Geomorphology 256 (2016) 3–16

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

# Appropriate complexity for the prediction of coastal and estuarine geomorphic behaviour at decadal to centennial scales

Jon French [a,*], Andres Payo [b], Brad Murray [c], Julian Orford [d], Matt Eliot [e], Peter Cowell [f]

[a] Coastal and Estuarine Unit, UCL Department of Geography, University College London, Gower Street, London WC1E 6BT, UK
[b] Oxford University Centre for the Environment, South Parks Road, Oxford OX1 3QY, UK
[c] Division of Earth and Ocean Sciences, Nicholas School of the Environment, Center for Nonlinear and Complex Systems, Duke University, Box 90227, Durham, NC 27708, USA
[d] School of Geography, Archaeology and Palaeoecology, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland, UK
[e] Damara WA Pty Ltd, 5/19 Wotan St, Innaloo WA 6018, Australia
[f] School of Geosciences, University of Sydney, NSW 2006, Australia

ARTICLE INFO

*Article history:*
Received 20 August 2014
Received in revised form 10 October 2015
Accepted 13 October 2015
Available online 22 October 2015

*Keywords:*
Coastal evolution
Complexity
Systems theory
Modelling

ABSTRACT

Coastal and estuarine landforms provide a physical template that not only accommodates diverse ecosystem functions and human activities, but also mediates flood and erosion risks that are expected to increase with climate change. In this paper, we explore some of the issues associated with the conceptualisation and modelling of coastal morphological change at time and space scales relevant to managers and policy makers. Firstly, we revisit the question of how to define the most appropriate scales at which to seek quantitative predictions of landform change within an age defined by human interference with natural sediment systems and by the prospect of significant changes in climate and ocean forcing. Secondly, we consider the theoretical bases and conceptual frameworks for determining which processes are most important at a given scale of interest and the related problem of how to translate this understanding into models that are computationally feasible, retain a sound physical basis and demonstrate useful predictive skill. In particular, we explore the limitations of a primary scale approach and the extent to which these can be resolved with reference to the concept of the coastal tract and application of systems theory. Thirdly, we consider the importance of different styles of landform change and the need to resolve not only incremental evolution of morphology but also changes in the qualitative dynamics of a system and/or its gross morphological configuration. The extreme complexity and spatially distributed nature of landform systems means that quantitative prediction of future changes must necessarily be approached through mechanistic modelling of some form or another. Geomorphology has increasingly embraced so-called 'reduced complexity' models as a means of moving from an essentially reductionist focus on the mechanics of sediment transport towards a more synthesist view of landform evolution. However, there is little consensus on exactly what constitutes a reduced complexity model and the term itself is both misleading and, arguably, unhelpful. Accordingly, we synthesise a set of requirements for what might be termed 'appropriate complexity modelling' of quantitative coastal morphological change at scales commensurate with contemporary management and policy-making requirements: 1) The system being studied must be bounded with reference to the time and space scales at which behaviours of interest emerge and/or scientific or management problems arise; 2) model complexity and comprehensiveness must be appropriate to the problem at hand; 3) modellers should seek a priori insights into what kind of behaviours are likely to be evident at the scale of interest and the extent to which the behavioural validity of a model may be constrained by its underlying assumptions and its comprehensiveness; 4) informed by qualitative insights into likely dynamic behaviour, models should then be formulated with a view to resolving critical state changes; and 5) meso-scale modelling of coastal morphological change should reflect critically on the role of modelling and its relation to the observable world.



## 1. Introduction

Landform behaviour is intrinsically complex due to the nature of the feedbacks between morphology and sediment transport and the range of scales over which these operate (Schumm and Lichty, 1965). Geomorphological systems are also complicated on account of the

* Corresponding author.
*E-mail addresses:* j.french@ucl.ac.uk (J. French), andres.payo@ouce.ox.ac.uk (A. Payo), abmurray@duke.edu (B. Murray), j.orford@qub.ac.uk (J. Orford), matt.eliot@damarawa.com (M. Eliot), p.cowell@usyd.edu.au (P. Cowell).

http://dx.doi.org/10.1016/j.geomorph.2015.10.005

multiplicity of connected morphological components within the landform complexes that constitute the broader landscape (Werner, 1999; French et al., 2016). Morphodynamic complexity arises in several ways, including the residual influence of previous states (*state dependence*, or *inheritance*; Wright and Short, 1984; Favis-Mortlock, 2013); the interplay between self-regulation (or *equilibrium tendency*; Howard, 1965; Thorn and Welford, 1994; Orford et al., 2002) and self-forcing (which leads to *thresholds* and *complex response*; Schumm, 1973; Brunsden and Thornes, 1979), and the non-linear nature of many of the functional linkages between system components (see, for example, Wright and Thom, 1977; Cowell and Thom, 1994; Murray et al., 2008). Predicting such complex non-linear behaviour beyond the short-timescales at which we can tightly specify governing physics and boundary conditions continues to present major difficulties. From the perspective of understanding the impacts of contemporary climate change, relevant time scales span decades and, potentially, centuries. Corresponding spatial scales are less clear-cut. In a coastal context, management planning is increasingly engaged with regional shoreline behaviour at scales of the order of $10^2$ km (e.g. Stive et al., 1991; Mulder et al., 2011; Nicholls et al., 2013). However, there is still a demand for improved prediction of changes likely to occur locally, especially in the context of proposed engineering or management schemes. At extended spatial scales, the complicated nature of landscapes becomes problematic, since much of our modelling capability is restricted to the consideration of individual landforms. This leads naturally to the question of whether landscape evolution is best understood through the coupling of specialised landform-scale models or through the development of more tightly integrated models that are able to simulate morphological evolution at whole landscape scales; this is explored further by van Maanen et al. (2016).

As Thieler et al. (2000) have argued in the context of beach behaviour modelling, the transition from models intended to advance and articulate scientific understanding to those capable of application to societal problems has not been a smooth one. Indeed, widespread engineering application of shoreline change models based on the equilibrium shoreface profile (Dean, 1991) has provoked intense criticism from geoscientists concerned at the weak theoretical and empirical support for this concept as well its neglect of the broader-scale geological context (e.g. Pilkey et al., 1993; Young et al., 1995; Cooper and Pilkey, 2004a). Moreover there is considerable scepticism over whether quantitative prediction of shoreline change is actually possible at multidecadal scales (Cooper and Pilkey, 2004b; Pilkey et al., 2013) and whether expert judgement or more qualitative modelling approaches (e.g. Cooper and Jay, 2002) might be the best way to bring scientific understanding of coastal behaviour to bear on management problems. Predictions of morphological change at the coast are increasingly important, however, since coastal landforms provide a physical template that not only accommodates diverse ecosystem functions and human activities (Murray et al., 2008), but also mediates flood and erosion risk (Sayers et al., 2002; Narayan et al., 2012).

This position paper arises from a need to formulate an overarching theoretical framework for a programme of mesoscale coastal behaviour model development being undertaken in the Integrating Coastal Sediment Systems (iCOASST) project (Nicholls et al., 2012). In it, we unpack the problem of how to deliver such predictions into a series of issues pertaining to our conceptualisation of geomorphological systems at the time and space scales of interest and the translation of geomorphological process understanding into models that deliver the insights demanded by managers and policy makers. Firstly, we revisit the well-worked question of how to define the relevant scales at which to seek quantitative predictions of landform change within an age defined by historical interference with natural sediment systems and also by the increasing prospect of significant changes in climate and ocean forcing. Secondly, we consider the theoretical bases for determining which processes are most important at a given scale of interest and the related problem of how to represent the processes of interest into models that are computationally feasible, retain a sound physical basis and demonstrate useful predictive skill (French and Burningham, 2013). Specifically, we explore the limitations of a primary-scale approach (de Vriend, 1991) and the extent to which these can be resolved with reference to ideas drawn from complex-systems theory (Werner, 1999, 2003). Thirdly, we consider the nature of the change to be modelled and the particular need to resolve not only incremental evolution of morphology but also changes in either the gross configuration (e.g. barrier breakdown; Orford, 2011) or the dynamic nature of system operation (e.g. a shift between estuary flood and ebb dominance; Dronkers, 1986). We note that whilst geomorphology has increasingly embraced so-called 'reduced complexity' models as a means of moving away from an essentially reductionist focus on the mechanics of sediment transport towards a more synthesist view of landform evolution at broader scales (Murray and Paola, 1994; Coulthard et al., 2002; Paola, 2002; Brasington and Richards, 2007; Murray, 2007), there appears to be little formal consensus how to define a reduced complexity model or what constitutes an appropriate level of complexity. Accordingly, we identify a set of requirements for what might be termed 'appropriate complexity modelling' of quantitative coastal morphological change at a mesoscale that is commensurate with contemporary management and policy-making requirements.

## 2. Relating scale to the demands of coastal management

As Schumm and Lichty (1965) convincingly demonstrated, the scale at which we approach geomorphological phenomena introduces – indeed imposes – choices to do with the relationship between cause and effect, the levels of abstraction that are relevant and the modes of explanation and prediction that are possible. Within coastal geomorphology, as in other areas of the discipline, nested temporal hierarchies have been proposed to accommodate disparate styles of research that range from reconstructions of past coastal and estuarine evolution over extended geological timescales to interactions between fluid mechanics, sediment movement and bedforms at timescales measured in seconds. Terminology varies, with significant differences between the geoscience and engineering communities (e.g. Kraus et al., 1991; Stive et al., 1991; Fenster et al., 1993; Cowell and Thom, 1994; Komar, 1999). Almost all schemes emphasise the correlation between temporal and spatial scale, and invariably include one or more areas of study that lie comfortably within the realm of geophysical fluid dynamics and process geomorphology, and which encompass both the fundamentals of sediment transport under the influence of waves and tides and the effect of intermittent events on landform morphology. At the other end of the spectrum, geological studies are primarily descriptive and rely on palaeoenvironmental evidence to infer past coastal dynamics. A particularly active area of study concerns recent historical timescales at which various forms of observational evidence, including instrument records and systematic monitoring, can inform explanations for documented coastal morphological change. This is also the scale at which humans have sought to manage and constrain natural shoreline dynamics, such that the term 'engineering scale' is also commonly applied (e.g. Cowell and Thom, 1994).

Whilst these kinds of classification are typically applied to the past, they can also inform our approach to the future (Gelfenbaum and Kaminsky, 2010). Coastal stakeholders worldwide increasingly demand more reliable and more quantitative assessment of likely changes in coastal morphological response to human interventions and climate change, not least to quantify the damage and adaptation costs (e.g., Hinkel et al., 2014; Kousky, 2014). Despite inconsistencies in terminology, there is a broad consensus that the relevant time scales here extend from a few decades to a century or more. Such a time frame is clearly determined in part by human lifespans, political horizons and the extent to which these condition societal actions more generally and strategic coastal management and planning in particular. As Nicholls et al. (2013) note, a more strategic approach emerged after the 1970s under separate paradigms of coastal zone management and shoreline management. The latter has dominated the management of coastal geohazards in many countries, including the USA, UK and Netherlands (Mulder et al., 2011; Mitsova and Esnard, 2012) and a recent tendency has been for the timescales considered to extend beyond those associated with the lifespan of engineering structures (typically a few decades) to the 2100 horizon adopted initially by climate change science. The current IPCC synthesis (Stocker et al., 2013) incorporates results from multi-century projections of climate change. These have important implications for the vulnerability of major cities (Nicholls, 2011), especially since even under stabilised conditions of radiative forcing, it would take 200 to 400 years for global mean sea-level rise to return to its mid-20th century rate (Jevrejeva et al., 2012). Timescales in excess of a century are also relevant to certain critical infrastructure — notably nuclear power stations at coastal sites, given that generation and decommissioning schedules extend well beyond 100 years.

