence of open coast sections interrupted by estuaries (see also French et al. (this issue — b)) suggests that the mesoscale morphological behaviour of the coast as a whole might best be handled using a composition of coupled landform complex models (Fig. 5a; see also arrow 9 in Fig. 2, which represents the coupling of multiple landform

Fig. 4. Rapidly eroding soft rock cliffs along the Suffolk coast (close to Southwold) with residential properties only a few metres from the cliff edge. Photo courtesy of Dr. Sally Brown.

behaviour models). Different models are already available that could be used to simulate some of the interactions occurring on the open coast. The aforementioned SCAPE model, for example, has been shown to represent the emergence of realistic soft rock and beach profile geometries, and mesoscale planform evolution (Walkden and Hall, 2005). SCAPE has also been used to explore the sensitivity of cliff recession rates to changing management practise (Dickson et al., 2007). Although soft rock cliffs are a locally dominant feature, the open coast of Suffolk is also characterised by the presence of barrier beaches, which separate (and protect) various lagoons from the sea (Spencer and Brooks, 2012). The morphodynamic behaviour of such barriers can be rather complex, especially in the context of sea-level rise (Lorenzo-Trueba and Ashton, 2014). For management purposes, it is important to address the potential of barrier overwashing/breaching processes as this can result in temporary or permanent state-changes (Pontee, 2007). The processes and feedbacks that drive the evolution of these barriers thus need to be incorporated, requiring extension of available open coast cliff-beach models or the coupling of such models to distinct barrier models.

In the Suffolk composition, open coast models need to be applied in conjunction with estuarine models (blue components in Fig. 5a). Estuarine dynamics can have profound and far-reaching effects on the adjacent coastline as these systems may act as sediment sinks or sources. In this context, it is important to note that the import or export of sediment might change in the future as a result of sea-level rise (van der Wegen, 2013; van Maanen et al., 2013b) or human interventions such as managed realignment (French, 2008). Comprehensive treatment of the Suffolk coast thus requires modelling of the estuarine