Timescales of relevance to shoreline management do, of course, also reflect intrinsic aspects of coastal system behaviour. Variability in marine forcing and coastal response is high at shorter timescales associated with periodic tidal and intermittent wave and surge-driven processes. Given that the management of progressive change is typically the primary concern (Cowell et al., 2003a; Van Rijn, 2011), it clearly makes sense to filter in some way phenomena predominantly associated with sub-annual scales. There is also much interest in disaggregating secular trends in coastal behaviour from significant interannual variability arising from dominant modes of atmospheric behaviour such as ENSO and NAO (e.g. Storlazzi and Griggs, 2000; Esteves et al., 2011; Burningham and French, 2013). This further justifies a focus on multidecadal to century timescales, though even at these scales 18.6 year nodal tidal variation can be significant in macro-tidal estuaries (Townend et al., 2006) and in some open coastal settings (e.g. Gratiot et al., 2008).

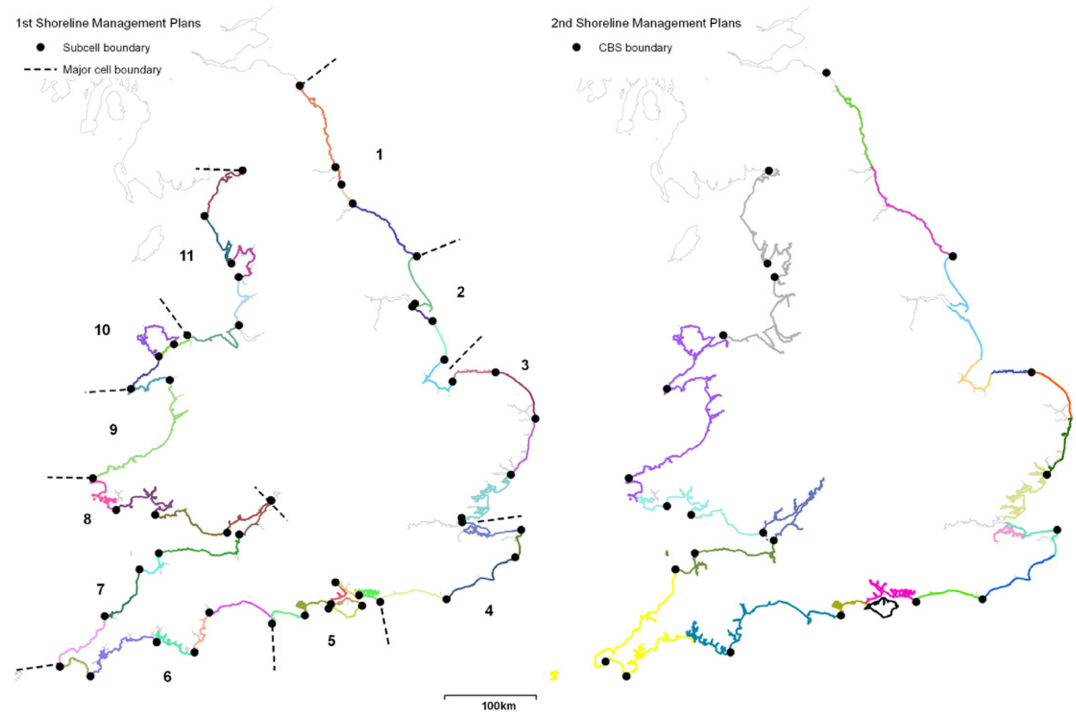
The spatial dimensions associated with the timescales considered above are largely implicit, with an underlying assumption that extended timescales require consideration of broader spatial scales. The oft-assumed correlation between time and space scales is weakened by the fact that the range of circumstances encountered in coastal management planning is such that spatial scales appropriate for understanding, intervention and planning become diffuse and arbitrary (Capobianco et al., 1998). Moreover, it is clear that not all geophysical phenomena conform to such a simple scaling relationship, surge-generated extreme water levels, tsunamis and isostatic adjustment being example exceptions.

Translation of basic time and space geomorphic principles into applied coastal understanding has not been an easy discourse. This is exemplified by the situation in Britain where, prior to the 1990s, coastal protection was seen as an expensive and essentially reactive approach to coastal change with a virtual disregard for geomorphological concepts. Initial progress came with the implementation of a first generation of 42 Shoreline Management Plans (SMPs) for England and Wales (around 7000 km of open coast). These were nested in a two-tier hierarchy of major coastal cells (median length approximately 550 km) and sub-cells (mean length 100 km; Motyka and Brampton, 1993; see also Fig. 1). At the sub-cell scale, each SMP divided the coast into finer-scale management units, for which alternative strategic defence options were evaluated for a somewhat arbitrary 50-year epoch. A second generation of SMPs, initiated in 2006, incorporated more substantive geomorphological thinking, largely emanating from the DEFRA-funded FutureCoast project (Burgess et al., 2002; Cooper and Jay, 2002). This departed from the previous place-specific analysis of coastal problems in favour of a broader context that embraced the spatial and temporal scales by which the coast and its human problems had evolved and (considering anticipated change in climate, or more specifically, mean sea level) would likely evolve. FutureCoast identified a three-tier spatial hierarchy of 424 local shoreline response systems, 108 shoreline behaviour systems and 23 coastal behaviour systems. The latter translated into 22 Phase 2 SMPs that are rather larger than their predecessors, ranging from approximately 30 to 950 km (median 170 km), subdivided into around 1500 policy units. The principal tract remained the wave-sediment cell though in reality it was the sediment pathway that dominated the cell definition. The overall conditional status of each cell was evaluated against two coastal behavioural types, swash-aligned and drift-aligned shorelines. These two dynamic types were a conceptual recognition of sediment supply and, tacitly in terms of wave exposure, longshore sediment transport. They were in effect time-averaged statements of temporal and spatial variation in the sediment pathway, and given the alongshore interconnection of such structures, a means of establishing a qualitative forecasting position for multiple future epochs (0 to 20; 20 to 50; and 50 to 100 years). A small number of similarly-founded SMPs have been implemented in Scotland, although the more indented nature of the Scottish coast and weaker littoral-drift systems mean that sediment cell-based management plans might not be the best way forward (Hansom et al., 2004).

Several issues arose from this type of analysis: i) the understanding of what drift- and swash-alignment meant in terms of coastal behaviour was not widely understood beyond academic geomorphology; ii) the interaction of estuaries with the open coast was not given real prominence, given the difficulty of developing pathways for finer non-beach grade sediment (Cooper and Pontee, 2006); and iii) sediment pathways, as articulated by supply changes, were not recognised as the major time and spatial scale determinant of coastal evolution. These limitations meant that the structure of these pathways and their dynamics (including decaying impacts of past climate shifts, as well as potential future inputs due to climate change) were not easily translated into individual SMPs. There was a major requirement in for geomorphic 'expertise' to translate scientific understanding of coastal behaviour into an underlying formulation of larger-scale process and expected outcomes that, if unrecognised by planners, meant the loss of both SMP function and the ability to devise realistic scenarios of coastal evolution.

The British experience of incorporating geomorphological principles into shoreline management has thus been mixed. On the positive side, an explicit spatial up-scaling has moved planners to consider a more integrated coastal perspective, whereby local problems have to be considered in the context of broader-scale sediment pathways. However, management plans remain somewhat truncated in their time-scale perspectives. Much of this limitation must be tied back to lack of understanding of larger-scale coastal behaviour (e.g. shoreline status and sediment cells (see Cooper and Pontee, 2006)). Such limitations are especially apparent at the critical multi-decadal to centennial scales over which systems-level behaviour is seen to emerge as a complex function of a set of uncertain forcings, whose uncertainty appears to increase into the 21st century. Quantitative modelling of such outcomes has thus remained largely restricted to local spatial scales, and at a reductionist level that is unsuited to problems arising at a mesoscale. The FutureCoast project (Burgess et al., 2002), and the revised SMPs that it underpinned, formalise a wealth of knowledge that could inform predictive modelling, but which has still to be taken up in any substantive manner.

The UK is something of an outlier in terms of the extent to which scientific knowledge pertaining to a large proportion of its open coast has been formalised and systematically incorporated into successive generations of strategic management plans. It is instructive to compare this situation with that in the USA, where a more complex interplay of federal and state government and stakeholders (e.g. Kousky, 2014) has precluded analysis and management at a national scale. However, this is partly a question of scale, and similarly cohesive assessments of coastal vulnerability are emerging at a state level, one of the most obvious initiatives being the Louisiana Coastal Masterplan (Coastal Protection and Restoration Authority, 2012; Peyronnin et al., 2013), which covers 100,000 $km^2$. This project is of particular interest in that it marks a departure from analysis of historic change and qualitative synthesis of coastal behavioural tendencies in favour of quantitative predictive modelling. To this end, an integrated suite of mesoscale sediment




| | Cells | Subcells (~SMP1) | CBS | SBS | SMP2 |
|---|---|---|---|---|---|
| N | 11 | 47 | 23 | 108 | 22 |
| Min length (km) | 296 | 33 | 60 | 6.9 | 29 |
| Max length | 663 | 388 | 439 | 217 | 946 |
| Median length | 550 | 100 | 207 | 38 | 171 |

CBS Coastal Behaviour Systems
SBS Shoreline Behaviour Statements
SMP1, SMP2 Shoreline Management Plans (1st and 2nd generation)

**Fig. 1.** Comparison of Motyka and Brampton (1993) mapping of major cells and sub-cells for England and Wales (which broadly correspond to phase 1 SMPs) and the coastal behaviour systems derived from the FUTURECOAST project (Burgess et al., 2002), used for the phase 2 SMPs.

balance and ecohydrological models is used to evaluate nearly 400 coastal protection and restoration projects and to capture the essential trends in coastal behaviour necessary to inform strategic planning over a 50 year timescale (Meselhe et al., 2013).

## 3. Matching understanding to mesoscale problems

The challenge is to meet the demand for long-term morphological simulations with theoretical and mechanistic knowledge based on sound physical principles and empirical knowledge. Progress on this front is still hindered by the lack of a generally accepted up-scaling theory. In the following, the rationale for a more robust approach to up-scaling and limitations of three proposed conceptualizations; the primary scale relationship, the coastal tract and the hierarchical approach, are presented.

### *3.1. Up-scaling on the basis of the primary scale relationship*

It is clear from the preceding analysis that the scales of shoreline management, whilst partly defined by dominant system forcings, are also substantially imposed by timescales of policy-making that is increasingly conducted within an overarching paradigm of climate change science. Both imply an entry into coastal system behaviour at a scale that is rather far removed from that at which much of our primary knowledge resides. This gives rise to an up-scaling problem, since much of our understanding of the mechanisms of landform change is obtained at the relatively small temporal spatial scales of experimental studies. This is not to say that we do not have access to historical and geological insights into the evolutionary behaviour of coastal environments at scales from centuries to millennia (Woodroffe and Murray-Wallace, 2012). However, much of the mechanistic detail that is pertinent to such scales continues to elude us. Such a predicament is by no means unique to geomorphology. In ecology, for example, it is widely acknowledged that we know a lot about organisms, less about populations and even less about entire ecological landscapes (e.g. Urban, 2005). As noted above, the scales of interest for shoreline management necessitate the disaggregation of progressive trends from extreme variability, some of which extends into the mesoscale range. From a sediment budget perspective, this boils down to the resolution of tiny residual fluxes from much larger gross transports. Some of these fluxes, for example cross-shore exchange between lower and upper shoreface or, estuarine sediment sinks, cannot be resolved directly through measurement. Long-term geological context can guide our understanding of both the mode/direction of coastal change under specified forcing and also help to constrain the fundamental driver of sediment supply (e.g. McNinch, 2004). However, there is an ultimate information limit associated with historic data, since these can only represent a small portion of the environmental state space. Furthermore, there has been massive variation in terms of sediment availability and processes, especially over the later Holocene, which makes it difficult to extrapolate with confidence.

Together with sheer extent of human interference in natural sediment systems (Syvitski and Kettner, 2011; Knight and Harrison, 2014) this means that the past is not always a good guide to the future and this is especially so of systems that exhibit the possibility of divergent future states and emergent behaviours (Dearing et al., 2010; see also Section 4 below). Rather, future coastal behaviour is best understood and predicted through modelling that is able to capture the non-linearities evident in many aspects of geomorphological system behaviour.

In the absence of a formal aggregation theory, and based on the seminal work of Schumm and Lichty (1965) on time and space causality in geomorphological systems, the largely implicit relationship between temporal and spatial scale has afforded a convenient basis for specifying quantitative modelling approaches (e.g. de Vriend, 1991; de Vriend et al., 1993). As de Vriend (1991) observes, such a 'primary-scale relationship' implies that "the explanation of a phenomenon in coastal behaviour is primarily sought in physical processes in a similar scale range". As our process understanding improves, however, there are a number of issues that mitigate against uncritical use of the primary-scale relationship as an aggregation theory. For example, bar formation at sub-annual timescales may influence longer-term shoreline stability through the cumulative effect of repeated cycles of formation and dissipation. For example, the seasonal arrival and migration of mud banks significantly increases the storm and tsunami resistance of villages on the southwest coast of Brazil and in India (e.g. Elgar and Raubenheimer, 2008; Holland et al., 2009). A particularly impressive example occurred in 1998 at Cassino Beach (Fig. 2), southern Brazil, where deposition of fluid mud on the beach during a single storm event caused a total absence of breaking waves along 13 km of shoreline for nearly 14 months (Holland et al., 2009). Anthony and Dolique (2004) document a slightly different interplay between the interannual morphodynamics of sandy beaches in Cayenne, French Guiana, and migrating mud banks fed by sediment supply from the Amazon. This mud bank migration drives beach rotational responses that are completely unrelated to any variability in deepwater wave climate, with extreme instances resulting in muting of normal ocean beach dynamics for several years until mud dispersal.

Various attempts have been made to formalise alternative bases for applying our knowledge of coastal processes to modelling of morphological change at broader scales. One of the earliest comprehensive treatments is that of de Vriend et al. (1993), who identify three distinct approaches to longer-term modelling of coastal morphology. Firstly, input reduction methods are based around the premise that one can capture the essence of complicated forcings by simpler representative inputs. A classic example is the use of a 'morphological tide' (i.e. a characteristic tidal cycle than can be continuously repeated to achieve an effect similar to a real sequence of individual tides) to model long-term bed evolution using hydrodynamic and sediment transport models (e.g. Latteux, 1995). In effect, this up-scales observational data in a way that permits application of reductionist models at extended space and, especially, time scales. The second approach, model reduction (or process filtering; see Capobianco et al., 1998) endeavours to reformulate the model around processes relevant at the scale of interest whilst averaging or neglecting finer scale phenomena. A distinction is made here between the explicit representation of finer-scale processes and the inclusion of their effects (Murray, 2007). This is akin to the turbulence closure schemes used in fluid dynamics; an example from coastal morphodynamics is the use of tide-averaging to resolve the long-term sediment fluxes and bathymetric evolution of tidal basins (e.g. Di Silvio et al., 2010). A third approach side-steps the scaling problem by using a simplified model that exhibits behaviour that is consistent with observation or theory. Examples of such a behaviour-oriented approach include highly aggregated (0-dimensional) models for the evolution of coupled tidal delta, inlet channel and tidal flat systems (Stive et al., 1998; Kragtwijk et al., 2004), and the shoreface translation model of Cowell et al. (1999). With regard to the two upscaling approaches, a variety of formal methods exist although these are often heavily influenced by place-specific considerations such that generalisation is difficult (de Vriend et al., 1993). In contrast, no general procedure for aggregation exists and substantial reliance is placed on the imagination and ingenuity of the modeller in elucidating the essential system behaviours and devising appropriate modelling analogues. Such models need not be directly founded on physical principles and many are essentially phenomenological (cf Urban, 2005). As, such, their nature and explanatory and predictive power depend greatly on the conceptual framework within which they are formulated.

### 3.2. The coastal tract

Perhaps the most fully developed conceptual framework is that of the coastal tract (Cowell et al., 2003a). This introduces a composite morphology of interacting landscape components within which a hierarchical cascade of processes drive coastal morphological change. At any level within the hierarchy, morphological change is driven not only by processes that are naturally observed at the associated range of time and space scales but also by the accumulated residual effects of higher order processes acting at smaller scales (Fig. 3). The tract concept is important in that it explicitly sets out to define a spatially-extended meta-morphology that encompasses not only the coast, or upper shoreface, but also connected back-barrier (including estuarine) environments as well as the lower shoreface. The tract constitutes the lowest order within a temporal scale hierarchy and constrains, via the operation of internal boundary conditions, the operation of higher order processes. As a framework for aggregation of processes into mesoscale models, the tract concept fulfils a number of roles. First, it seeks to

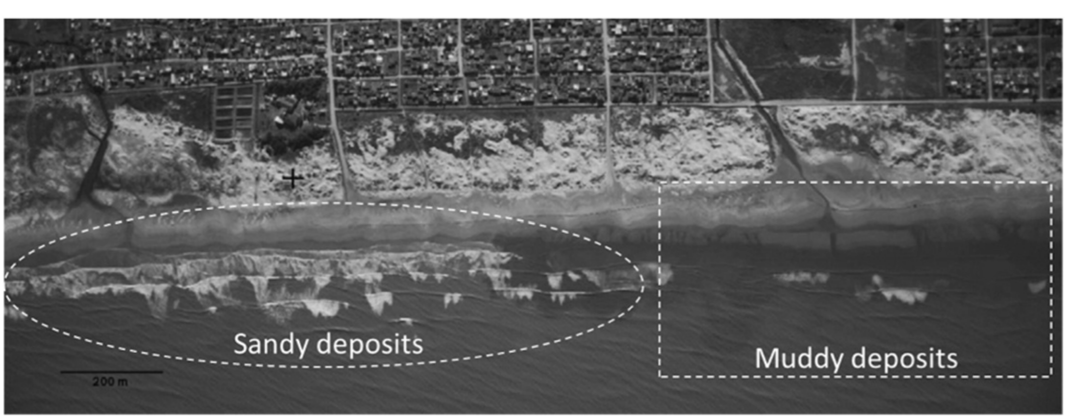



**Fig. 2.** Example of how seasonal timing and non-linear energy transfer might influence long-term shoreline morphological evolution. Airborne image showing differential wave breaking due to ephemeral shallow water mud deposits off Cassino beach in southern Brazil.
From Holland et al. (2009).

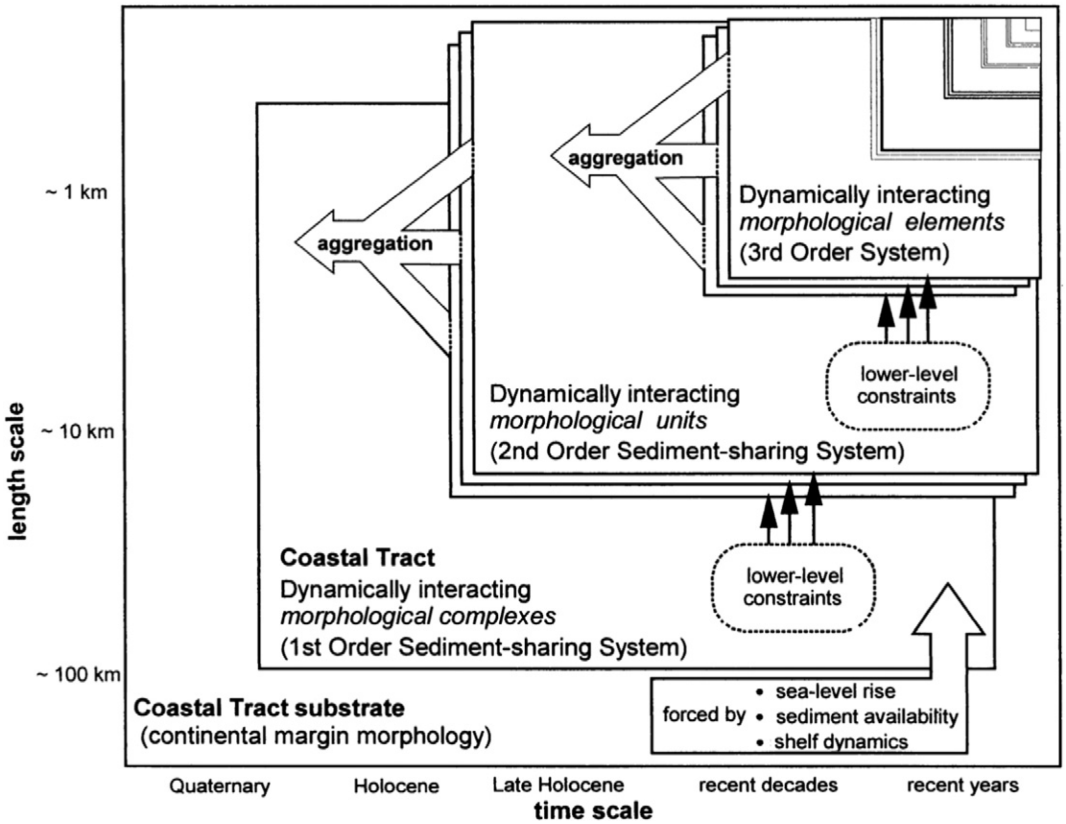



**Fig. 3.** The nesting of the coastal tract cascade highlights the needs to aggregate smaller scale processes up to larger scales of interest as well as the role of lower-order constraints that act at each level within the cascade.
Reproduced from Cowell et al. (2003a).

resolve progressive (low order) changes, which tend to be associated with the more pressing shoreline management problems, from higher order variability. Second, it nests the processes and sub-systems associated with such changes within a geological framework that provides a degree of closure of the sediment budget that, together with external climate and ocean forcing, is a primary driver of landform change. Such a geological context is necessarily region-specific. Third, it presents a method for defining a hierarchy of morphodynamic behaviours that take place within the tract, and a protocol for mapping site-specific real-world problems onto this, to facilitate the formulation of appropriately dimensioned and scaled models (Cowell et al., 2003b).

However, there remains the issue of how best to aggregate the effects of finer scale processes as we move up the scale hierarchy (Fig. 3). In part, this can be accomplished through careful structuring of the scale hierarchy. Accordingly, in their 'tract cascade', Cowell et al. (2003a) invoke three orders of landform complex, morphological unit and morphological element to accommodate the spatial and functional complexity that is evident in nature. This discourages overly simplistic aggregation and also better accommodates place-specific circumstances. That said, regional application will invariably involve subjective modification of the detail, and there is scope for different assignments of specific landforms (tidal flats, saltmarshes, dunes etc.) within the absolute scale hierarchy that they present (see, for example, French et al., 2016).