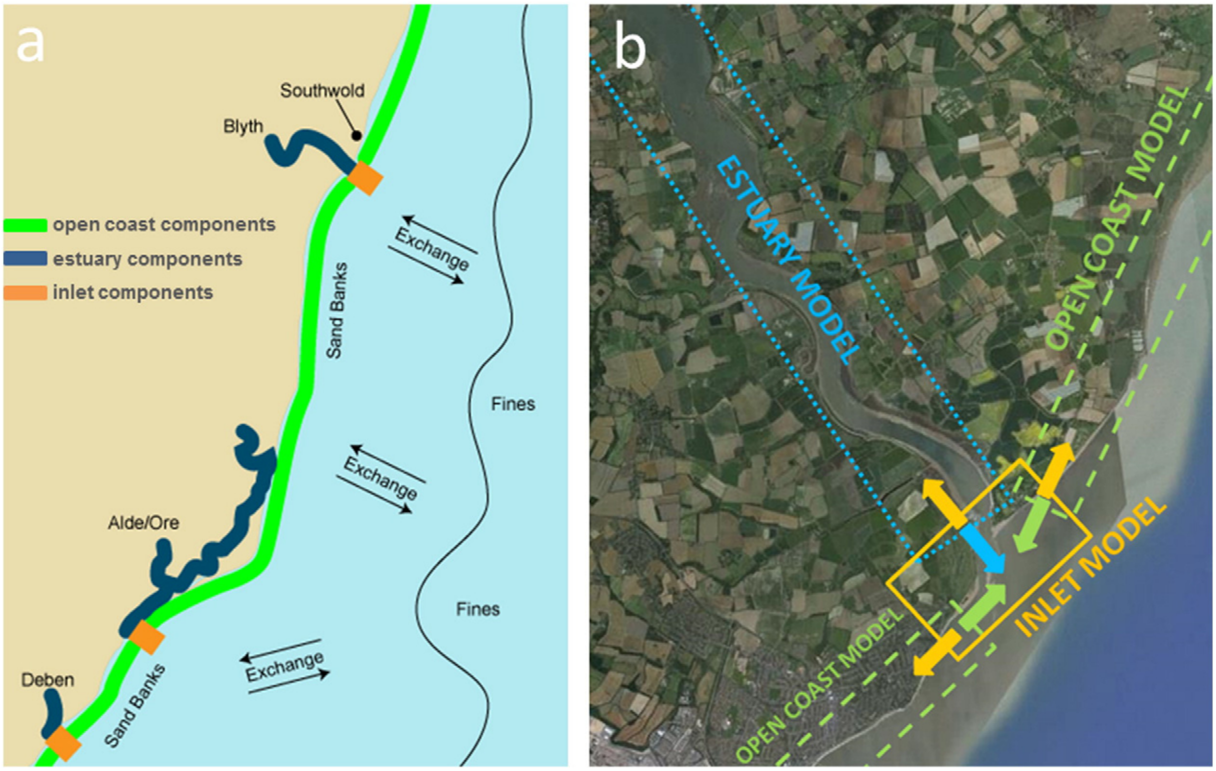

Fig. 5. (a) Schematisation of a possible composition of reduced complexity models for a ~ 70 km long section of the Suffolk coast. The composition comprises coupled models of the open coast, estuaries and their inlets. (b) Detailed view of a possible modelling composition for the Deben estuary and adjacent shorelines. The arrows indicate information exchange between the different models, both in terms of sediment fluxes and hydrodynamic data.

systems of the Blyth, Alde/Ore and Deben (Fig. 3 and blue components in Fig. 5a). Long-term morphological dynamics in estuarine and lagoonal systems are often described in terms of perturbations with respect to an equilibrium condition that can be formalised in terms of a relationship between hydrodynamics and morphology or between hydrodynamics and sediment transport regime. ASMITA (Stive et al., 1998) is one such model that uses such empirically derived equilibrium relationships that are available for estuarine environments. It has been widely used in the study of Dutch Wadden Sea inlets to explore sea-level rise effects (van Goor et al., 2003) and to hindcast and predict the morphological response to the closure of the Zuiderzee (Kragtwijk et al., 2004). More recently, the application of ASMITA was extended to include UK estuaries and it was shown that the effects of dredging and reclamations could be accurately reproduced (Rossington et al., 2011). The ability to capture the effects of human interventions is of key importance when modelling the Suffolk estuaries as these systems have undergone major transformations in the past and further interventions are expected in the future, especially now that managed realignment is growing in popularity as a means of flood defence and to restore ecosystem functions (French, 2008). Other mesoscale estuarine models exist and in addition to the available modelling tools based on equilibrium concepts, it is worth mentioning here that developments have been carried out towards generating novel models of estuarine behaviour that apply cellular automata and/or other highly parameterized routing schemes to simulate tidal flows and morphodynamics (Dearing et al., 2006; D'Alpaos et al., 2007; Kirwan and Murray, 2007; Bentley and Karunarathna, 2012; Thornhill et al., 2015). These models are far less computationally intensive than traditional reductionist models, and can potentially resolve a richer set of behaviours than models confined by empirical equilibrium relationships.

Simulating coastal behaviour at the regional scale envisaged here requires capturing the exchanges and feedbacks between estuarine environments and the open coast. Although our knowledge of the governing processes at this interface is often limited, various approaches exist that might facilitate our representation of the open coast-estuary coupling. De Vriend et al. (1994), for example, connected a tidal inlet with the adjacent coast by building a behavioural model for the outer delta, adjusting a two-line model for uninterrupted coasts to include the principal transport mechanisms near the inlet. Kraus (2000) presented a model that can be used to calculate sand-bypassing rates at ebb-tidal shoals. Ebb delta volumes and the bypassing mechanisms are computed by analogy to a reservoir system, where each reservoir can fill to a maximum (equilibrium) volume. This model has been applied in numerous engineering and science studies and it has also been adopted to study broader scale morphodynamic change (Hanson et al., 2011). Existing ebb-tidal delta models have almost all been developed for sandy environments and this will need adapting for the mixed sand-gravel inlets and shoals that characterise the Suffolk coast (Burningham and French, 2006, 2007). These inlet models will sit in between the models that simulate the behaviour of the open coast and estuaries (Fig. 5b) and a continuous exchange of information will occur between all these components, both in terms of sediment fluxes and hydrodynamic data. Such a model composition can then be used to study future morphological change under scenarios of sea-level rise, changing wave climate, and different open coast and estuary management strategies.