The tract cascade is defined with explicit reference to hierarchy theory (Simon, 1962; O'Neill et al., 1986; Haigh, 1987; Werner, 1999). Formal interpretations of hierarchy theory have been most numerous in ecology and ecosystem science (Müller, 1997), where it has long been appreciated that spatially-distributed environmental systems are naturally organised such that behaviour emerges on distinct temporal and spatial scales under the influence and constraint of relatively lower and higher levels (e.g. Valentine and May, 1996; Hay et al., 2001). A key aspect of hierarchy theory that is incorporated into the tract cascade is the asymmetric nature of the vertical coupling between levels. Vertical coupling is conditioned primarily by process rates and higher levels (lower orders in the scheme of Cowell et al., 2003a) exert constraints whereas lower levels (high orders of behaviour) influence the focal level through their accumulated residual effects.

### 3.3. Landforms as self-organised, hierarchical systems

A generalised analysis has been presented by Werner (1999, 2003) with reference to the self-organising properties of geomorphological systems (Hallet, 1990; Coco and Murray, 2007), as well as ideas drawn from complex systems science. Werner's hierarchical treatment is consistent with the primary-scale relationship and the coastal tract approaches, but generalizes similar ideas as an appropriate way to analyse any system in which the effects of processes occurring on specific time and space scales propagate over a wide range of scales. The hierarchical modelling approach arises from complex systems perspectives, including especially the idea of 'emergent phenomena' originally espoused in the physics community but subsequently finding widespread applications in the earth and environmental sciences. From this viewpoint, no single scale range exists in which the native processes are the 'fundamental' causes of phenomena at much larger scales (as is often implicitly or explicitly assumed when we attempt to construct numerical models starting with grain-scale interactions to address behaviours on much larger scales). Rather, as we move upward through the scales, the non-additive interactions between myriad degrees of freedom in one scale range collectively give rise to effectively new variables and interactions at much larger scales — for example, the way molecular motions give rise to macroscopic variable such as density and pressure (Murray et al., 2008). It is increasingly accepted that it is the interactions between these emergent variables that most directly cause the phenomena that occur on commensurate scale. For example, interactions between macroscopic fluid variables are generally viewed as the cause of phenomena such as water waves.

The hierarchical perspective also highlights the fact that cause and effect propagate downward through the scales as well as upward (Werner, 1999, 2003; Murray et al., 2014). Structures and behaviours that arise from emergent interactions on relatively large scales dictate the context within which the much smaller scale processes occur (for example, the way water waves influence molecular motions). In addition, the emergent variables and interactions in one scale range may be effectively independent of details of the much smaller scale processes. Although the larger scale processes would not occur if the smaller scale ones did not exist, the effects from the small scale processes that are important on the larger scale might not depend on all the properties of the small scale system. Formal downscaling analyses have been limited in geomorphology, but Eliot et al. (2013) present a hierarchical landform analysis framework that incorporates an evidence-based downscaling process. This approach can potentially address a number of the issues that confound up-scaling of geomorphic modelling, including sediment volume closure, external influences, geomorphic state-dependency (see Section 4 below) and the elucidation of dominant processes and feedbacks (see also Payo et al., 2015). It may also provide a basis for identifying or discriminating between alternative up-scaling pathways from more reductionist sediment transport modelling.

Taken together, these realizations – that analysing emergent interactions can provide the most direct explanations of phenomena in a given scale range (and possibly the most reliable predictions (e.g. Murray, 2007, 2013), and that cause and effect propagate at least as directly downward through the scales as upward – imply that smaller scale processes are not necessarily more 'fundamental' than larger-scale ones. Thus, when devising numerical models, it would seemingly be most effective to search for interactions at the 'primary scale' of the phenomena we are interested in.

As noted above, however, there are limitations to the straightforward implementation of a hierarchical approach when developing a model of mesoscale landscape phenomena. Many of the accepted, well-tested parameterizations available currently are based on the observation of processes on laboratory scales and relatively few parameterizations addressing mesoscale interactions have been developed thus far. Future work may help improve this situation, but at this stage, lacking a formal method that prescribes how to determine which effects of much smaller scale processes are most relevant for the scale of interest and how to most effectively represent those effects, we must rely heavily on scientific creativity to mint new parameterizations. Parameterizations, if they are to ultimately become widely accepted, should have a rational basis, although initially minted parameterizations (sometimes called 'rules') are not likely to have a high degree of quantitative accuracy. Ideally, time and rigorous field testing will determine which are the most effective mesoscale parameterizations, and strategic observation campaigns will improve the empirical grounding of those parameterizations. On the other hand, there is always the danger that convenience and a desire to predict regardless of the robustness of the underlying model may lead weak parameterizations to endure beyond their 'expiry date' in the science community. The so-called 'Bruun rule', in its original sense that involved only the shoreface (Bruun, 1962; Schwartz, 1967), is perhaps the most obvious case in point here. Although the conservation of mass assumptions employed in the in the original Bruun have been extended to encompass the broader coastal profile active over longer timescales (Wolinsky and Murray, 2009), making an 'extended' Bruun rule appropriate for evaluating a sea-level rise-driven component of coastline change, the original, restricted Bruun rule continues to be applied in inappropriate contexts (see also, Bruun (1988)). This particular example is noteworthy not only for the continued application of a highly idealised model of beach response to sea-level rise despite widespread criticism of its underlying assumptions, but also the fact that this model continues to be embedded in models that purport to offer far more sophisticated insights into mesoscale coastal behaviour (Cooper and Pilkey, 2004a).

One mesoscale parameterization for modelling wave-dominated coastlines that benefits from some history of use, is the treatment of alongshore sediment flux as a relatively simple function of shoreline orientation relative to wave-approach angles, or a distribution of them (Komar, 1998; Ashton et al., 2001; Hanson and Kraus, 2011). This has empirical support (Ashton and Murray, 2006a; Moore et al., 2013), and further refinements can be expected (not least to answer some of the criticisms levelled at the rather empirical approaches to the quantification of alongshore transport rate; Cooper and Pilkey, 2004c). As Lazarus et al. (2011) have demonstrated, gradients in net alongshore sediment flux appear to be responsible for cumulative change on wave-dominated coastlines on scales greater than a few kilometres and over years to decades. Their analysis of high resolution shoreline change data for 130 km of the predominantly sandy North Carolina coast shows that, whilst processes and patterns of shoreline change occurring on scales of a kilometre or less over storm time scales are fascinating in their own right and can adversely impact human development, they do not necessarily directly contribute to long-term coastline change and the spatial distribution of chronic erosion on this coast.

Analysing mesoscale coastline change in terms of gradients in alongshore sediment flux (treated relatively simply, without explicitly simulating processes on much smaller scales) provides an example of the hierarchical systems perspective applied to the meso-scale. Alongshore sediment flux can be related to flux of alongshore momentum entering the surf zone (Longuet-Higgins, 1970; Fredsoe and Deigaard, 1992; Ashton and Murray, 2006b). The commonly used semi-empirical CERC equation takes almost the same form as this alongshore (Komar and Inman, 1970; Komar, 1998). How these fluxes change as a function of shoreline orientation relative to offshore wave approach angles can drive the evolution of large-scale coastline shape (e.g. Ashton et al., 2001) and how that shape responds to changing forcing (Moore et al., 2013). The basic physics relating fluxes of energy and momentum to shoreline orientation do not depend on the details of how sediment is transported along the shore—it could hypothetically take place all in the surf zone, or all in the swash zone, and produce the same large-scale result.

Large-scale morphodynamic interactions thus arise from the basic relationship between momentum fluxes and shoreline orientation (Murray and Ashton, 2013); large-scale coastline shapes dictate large-scale patterns of alongshore sediment flux, and the patterns of sediment determine changes in coastline shape. These morphodynamic interactions can involve positive feedbacks that cause coastline undulations to increase in amplitude, as well as finite-amplitude interactions between growing coastline features that lead to self-organised coastline shapes (including cuspate capes and flying spits; Ashton and Murray, 2006a). In the case of self-organised rhythmic coastline patterns, it is clear that the emergent structures arise most directly from the large-scale interactions, rather than complicated details of processes on surf zone scales or smaller; interactions at the scale of coastline patterns determine local shoreline orientations and therefore processes on smaller scales, which can be interpreted as cause and effect propagating directly downward through a range of scales (Murray et al., 2014). However, these findings are not limited to coastlines with large-scale rhythmic patterns; large-scale morphodynamic interactions will drive or influence coastline change on any wave-dominated coastline (even where boundary conditions such as headlands that compartmentalize the coastline influence shoreline orientations).

## 4. The importance of changes in system state

Much of geomorphology is concerned with the elucidation or prediction of incremental changes in either process rates or morphology. These aspects of geomorphological system functioning can be increasingly resolved by reductionist modelling that is grounded in hydrodynamic and sediment transport principles (Roelvink and Reniers, 2012; Villaret et al., 2013). As the scale of investigation expands to encounter the self-organisational tendencies discussed in the preceding section, qualitative changes in state are encountered. These include changes in a critical aspect of system dynamics (e.g. a shift from flood-dominance to ebb-dominance in an estuary) as well as changes in gross configuration (as in the breaching and detachment and degradation of a spit). At the mesoscales of primary interest here, both kinds of state change constitute important aspects of landform behaviour that must be captured in any quantitative model.

Phillips (2014) presents a slightly different schematisation of state changes, classified on the basis of their network properties with reference to graph theory. It is beyond the scope of the present paper to fully enumerate all these types; a subset, however, is prevalent enough in coastal and estuarine settings to merit immediate attention from landform behaviour modellers. The most straightforward case involves a sequential transition between discrete states, as in the classic tidal flat, lower saltmarsh, upper saltmarsh sequence. A second case involves a sequence that repeats in a cyclical manner; examples are some circumstances of tidal flat–saltmarsh alternation (e.g. Pedersen and Bartholdy, 2007; Singh Chauhan, 2009) or bypassing cycles that involve growth, detachment, migration and reattachment of inlet sediment shoals (Burningham and French, 2006). Other important modes of state change involve either divergent or convergent evolution. Divergence is of particular interest in that it implies the existence of multiple evolutionary pathways that may culminate in alternative stable states. An important example in the present context is the potential for evolution towards either wave-regimes or tide-dominated intertidal sedimentation (Fagherazzi and Wiberg, 2009; Kirwan et al., 2010). Here, state changes may simultaneously encompass both changes in configuration (e.g. replacement of tidal flat by saltmarsh or vice-versa) and shifts in process dynamics (e.g. a shift from estuary sediment import to export; French et al., 2008).

State change has been widely recognised in the context of beach morphodynamic regime. This is thought to exhibit state transitions between distinct beach states varying from nil at the regime continuum ends (reflective and dissipative) to annual to decadal variation in state in the middle or intermediate states (Wright and Short, 1984). However, for multi-decadal modelling of state change one needs to upscale to 'state' definitions that can accommodate aspects of wider (time and space) coastal change and associated sediment paths. This may entail some subjective judgments about what precisely constitutes a discrete state. This problem is neatly illustrated with reference to recent work on gravel barrier dynamics. A tradition of coastal barrier recognition in the context of drift-alignment, and swash alignment (Orford et al., 2002) can provide two potential end member states that have been interpreted as mutually exclusive attractors (Orford et al., 1996). However, in the context of long-term sediment supply reduction or loss, then two more states are worth defining: 'segmented barriers' where underlying terrestrial basements have taken control of residual sediment volumes into a headland and bay configuration; and 'barrier breakdown' which the thrust of residual sediment is in a dominant onshore direction given then loss of alongshore sediment pathway. An extension to $n > 2$ states enables the structuring of a transition matrix by which characteristics and statistical significance of transition probabilities are potentially delimited using Markovian-based models.

Once putative states are defined, the question of state-change timing has to be considered. There is evidence of such changes in the form of a switch from drift to swash alignment at $10^2$ to $10^3$ yr scales (Orford and Jennings, 2007). Such shifts can be regarded as one way unless major forcing conditions occurred (notably changing sea level so as to revitalize sediment supply). The transition from drift to swash alignment was not necessarily due to catastrophic forcing changes. Isla and Bujalesky (2000) have offered a mechanism through what is termed as barrier cannibalization that defines a slow state change potentially measured at centennial plus scale. The inevitably of a one-way state change in barrier structure has been challenged by Orford and Jennings (2007) with reference to mid- to late-Holocene coastal barrier changes on the south coast of England (Sussex) as reconstructed from related estuary palaeoecological changes. These show how open and closed phases of estuary conditions (freshwater–brackish variability) can be related to state change between swash and drift aligned coastal tracts at multi-centennial scales. Such changes appear to occur under the influence of a relatively slow rate of sea-level change (around 5 m in 5 ka to 1 mm $yr^{-1}$) and restricted spatial freedom of barrier morphology movement due to lithified basement and cliff morphology. On open coasts, temporal and spatial changes between swash and drift alignment are therefore sensitive to changes in sediment supply rates and by changes in near-shore water depth as lower beachfaces react to reducing supply rates.

Efforts to model state change should also assess the conditional probabilities by which system components would act against state change. The principal components are those that control sediment supply per se, as well as the conditional control imposed by barrier resilience. Orford (2011) explored the time scales by which resilience could be defined, thus de facto imposing conditional probabilities on an absence of state change. Our present understanding indicates that this control operates at sub-annual to multi-annual scales and as such would be likely filtered from any treatment of mesoscale behaviour at multi-decadal to centennial scales. What might be more effective as a conditional control of state change are catastrophic storm events. However, in temperate climates (even with the possibility of extra tropical hurricane incursion) significant changes in the incidence of extreme events (susceptibility) have not been evident in the 20th century (Orford, 2011). This would suggest that in some forcing regimes, and in the case of coastal barriers at least, present state is well-tuned to quite a broad a range of high magnitude events, none of which standout as being so extreme as to cause major state change in terms of landform breakdown (Orford and Anthony, 2011).

From the above, it is clear that state change is an important aspect of coastal behaviour that becomes more, not less significant as we approach the mesoscale. Gross changes in configuration are clearly part of the normal sequence of landform evolution in some contexts, notably within the estuarine intertidal zone. On the open coast, they may be associated with abrupt changes in system functioning, possibly with major implications for flood and erosion risk (for example, a persistent barrier breach and the creation of new inlet and estuary). However, the inherent resilience of many coastal sediment systems means that such changes may not be particularly common at decadal scales. That said, there are clearly implications for mesoscale modelling in that models have to potentially capture not only subtle shifts in behaviour that can ultimately be reduced to the direction of a mediating sediment flux (especially in the case of estuaries), but also the appearance or disappearance of discrete landforms and or changes in the structure of the interactions in a broader-scale complex of landforms. Certainly, as idealised modelling by Slott et al. (2006) shows, responses to climate change will by no means by restricted to uniform retreat as envisaged by some applications of the Bruun model, and reconfiguration of more complex planform geometries is possible under plausible changes in wave climate.

Whilst capturing the existence or potential for such behaviour is clearly crucial, it is not always clear how the range of discrete states can be anticipated. Whilst some 'pressure points' may be obvious from local knowledge and previous research (e.g. the potential for breaching of a barrier beach to create a new inlet; Hartley and Pontee, 2008) other dynamic state changes may be harder to discern a priori. Alternatively, some insights may be obtained qualitative modelling of systems depicted as network graphs (Capobianco et al., 1999; Phillips, 2012). Causal loop analysis (CLA) is a particularly promising technique for elucidating qualitative aspects of system dynamic behaviour that has hitherto seen little application in geomorphology. Payo et al. (2015) extend

CLA to the analysis of coastal geomorphological systems and demonstrate its potential to reveal the existence of alternative equilibria in advance of quantitative modelling. Divergent configurational states can also be captured in the Coastal and Estuarine System Mapping methodology proposed by French et al. (2016).

## 5. Towards an appropriate complexity for mesoscale modelling

The preceding sections have set out a case for focusing quantitative models of coastal change on a mesoscale that is bounded in time by the roughly decadal time frame required to exclude seasonal and interannual variability and, at the upper end, by a timescale of one or more centuries that frames contemporary climate-change impact debates. At these time scales, coastal morphology exerts a significant mediating effect on the vulnerability of human communities and assets to erosion (especially on open coasts) and flooding (especially in estuaries) (see also Lazarus et al., 2015). Spatial scales emerge less obviously from application of hierarchy theory to natural geomorphological systems and only in an arbitrary manner from the needs of shoreline management planning. Moreover, as shown schematically in Fig. 4, the association between time and space scales is not quite as tight as textbook conceptualisations imply.

Much of the discussion thus far has been concerned with how to deal with complexity that arises due to non-linear behaviour and the way that this complicates scaling of our predictive ability along the time axis. In fluvial geomorphology, there is considerable scope to reduce the complexity of the problem in that many of the most problematic aspects of fluid-sediment interaction can be dispensed with in favour of simplified routing algorithms that effectively replace hydraulics with hydrology (e.g. Coulthard et al., 2002; Nicholas, 2009). Similarly the dynamics of sediment transport can be approximated by slope-dependent functions that dispense with much of the physics that gives rise to non-linear effects that accumulate erroneously and which are sensitive to initial conditions that are hard to specify. In this sense the 'reduced complexity' label may well be appropriate in that difficult problems are made tractable largely by replacing complex phenomena by simplified parameterizations. Of course, as Nicholas and Quine (2007) observe, this form of abstraction is virtually ubiquitous in modelling.

For coastal problems a different set of considerations emerges. Most fundamentally, the dependence of sediment transport on geophysical flows cannot be quite so readily parameterised as a simple function of topography. Tidal flows, for example, arise from pressure rather than topographic gradients and drive sediment movements that emerge as tiny residuals of opposing gross fluxes. The residual water and sediment movements are much less amenable to robust parameterisation, which favours the retention of more of the hydrodynamic complexity in models that aim to resolve morphological change. This particularly applies to estuaries and to systems dominated by cohesive sediments. The sediment transport pathways that drive morphological change are highly grain-size dependent (e.g. Bass et al., 2007) and the interaction between cohesive and non-cohesive sediment pathways can be quite complex, even involving opposing residual fluxes in some tidal inlets (e.g. Van der Kreeke and Hibma, 2005).

There is also the question of how comprehensively to model coupled systems that are complex in their own right and exhibit different scales of behaviour and strengths of horizontal coupling. Change on open coasts is typically mediated by beach grade material (sands, gravels) and littoral drift systems that tend to have a strong serial dependency. Even in the case of a dependence on more distant sources, the filtering effect (e.g. via slower shelf transport rates) acts to decouple sources from their ultimate sinks, such that the problem reduces to one of shorter-range transfers with serial dependency (i.e. dominant direction

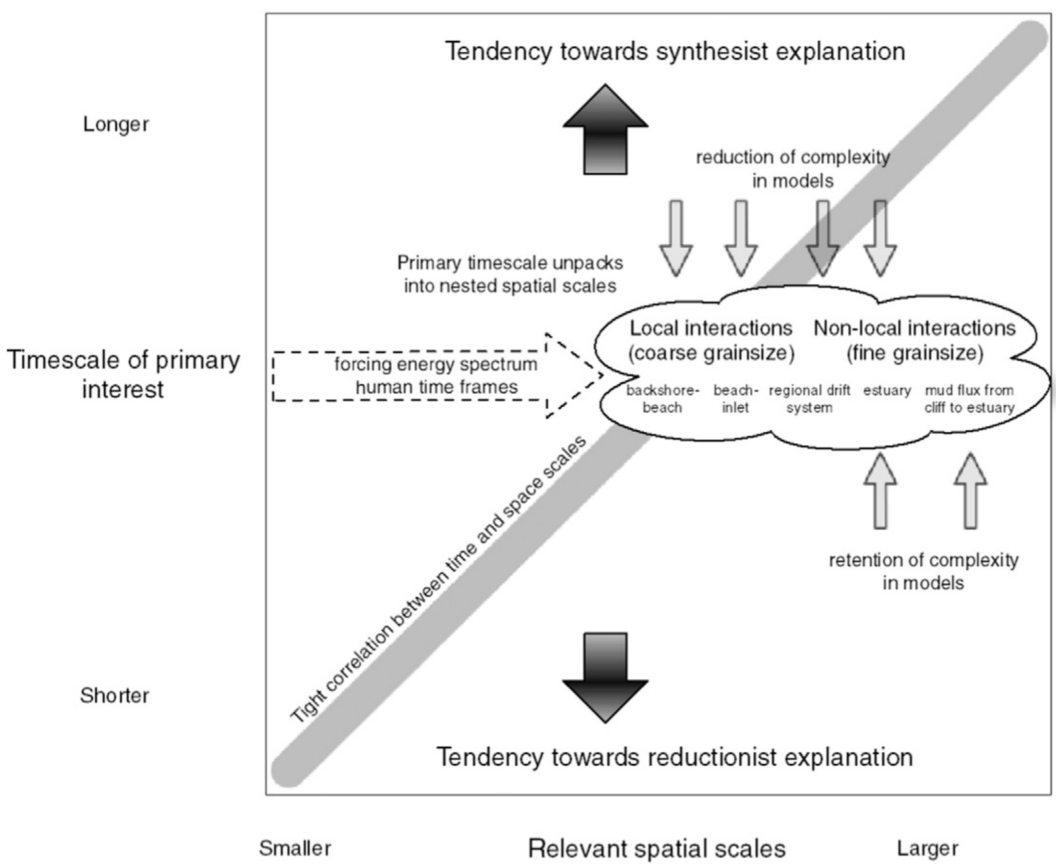



**Fig. 4.** Schematic representation of linkages between a timescale of primary interest (determined with reference to intrinsic forcing periodicities as well as engineering, social and political timeframes) and the associated multiple spatial scales of interaction in coupled coast–estuary–shelf systems (the latter being strongly associated with distinct sediment size fractions). From a modelling perspective, broadly synthesist and reductionist approaches can be brought to bear on various aspects of this coupled system.

of littoral drift system). Some estuarine systems also participate in short-range coupling with adjacent coast via tidal deltas and inlet bypassing processes (e.g. Burningham and French, 2006) and the evolution of estuary morphology can exert a considerable influence on the open coast (e.g. Stive et al., 1991; Fitzgerald et al., 2006). Other estuaries and inlets are only weakly coupled via inlet dynamics to up- and down-drift coasts, such that much longer-range transfers of cohesive material determine their sediment budget and morphological evolution. A comprehensive model of coupled estuary and coastal behaviour at decadal timescales thus has to incorporate spatial scales of interaction that range from a relatively small multiple of the spatial resolution up to potentially hundreds of kilometres to handle different pathways within the shelf-scale sediment system (Fig. 4). In the case of, estuaries, fusion of reductionist and synthesist approaches may offer the best basis for prediction, especially where the timescale of interest lies in the decadal to centennial range (Thornhill et al., 2015).