4.2.2. Informing the estuary-inlet-open coast composition

In addition to the interaction between the estuaries, their inlets and the open coast, there are other factors that affect the long-term and large-scale morphodynamic evolution of the Suffolk coast. The offshore topography, in particular, is highly complex with numerous sandbanks (Burningham and French, 2015b). These sandbanks provide wave sheltering and determine the overall amount of energy that reaches the coast in turn driving alongshore variations in coastal retreat rates. A way forward here is to include these effects by running a coastal area model to simulate wave propagation from deep water over the complex bathymetry to the boundary of the morphological model. Dawson et al. (2009) followed this strategy in a study of the Norfolk coast of England. They applied the TOMAWAC wave model to generate the boundary conditions necessary to conduct SCAPE simulations of cliff erosion and a similar approach could be adopted for Suffolk.

When addressing the mesoscale, appreciation of the abundance of different sediment size fractions and their potentially different responses to a given forcing is crucial (Luo et al., 2013). Over spatial scales of 10 to 100 km, for example, fine sediment supply through cliff erosion might feed estuarine systems by transport in suspension, including those at a significant distance, while coarse material can build the beaches more locally (within the relevant sub-cell and cell). Usually, in beach-cliff models like SCAPE, the fate of fine sediments that are released by cliff erosion is not assessed and the material is lost from the system. Coastal area models can play another important role here as these models can be used for particle tracking to define large-scale sediment pathways and provide information on sediment availability that can be used as boundary conditions for the estuarine morphodynamic models (see also Brown et al., 2015). Assessing the effect of sandbanks on wave impacts and exploring the fate of fine sediment released by cliff erosion are two concrete examples of how coastal area models can help to inform simulations of mesoscale coastal morphodynamic behaviour.

5. Model coupling

The process of effectively linking model components and assembling them into new configurations is critical, as this allows a wide range of real-world situations to be simulated and a wider variety of scientific problems to be solved (Peckham et al., 2013). In the context of our approach to coastal modelling and highlighted by the Suffolk case-study as presented in the previous section, an example would be linking a model of the open coast with an estuary model as a way of examining the influence of one landform complex on another. The framework proposed here requires the static (one-way) and dynamic (two-way) coupling of multiple models at a range of spatial-temporal scales. There are several standards and platforms currently available that provide a flexible linking environment (Buis et al., 2006; Gregersen et al., 2007; Pearce et al., 2011; Craig et al., 2012; Peckham et al., 2013) and some of these platforms, such as CSDMS (Peckham et al., 2013) and OpenMI (Gregersen et al., 2007; Harpham et al., 2014) have already been used to control dynamic linkages within coastal environments (Ashton et al., 2013; Rogers and Overeem, 2013; Zhou et al., 2013). However, coupling models is not a trivial task and in the remainder of this section we highlight some key caveats.

When linking complex models the choice of exchange parameters and variables is crucial. In the design of new models sufficient thought must be given to define which quantities other models may need to use. This is complicated by the fact that the model developer will not necessarily know a priori what other models may be coupled to their own, and what quantities those models would need to utilise as inputs (Sutherland et al., 2014). Associated with this is the issue of differing time steps, units, grid sizes and types, all of which may be incompatible between models (see also Voinov and Shugart (2013)). A way forward here is to write additional modules that can take the output from one model, and then adapt it by (for example) converting units, resampling grids, or interpolating time steps (Harpham et al., 2014).

A further issue to be considered is at what conceptual level the models will be linked. Referring back to the Suffolk composition (Fig. 5) as an example, a cliff evolution component can form an integrated part of the mesoscale open coast model, with variables and parameters that are exposed for use by other models at the overall open coast level. Alternatively, the cliff model could be provided as a stand-alone landform model that can be linked to a beach model and a platform model in an open coast composition via one of the linking platforms.

The choice depends on the intended model use and potentially also on the model developer. Basing compositions on landforms could rapidly produce unwieldy compositions of many models, with implications for both the computational overhead of data exchange, and the complexity of the various adaptors that may be required to connect the models. On the other hand, the coupling of a multitude of stand-alone landform models increases the flexibility in terms of model choice and facilitates experimenting with different approaches as individual models may be more easily replaced.