How best to approach the problem of deciding upon an appropriate model complexity therefore? Building on the preceding synthesis of ideas, we see a number of requirements for successful predictive modelling at a mesoscale.

1. The system being studied must be bounded with reference to the time and space scales at which behaviours of interest emerge and/or scientific or management problems arise. Natural timescales may be revealed more-or-less objectively through analysis of the forcing energy spectrum, supplemented by increasingly sophisticated data-driven analysis of coastal change (Tebbens et al., 2002; Kroon et al., 2008; Lazarus et al., 2011), although it is clear that timescales will invariably be societally imposed in many instances. The concept of a low-order coastal tract that contains a hierarchy of higher-order sediment-sharing morphological units (Cowell et al., 2003a) provides a vital conceptual framework through which we can bound the system in a way that specifies key sediment exchanges and constraints on supply. These include contemporary terrestrial sources, exchanges between coast and inner shelf, and the magnitude of active stores that integrate a long history of time-varying inputs and outputs and estuarine sinks. However, we here advocate a slightly different approach to the treatment of scales within the tract hierarchy in favour of relative rather than absolute time scales allied to a broader spectrum of spatial scales. Identification of nested littoral sediment cells is not sufficient to resolve the web of interactions that drive coupled coastal and estuarine behaviour and a more sophisticated mapping of morphological components and influence (including sediment) pathways is an essential first step in establishing the configuration of the system, and especially the multiplicity of spatial interactions that need to be modelled within a specified time frame. This mapping should also identify the various geological (e.g. Burningham, 2008; Cooper et al., 2012) and human constraints (structures, interventions in the sediment regime) that constrain evolution towards a natural equilibrium. The Coastal and Estuarine System Mapping methodology advocated by French et al., 2016) provides a basis for deriving these constraints and interactions in a consistent and transparent way based on formalisation of current knowledge.
2. Levels of model complexity and comprehensiveness must be appropriate to the problem at hand. Whilst is clear that progress is more likely to be made through models that are predominantly synthesist, (in the sense of Paola, 2002), the nature of marine forcing, especially in estuaries, means that it is frequently appropriate to retain a degree of hydrodynamic complexity that can only be obtained from a primarily reductionist approach. Accordingly, we see great potential in fusing these approaches rather than deploying them in isolation as end members of a modelling spectrum. This can be achieved in two ways. Firstly, the power of reductionist coastal area models can be harnessed to extend the spatial scale of shelf sediment transport (e.g. Barnard et al., 2013; Bian et al., 2013). Again, this possibility reflects the observation that spatial and temporal scales are not quite as tightly intertwined as conventional scale-based classifications of geomorphic phenomena typically assume (see also Fenster et al., 1993). Crucially, this allows us to use the proven explanatory power of computational hydrodynamics both to generate large-scale pathways and also to resolve potentially important local cross-shore exchanges that are below the limits of direct observation. Secondly, hybrid model architectures can be devised to retain physically complete representations where these are necessary to generate behaviours we expect to be important at the scale of interest but which otherwise reduce complexity in favour of a more synthesist approach. Exploratory work of this kind has been undertaken in estuaries (Hinwood and McLean, 2002; Dearing et al., 2006) and Fig. 5 illustrates how this vision is being implemented in the Estuary SpaTial LandscapE Evolution Model (ESTEEM; Thornhill et al., 2015) that is being developed as part of the iCOASST Project in the UK (Nicholls et al., 2012).
3. Modellers should seek a priori insights into what kind of behaviours are likely to be evident at the scale of interest and the extent to which the behavioural validity of a model may be constrained by its underlying assumptions and its comprehensiveness (i.e. the range of processes included). Since such behaviours emerge at the scale of interest from non-additive interactions between more fundamental components, they are often not easily predictable. However, as Payo et al. (2015) show, qualitative mathematical modelling of alternative functional representation of system structure can provide invaluable insights into sets of indicative behaviours and the processes that are most important in driving them. Anticipation of modelled behaviours is not purely of intellectual interest — it can guide evaluation of model performance by suggesting appropriately objective criteria against which to evaluate model performance. This can be problematic with models of landform evolution, since conventional point-based accuracy metrics struggle to accommodate subjective judgements of morphological similarity (Bosboom and Reniers, 2014). Eliot et al. (2013) advocate enhanced validation with reference to a multi-axis observational space that takes account of a broader suite of distinct processes than conventional assessments of hydrodynamic and sediment transport models. Finally, if we know the behaviours involved, model output indicators can be chosen that more closely map on to user needs (Van Koningsveld et al., 2005).
4. Informed by qualitative insights into likely dynamic behaviour, models (and compositions of models) should then be formulated with a view to resolving critical state changes. Here too, appropriate complexity is required. Dynamic changes, such as changes in the sign of a cohesive sediment flux, may well depend on more complex representation of shallow water tidal asymmetry. Divergent end states, such as transitions between wave and tide-dominated intertidal landform states may be accommodated more parametrically but a mechanistic treatment of some form is essential (e.g. Mariotti and Fagherazzi, 2013) — such behaviours are not easily resolved at all in simpler rule-based schemes such as SLAMM (Clough et al., 2010). But as we engage more fully with the meso-scale, we also need models that can handle configurational change. Model coupling (Warner et al., 2008; van Maanen et al., 2016) is a way forward here, especially when carried out within a conceptual framework that identifies potential changes in state (French et al., 2016). Indeed, the ability to dynamically assemble sets of component coastal and estuary models on the fly to handle the appearance or disappearance of individual landforms or landform complex may well be a factor favouring externally coupled compositions of disparate models rather than more tightly integrated models (see also Voinov and Shugart, 2013).
5. Meso-scale modelling of coastal morphological change should reflect critically on the role of modelling and its relation to the observable world. Conventionally, models have provided a means of articulating

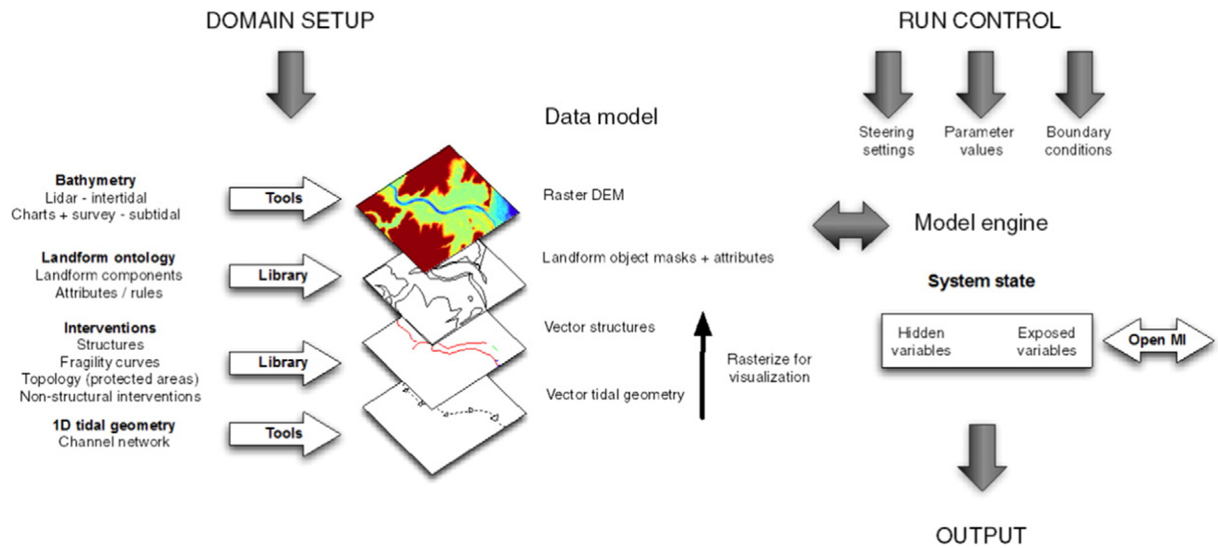



**Fig. 5.** Schematization of Estuary SpaTial LandscapE Evolution Model (ESTEEM) model code architecture (Thornhill et al., 2015), showing fusion of low-dimensional but essentially reductionist representation of tidal hydrodynamics and channel sediment flux, parameterized ('reduced complexity') intertidal flat sedimentation, and largely rule-based saltmarsh sedimentation.

and testing theories in a well-worked (though occasionally critiqued; Oreskes et al., 1994; Thieler et al., 2000) validation framework. As Manson (2007) observes, this is accommodated within both the classical axiomatic and normal conceptions of science (Fig. 6). As the ambition of our modelling grows, however, we encounter problems involving too many components and interactions (size, comprehensiveness) to be amenable to such a treatment. At this point we enter territory that has become the realm of complex systems science in which the relation between model and data becomes somewhat different. This relates, in part to the 'complexity paradox' of Oreskes (2004) under which the more we strive to incorporate real world complexity in increasingly sophisticated and comprehensive models, the more we struggle to make sense of the model. In this situation, the model becomes almost as complex as reality and, arguably, reveals as much about the consequences of adopting a particular view of how the world works as it does about the world itself.

Whilst the preceding observations are undoubtedly of academic interest, they do have implications, especially for comprehensive simulations using compositions of coupled models to advance coastal science as well as to inform management decision-making. At the very least, it necessitates a subtler approach to the question of validation. Rather than conventional point-based metrics in a calibration–validation sequence, we should seek metrics that diagnose qualitatively correct behaviours and distributions of outcomes within probabilistic uncertainty frameworks (e.g. Murray and Paola, 1996; Murray, 2003).

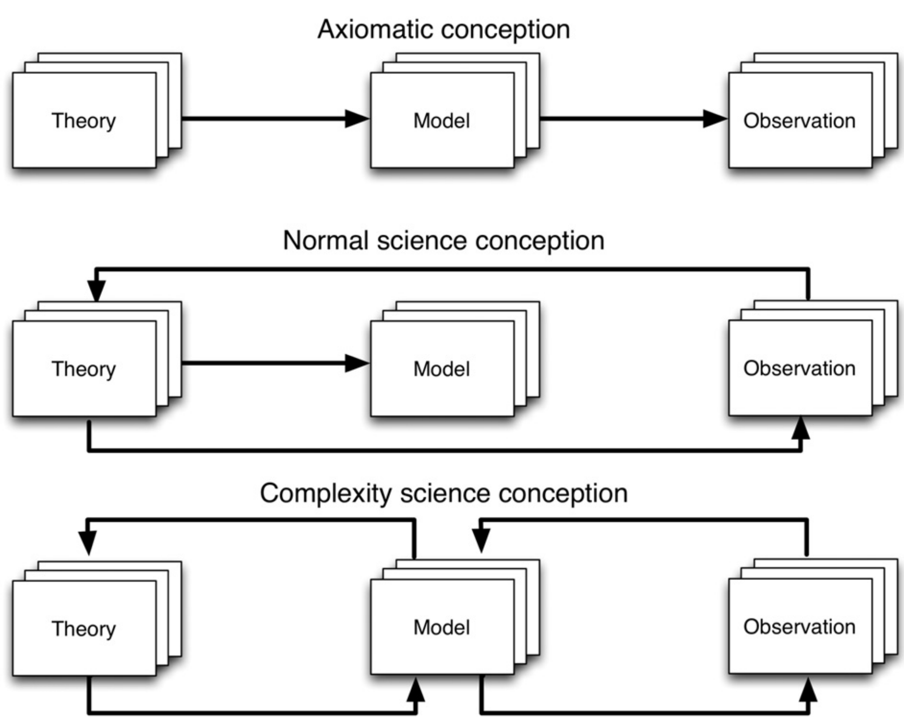



**Fig. 6.** Axiomatic, normal-science and complexity science conceptions of the relationships between theory, models and observables (based on Manson, 2007). The last of these more closely corresponds to many of the modelling endeavours considered in the present paper.