6. Model testing and assessing uncertainty

Different kinds of models are designed to address different sorts of questions and thus require custom-fit methods of evaluating model utility. For the bottom-up reductionist models, constructed to represent a geographically specific location with maximum realism and detail, testing model utility by using the common approach of quantitatively comparing the value of variables at particular locations and times in the model with observations is appropriate (Sutherland et al., 2004; French, 2010). However, for models on the other side of the modelling spectrum, i.e. highly abstracted models, which are intended to enhance generic understanding of coastal change, other ways of model testing are needed (Murray, 2003). When simulating the long-term and large-scale evolution of coastal systems, the traditional approach of making a direct comparison between modelled and measured variables to test the model may be challenging for other reasons. Model imperfections, combined with instabilities and emergent behaviours, mean that model results become less likely to be accurate in detail (e.g. morphological structures occurring in the same times and places in model and observations) as the simulation progresses through time (Kamphuis, 2013), although there are notable exceptions related to the strong influence from lateral boundary conditions as shown by van der Wegen and Roelvink (2012) in their modelling study of long-term estuarine morphodynamics. In cases where boundary conditions do not steer the long-term evolution, and where morphodynamic instabilities are inherent in a system, comparing the characteristic behaviours exhibited by the model with the characteristic behaviours observed in nature is more appropriate. Papers describing simulations of morphodynamic evolution in tidal embayments have shown how model results can be tested at a more aggregated level, using morphological characteristics such as basin hypsometry and tidal network properties (D'Alpaos et al., 2005; Marciano et al., 2005; Yu et al., 2012; van Maanen et al., 2013a).

The issue of error accumulation through time can be different for certain types of reduced complexity models developed specifically for the mesoscale. Over the short-term, errors are likely to be large (relative to a reductionist model) due to the more abstract representation of processes. However, the inclusion of broader sets of processes and the feedbacks that govern them brings the possibility of actually avoiding the accumulation of small errors. In this context, it is not always the aim of the reduced complexity model to precisely represent reality, but instead to not deviate too far from it. This has implications when choosing the model initial conditions, as a feedback-based behavioural model of a real site will tend to require a period of spin-up, during which it is run to establish some sort of dynamic equilibrium. This becomes the starting condition for subsequent projections of future change (as opposed to using an observed state of the site, which is more normally the case with traditional reductionist modelling). Such an approach has been adopted in modelling studies of for example cliff coasts and barrier islands to assess the impacts of future sea-level rise (Dickson et al., 2007; Moore et al., 2014). It further undermines the process of validation based on direct comparisons with measured variables. Instead such a reduced complexity model may be better judged by its capacity to represent real-world forms, perhaps from quite unrealistic starting conditions, and by its ability to simulate relative changes.

Testing and understanding model outcome and, related to this, evaluating uncertainties, becomes even more complex when a coupled landform system is being simulated with a set of sub-system models, as proposed here. A potential way forward lies in the use of Monte Carlo techniques. Current advances in processing power allow the use of these techniques on increasingly complex, coupled, modelling systems (Lee et al., 2001; Lastra et al., 2008; Callaghan et al., 2013). Monte Carlo techniques provide a general framework that allows for the assessment of uncertainty and for defining a range of possible outcomes. As part of this strategy, the model or model composition is run many times with different forcing conditions and model settings based on a repeated random sampling method to obtain a distribution of the unknown entity. Clearly, this is facilitated by model codes that are computationally efficient. To refer back to the cliff model SCAPE, this model has been applied in Monte Carlo mode to define potential cliff recession rates in response to sea-level rise (Walkden and Hall, 2005; Walkden et al., 2015). One can imagine how Monte Carlo techniques can be used to analyse the cascade of uncertainty from climate forcing, through coastal response to natural hazards on the coast. It is this type of information that is of specific interest to coastal managers as it provides the basis for risk-based land use planning and engineering decision-making (Hall et al., 2002).

7. Discussion and conclusions

The development of sound coastal and shoreline management strategies requires improved predictions of coastal change at the mesoscale. This drives the need to simulate the coastal environment at the system-level and to appreciate the crucial interactions that occur between the open coast, estuaries, and the shallow sea bed. Given the strength and weaknesses of the various model types currently available, a multi-model approach guided by an integrated framework is likely to be required. In this paper, we have proposed such a framework, which brings together a variety of different modelling approaches and which can support compositions existing of reduced complexity models informed by reductionist, data-driven, and also conceptual models. This integrated approach could help us to deliver quantitative predictions of mesoscale coastal change and provide a key step forward in our attempt to simulate such a complex system. Moreover, the proposed framework facilitates a participatory modelling approach (Voinov and Bousquet, 2010), which allows for a more active engagement with the relevant stakeholders. This is partly accomplished through the use of Coastal and Estuarine System Mapping (French et al., this issue - b). Stakeholders can actively participate in the process of developing these system maps and, as such, share their knowledge of the coastal system and its behaviour. Since it is the system mapping that defines the landforms and landform complexes that need to be modelled, stakeholders can thus directly influence the way model composition are being built. The present tendency towards open source community models and the ongoing efforts to develop external model coupling interfaces and standards (as exemplified by e.g. the Community Surface Dynamics Modeling System, CSDMS and OpenMI) also stimulate a participatory approach as it becomes increasingly possible to put together new compositions and discuss with stakeholders the type of models that need to be included.

Specific attention has been given here to describe the various possible information exchanges between the different modelling approaches. To illustrate the proposed modelling framework, the Suffolk coast has been presented as a system for which an integrated modelling approach could be beneficial. This example case study represents a specific geographical location for which particular processes and feedbacks drive the long-term and large-scale morphodynamic behaviour. Nonetheless, the described process of developing a coupled modelling system is generic at a high level, and can readily be applied to coastal systems elsewhere.

A key issue is related to the level at which physical processes should be explicitly represented within the models of mesoscale landform evolution. In this context, the reduced complexity modelling approach has been found to be particularly useful. These models have proven to be effective in modelling realistic emergent behaviours and geomorphic change over larger spatial and temporal scales. With increasing computing power and the ongoing development of reductionist modelling techniques, however, it is clear that the range of large-scale and long-term phenomena that can be modelled starting from the scales required for direct hydrodynamic simulation are growing. For certain kinds of constrained estuarine systems, the reductionist approach has already proven to be capable of providing a sound basis for predictions of future evolution (Ganju and Schoellhamer, 2010) and, as such, this opens up possibilities to apply reductionist coastal area models to answer practical management questions. The overlap between the scales of coastline and estuary behaviours that can be addressed with both reduced complexity and reductionist models is thus growing as well. While debate remains in the community about which of these end members to lean towards, agreement exists that: 1) some degree of synthesis of the effects of relatively small scale processes into parameterizations for models of larger-scale phenomena should be embraced; and 2) that when more than one model, or type of model, can be used to address the same question, using all the models available (an effort-intensive endeavour) is desirable. This is because different models have different strengths, and comparing model results promotes insight and practical forecasts, as well as shedding light on issues around confidence and uncertainty.

It can also be expected that in the near future reductionist and reduced complexity models will become increasingly and more tightly linked. A morphodynamic coastal area model, for example, could be set up for the simulation of the foreshore domain of a tidal inlet to study the ebb tidal delta behaviour over decades. This model can be connected at the inlet with an ASMITA type of model (not including high resolution grids in the estuarine basin) or beach/dune/cliff/platform models at the coast, allowing for fast runs including dynamics in the basin and at the coastline. This type of coupling is promising and could give new insights to the study of coastal morphodynamics.

Regardless of the type of modelling approach that is being adopted, it remains essential to realise the importance of communicating the model results to the wider public, especially when it involves studying the effects of human interventions and climate change. In the end, improving predictions of mesoscale coastal change is set out here as a specific goal within the overall aim to advance the way coastal systems are managed. Our coasts, however, evolve in a complex socio-economic environment and management decisions directly affect the livelihoods of many coastal communities. This clearly drives the need to make the model output, assumptions, as well as operational limitations as transparent as possible. Developing a solid and continuous dialogue between coastal scientist, stakeholders and policy makers is thus of the utmost importance and determines the overall success of the modelling process. Also, while improved predictions of mesoscale coastal change will support the management of flooding and erosion risks, a more sustainable socio-economic outlook on a society living near an eroding coast, including the development of a range of adaptive responses that take into account human needs, is equally important (Brown et al., 2014). In the end, it is a better understanding of the multiple interacting drivers of change, including both climatic and non-climatic factors, which will help us to achieve a less hazardous environment for coastal communities.

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