Where validation in the traditional sense is not feasible, inter-model comparison to test specific aspects of highly parameterised system behaviour against that modelled using more physically-complete (e.g. computational fluid dynamics) models is likely to play a larger role in evaluating more synthesist model codes (Nicholas and Quine, 2007). A potentially fruitful approach to the alignment of model complexity and observable reality is to derive meta-models that parameterise and reproduce behaviours of finer-scale models. Urban et al. (1999) demonstrate this in the context of landscape ecology and the problem of scaling knowledge of trees, through stands, to whole forests. Fine-scale models generate behaviours that can be statistically abstracted into simpler meta-models that generate essentially consistent results since they share a conceptual foundation and empirical base. Moreover, the meta-models can be tuned to meet the needs of specific applications, thereby mitigating some of the pitfalls of comprehensive broader-scaling modelling outlined above. This track does not appear to have been widely followed in geomorphology, but would seem to have potential in the coastal contexts considered here.

As models and their outputs become more complex, clear communication of modelling goals, approaches and capabilities to stakeholder audiences also becomes critically important. As Hall et al. (2014), observe, some of the best known, but worst understood models have emanated from climate science. In a coastal context, relatively simple models (notably those found on the original 'Bruun rule' of beach response to sea-level rise) have generated a broader scepticism (e.g. Pilkey et al., 2013) concerning the practical feasibility of quantitatively modelling coastal process and morphological change. As we acknowledge above, this is partly a consequence of the continued use of weak mesoscale parameterizations in the form of the shoreface profile of equilibrium. But it also arises through uncritical translation of scientific models, intended as exploratory tools, to applied ones. If we wish to avoid a similar fate for the emerging generation of meso-scale coastal change models, we clearly need to supplement our technical modelling effort with effective strategies for achieving a mutual understanding of key concepts, how complicated systems operate, and how scientific model predictions can be reconciled with non-modellers' knowledge of environmental systems and behaviours (often accumulated informally over many years, even generations, of first-hand experience). As Voinov and Gaddis (2008) have argued (albeit in the context of participatory catchment modelling), it is critical to engage with stakeholders early on and gain acceptance of the modelling methodology well ahead of the presentation of model results.

## 6. Concluding remarks

It should be fundamental to any modelling endeavour to match the level of mechanistic understanding with scale of the problem. In the context of understanding and managing coastal change, that scale of interest is often as much determined by applications and stakeholder needs than by any intrinsic organisational property that the geomorphological systems involved are dependent upon. One of the major challenges of applied coastal modelling is that highly abstract models, useful for exploring specific aspects of system behaviour and honing our scientific understanding, are typically rather far removed from stakeholder perceptions of how the world works and, moreover, do not generate the kind of quantitative predictions that management problems increasingly demand. Whilst there is certainly scope for changing the kind of questions that we demand of models there remains a real demand for quantitative prediction of coastal morphodynamic behaviour, even if this is ultimately translated into semi-qualitative outcomes — such as the probabilistic assessment of potential changes in state.

As we engage with the evolution of coastal morphological changes at the decadal to centennial mesoscales of greatest human interest, it is clear that model complexity must be adjusted away from the tendency towards reductionism that continues to characterise much existing work in coastal morphodynamics in favour of more synthesist principles. A crucial step here is the recognition that analysing emergent mesoscale interactions can provide the most direct explanations of phenomena and, quite likely, the most reliable predictions. Whilst this is often carried out as a prelude to what has come to be known, in geomorphology at least, as 'reduced complexity' modelling, the arguments that we have advanced in this paper reinforce the view that smaller scale processes are not necessarily more 'fundamental' than larger-scale ones.

Reduced complexity modelling has proved especially popular in the context of landscape evolution under the influence of hydrological processes at the catchment scale. However, coastal and estuarine hydrodynamic forcings are harder to parameterise than their hydrological equivalents. Moreover, as we have argued here, the nesting of time and space scales is not quite as tight as is commonly envisaged. For these reasons, we advocate not a reduced complexity approach, per se, but an 'appropriate complexity' one that balances reductionism and synthesism to capture the behaviours that provide the explanatory and predictive capabilities we need. Aside from a neater philosophical rationale, such an approach would also dispense with the negative connotations that 'reducing complexity' conveys to lay audiences who may pose simple questions but who undoubtedly assume that solutions must address real world complexity and be technologically sophisticated.

## Acknowledgements

This work was funded by NERC (http://www.nerc.ac.uk) as part of the Integrating COAstal Sediment SysTems (iCOASST) project (NE/J005541/1), with additional support from the Environment Agency (http://environment-agency.gov.uk) as an embedded stakeholder. The authors gratefully acknowledge helpful discussions with other iCOASST project team members and with the invited attendees of the iCOASST International Conference on Simulating Decadal Coastal Morphodynamics, held from 15 to 17 October 2013 in Southampton, UK. Dr. Helene Burningham (UCL) is also thanked for her invaluable assistance with the production of Fig. 1. The paper has also benefited from comments by J.A.G. Cooper and one other anonymous reviewer.

## References

Anthony, E.J., Dolique, F., 2004. The influence of Amazon-derived mud banks on the morphology of sandy, headland-bound beaches in Cayenne, French Guiana: a short- to long-term perspective. Mar. Geol. 208, 249–264.
Ashton, A., Murray, A.B., 2006a. High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature. J. Geophys. Res. 11, F04012.
Ashton, A., Murray, A.B., 2006b. High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. J. Geophys. Res. 11, F04012.
Ashton, A., Murray, A.B., Arnoult, O., 2001. Formation of coastline features by large-scale instabilities induced by high-angle waves. Nature 414, 296–300.
Barnard, P.L., Erikson, L.H., Elias, E.P.L., Dartnell, P., 2013. Sediment transport patterns in San Francisco Bay Coastal System from cross validation of bedform asymmetry and modeled residual sediment flux. Mar. Geol. 345, 72–95.
Bass, S.J., McCave, I.N., Rees, J.M., Vincent, C.E., 2007. Sand and mud flux estimates using acoustic and optical backscatter sensors: measurements seaward of the Wash, southern North Sea. In: Balson, P.S., Collins, M.B. (Eds.), Coastal and Shelf Sediment Transport. Geological Society of London, Special Publications 274, pp. 25–35.
Bian, C., Jiang, W., Greatbatch, R.J., 2013. An exploratory model study of sediment transport sources and deposits in the Bohai Sea, Yellow Sea, and East China Sea. J. Geophys. Res. Oceans 118, 5908–5923.
Bosboom, J., Reniers, A.J.H.M., 2014. Displacement-based error metrics for morphodynamic models. Adv. Geosci. 39, 37–43.
Brasington, J., Richards, K.S., 2007. Reduced-complexity, physically-based geomorphological modelling for catchment and river management. Geomorphology 90, 171–177.
Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Trans. Inst. Brit. Geogr. NS 4, 463–484.
Bruun, P., 1962. Sea-level rise as a cause of shore erosion. Proc. Am. Soc. Civ. Eng. J. Waterw. Harb. Div. 88, 117–130.
Bruun, P., 1988. The Bruun rule of erosion by sea-level rise: a discussion on large-scale two- and three-dimensional usages. J. Coast. Res. 4, 627–648.

Burgess, K., Orford, J., Dyer, K., Townend, I., Balson, P., 2002. FUTURECOAST — the integration of knowledge to assess future coastal evolution at a national scale. Proceedings 28th International Conference on Coastal Engineering. World Scientific vol. 3, pp. 3221–3233.
Burningham, H., 2008. Contrasting geomorphic response to structural control: the Loughros estuaries, northwest Ireland. Geomorphology 97, 300–320.
Burningham, J., French, J.R., 2006. Morphodynamic behaviour of a mixed sand-gravel ebb-tidal delta: Deben estuary, Suffolk, UK. Mar. Geol. 225, 23–44.
Burningham, H., French, J.R., 2013. Is the NAO winter index a reliable proxy for wind climate and storminess in northwest Europe? Int. J. Climatol. 33, 2036–2049.
Capobianco, M., Stive, M.J.F., Jimenez, J.A., Sanchez-Arcilla, A., 1998. Towards the definition of budget models for the evolution of deltas. J. Coast. Conserv. 4, 7–16.
Capobianco, M., de Vriend, H.J., Nicholls, R.J., Stive, M.J.F., 1999. Coastal area impact and vulnerability assessment: the point of view of the morphodynamic modeller. J. Coast. Res. 15, 701–716.
Clough, J.S., Park, R.A., Fuller, R., 2010. SLAMM 6 Beta Technical Documentation. Warren Pinnacle Consulting Inc. (49 pp.).
Coastal Protection and Restoration Authority, 2012. Louisiana's Comprehensive Master Plan for a Sustainable Coast. CPRA, Baton Rouge (190 pp. http://www.coastalmasterplan.la.gov).
Coco, G., Murray, A.B., 2007. Patterns in the sand: from forcing templates to self organization. Geomorphology 91, 271–290.
Cooper, J.A.G., Pilkey, O.H., 2004a. Alternatives to the mathematical modeling of beaches. J. Coast. Res. 20, 641–644.
Cooper, J.A.G., Pilkey, O.H., 2004b. Sea level rise and shoreline retreat: time to abandon the Bruun Rule. Glob. Planet. Chang. 43, 157–171.
Cooper, J.A.G., Pilkey, O.H., 2004c. Longshore drift: trapped in an Expected Universe. J. Sediment. Res. 74, 599–606.
Cooper, J.A.G., Jackson, D.W.T., Dawson, A.G., Dawson, S., Bates, C.R., Ritchie, W., 2012. Barrier islands on bedrock: a new landform type demonstrating the role of antecedent topography on coastal evolution. Geology 40, 923–926.
Cooper, N.J., Jay, H., 2002. Predictions of large-scale coastal tendency: development and application of a qualitative behavior-based methodology. J. Coast. Res. Spec. Issue 36, 173–181.
Cooper, N.J., Pontee, N.I., 2006. Appraisal and evolution of the littoral 'sediment cell' concept in applied coastal management: experiences from England and Wales. Ocean Coast. Manag. 49, 498–510.
Coulthard, T.J., Macklin, M.G., Kirkby, M.J., 2002. A cellular model of Holocene river basin and alluvial fan formation. Earth Surf. Process. Landf. 27, 269–288.
Cowell, P.J., Thom, B.G., 1994. Morphodynamics of coastal evolution. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp. 33–86.
Cowell, P.J., Roy, P.S., Cleveringa, J., de Boer, P.L., 1999. Simulating coastal tracts with the shoreface translation model. SEPM Spec. Publ. 62, 165–175.
Cowell, P.J., Stive, M.J.F., Niedoroda, A.W., de Vriend, H.J., Swift, D.J.P., Kaminsky, G.M., Capobianco, M., 2003a. The coastal-tract (part 1): a conceptual approach to aggregated modeling to lower-order coastal change. J. Coast. Res. 19, 812–827.
Cowell, P.J., Stive, M.J.F., Niedoroda, A.W., Swift, D.J.P., de Vriend, H.J., Buijsman, M.C., Nicholls, R.J., Roy, P.S., Kaminsky, G.M., Cleveringa, J., Reed, C.W., de Boer, P.L., 2003b. The coastal-tract (part 2): applications of aggregated modeling to lower-order coastal change. J. Coast. Res. 19, 828–848.
de Vriend, H.J., 1991. Mathematical modelling and large-scale coastal behaviour. J. Hydraul. Eng. 26, 727–753.
de Vriend, H.J., Capobianco, M., Chesher, T., de Swart, H.E., Latteux, B., Stive, M.J.F., 1993. Approaches to long-term modelling of coastal morphology: a review. Coast. Eng. 21, 225–269.
Dean, R.G., 1991. Equilibrium beach profiles: characteristics and applications. J. Coast. Res. 7, 53–84.
Dearing, J., Richmond, N., Plater, A., Wolf, J., Prandle, D., Coulthard, T., 2006. Modelling approaches for coastal simulation based on cellular automata: the need and potential. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 364, 1051–1071.
Dearing, J.A., Ademola, K.B., Anette, R., Sander Van Der, L., Billie, L.T., 2010. Complex land systems: the need for long time perspectives to assess their future. Ecol. Soc. 15, 21.
Di Silvio, G., Dall'Angelo, C., Bonaldo, D., Fasolato, G., 2010. Long-term model of planimetric and bathymetric evolution of a tidal lagoon. Cont. Shelf Res. 30, 894–903.
Dronkers, J., 1986. Tidal asymmetry and estuarine morphology. Neth. J. Sea Res. 20, 117–131.
Elgar, S., Raubenheimer, B., 2008. Wave dissipation by muddy seafloors. Geophys. Res. Lett. 35, L07611.
Eliot, M., Stul, T., Eliot, I., 2013. Revisiting landforms in coastal engineering. Coasts and Ports 2013: 21st Australasian Coastal and Ocean Engineering Conference and the 14th Australasian Port and Harbour Conference. Engineers Australia, Barton, A.C.T., pp. 733–738.
Esteves, L.S., Williams, J.J., Brown, J.M., 2011. Looking for evidence of climate change impacts in the eastern Irish Sea. Nat. Hazards Earth Syst. Sci. 11, 1641–1656.
Fagherazzi, S., Wiberg, P.L., 2009. Importance of wind conditions, fetch, and water levels on wave-generated shear stresses in shallow intertidal basins. J. Geophys. Res. 114, F03022.
Favis-Mortlock, D., 2013. Non-linear dynamics, self-organization, and cellular automata models. In: Wainwright, J., Mulligan, M. (Eds.), Environmental Modelling: Finding Simplicity in Complexity. Wiley, Chichester, pp. 349–367.
Fenster, M.S., Dolan, R., Elder, J., 1993. A new method of predicting shoreline positions from historical data. J. Coast. Res. 9, 147–171.
Fitzgerald, D.M., Buynevich, I., Argow, B., 2006. Model of tidal inlet and barrier island dynamics in a regime of accelerated sea level rise. J. Coast. Res. SI 39, 789–795.
Fredsoe, J., Deigaard, R., 1992. Mechanics of Coastal Sediment Transport: Advanced Series on Ocean Engineering. World Science, Singapore (392 pp.).
French, J.R., Burningham, H., 2013. Coasts and climate: insights from geomorphology. Prog. Phys. Geogr. 37, 550–561.
French, J.R., Benson, T., Burningham, H., 2008. Tidal and meteorological forcing of suspended sediment flux in a muddy mesotidal estuary. Estuar. Coasts 31, 843–859.
French, J.R., Burningham, H., Thornhill, G., Whitehouse, R., Nicholls, R.S., 2016. Conceptualizing and mapping coupled estuary, coast and inner shelf sediment systems. Geomorphology. 256, 17–35.
Gelfenbaum, G., Kaminsky, G.M., 2010. Large-scale coastal change in the Columbia River littoral cell: an overview. Mar. Geol. 273, 1–10.
Gratiot, N., Anthony, E.J., Gardel, A., Gaucherel, C., Proisy, C., Wells, J.T., 2008. Significant contribution of the 18.6 year tidal cycle to regional coastal changes. Nat. Geosci. 1, 169–172.
Haigh, M.J., 1987. The holon: hierarchy theory and landscape research. In: Ahnert, F. (Ed.), Geomorphological Models: Theoretical and Empirical ModelsCatena Supplement 10. Catena Verlag, pp. 181–192.
Hall, D.M., Lazarus, E.D., Swannack, T.M., 2014. Strategies for communicating systems models. Environ. Model. Softw. 55, 70–76.
Hallet, B., 1990. Spatial self-organization in geomorphology: from periodic bedforms and patterned ground to scale-invariant topography. Earth-Sci. Rev. 29, 57–75.
Hansom, J.D., Lees, G., McGlashan, D.J., John, S., 2004. Shoreline management plans and coastal cells in Scotland. Coast. Manag. 32, 227–242.
Hanson, H., Kraus, N.C., 2011. Long-term evolution of a long-term evolution model. J. Coast. Res. Spec. Issue 59, 118–129.
Hartley, L., Pontee, N., 2008. Assessing breaching risk in coastal gravel barriers. Proc. Inst. Civ. Eng. Marit. Eng. 161, 143–152.
Hay, G., Marceau, D.J., Dubé, P., Bouchard, A., 2001. A multiscale framework for landscape analysis: object-specific analysis and upscaling. Landsc. Ecol. 16, 471–490.
Hinkel, J., Lincke, D., Vafeidis, A.T., Parrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettwies, X., Leverman, A., 2014. Coastal flood damage and adaption coasts under 21st century sea-level rise. PNAS 111, 3292–3297.
Hinwood, J.B., McLean, E.J., 2002. Modelling the evolution of an estuary. Proceedings Littoral 2002 — The Changing Coast, Porto, Portugal, pp. 245–252.
Holland, K.T., Vinzon, S.B., Calliari, L.J., 2009. A field study of coastal dynamics on a muddy coast offshore of Cassino beach, Brazil. Cont. Shelf Res. 29, 503–514.
Howard, A.D., 1965. Geomorphological systems — equilibrium and dynamics. Am. J. Sci. 263, 302–312.
Isla, F.I., Bujalesky, G.G., 2000. Cannibalisation of Holocene gravel beach-ridge plains, northern Tierra del Fuego, Argentina. Mar. Geol. 170, 105–122.
Jevrejeva, S., Moore, J.C., Grinsted, A., 2012. Sea level projections to AD2500 with a new generation of climate change scenarios. Glob. Planet. Chang. 80-81, 14–20.
Kirwan, M.L., Guntenspergen, G.R., D'Apaos, A., Morris, J.T., Mudd, S.M., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophys. Res. Lett. 37, L23401.
Knight, J., Harrison, S., 2014. Limitations of uniformitarianism in the Anthropocene. Anthropocene 5, 71–75.
Komar, P.D., 1998. Beach Processes and Sedimentation. Prentice Hall, New Jersey (544 pp.).
Komar, P.D., 1999. Coastal change — scales of processes and dimensions of problems. In: Kraus, N.C., McDougal, W.M. (Eds.), Coastal Sediments'99 vol. 1. American Society of Civil Engineers, New York, pp. 1–17.
Komar, P.D., Inman, D.L., 1970. Longshore sand transport on beaches. J. Geophys. Res. 75, 5914–5927.
Kousky, C., 2014. Managing shoreline retreat: a US perspective. Clim. Chang. 124, 9–20.
Kraus, N.C., Larson, M., Kriebel, D.L., 1991. Coastal Sediments '91. American Society of Civil Engineers, Seattle, pp. 527–587.
Kragtwijk, N.G., Zitman, T.J., Stive, M.J.F., Wang, Z.B., 2004. Morphological response of tidal basins to human intervention. Coast. Eng. 51, 207–221.
Kroon, A., Larson, M., Moller, I., Yokiki, H., Rozynski, G., Cox, J., Laroude, P., 2008. Statistical analysis of coastal morphological data sets over seasonal to decadal time scales. Coast. Eng. 55, 581–600.
Latteux, B., 1995. Techniques for long term morphological simulation under tidal action. Mar. Geol. 126, 129–141.
Lazarus, E.D., Ashton, A., Murray, A.B., Tebbens, S., Burroughs, S., 2011. Cumulative versus transient shoreline change: dependencies on temporal and spatial scale. J. Geophys. Res. 116, F02014.
Lazarus, E.D., Ellis, M.A., Murray, A.B., Hall, D.M., 2015. An evolving research agenda for human–coastal systems. Geomorphology. http://dx.doi.org/10.1016/j.geomorph.2015.07.043.
Longuet-Higgins, M.S., 1970. Longshore currents generated by obliquely incident waves: 1. J. Geophys. Res. 75, 6778–6789.
Manson, S.M., 2007. Challenges in evaluating models of geographic complexity. Environ. Plan. B Plan. Des. 34, 245–260.
Mariotti, G., Fagherazzi, S., 2013. A two-point dynamic model of the coupled evolution of channels and tidal flats. J. Geophys. Res. Earth Surf. 118, 1387–1399.
McNinch, J.E., 2004. Geologic control in the nearshore: shore oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA. Mar. Geol. 211, 121–141.
Meselhe, E., McCoquodale, J.A., Sheldon, J., Dortch, M., Brown, T.S., Elkan, P., Rodrique, M.D., Schindler, J.K., Wang, Z., 2013. Ecohydrology component of Louisiana's 2012 Coastal Master Plan: mass-balance compartment model. J. Coast. Res. SI 67, 16–28.
Mitsova, D., Esnard, A.-M., 2012. Holding back the sea: an overview of shore zone planning and management. J. Plan. Lit. 27, 446–459.
Moore, L.J., McNamara, D., Murray, A.B., Brenner, O., 2013. Observed changes in hurricane-driven waves explain the dynamics of modern cuspate shorelines. Geophys. Res. Lett. 40, 5867–5871.
Motyka, J.M., Brampton, A.H., 1993. Coastal Management: Mapping of Littoral Cells. Wallingford Report SR 328. Hydraulics Research Ltd, Wallingford, UK (102 pp.).

Mulder, J.P.M., Hommes, S., Horstman, E.M., 2011. Implementation of coastal erosion management in The Netherlands. Ocean Coast. Manag. 54, 888–897.

Müller, F., 1997. State-of-the-art in ecosystem theory. Ecol. Model. 100, 135–161.

Murray, A.B., 2003. Contrasting the goal, strategies, and predictions associated with simplified numerical models and detailed simulations. In: Iverson, D., Wilcock, P. (Eds.), Prediction in GeomorphologyGeophysical Monograph 135. American Geophysical Union, pp. 151–165.

Murray, A.B., 2007. Reducing model complexity for explanation and prediction. Geomorphology 90, 178–191.

Murray, A.B., 2013. Which models are good (enough), and when? In: Shroder, J. (Editor in Chief), Baas, A.C. (Ed.), Treatise on Geomorphology, vol. 2. Academic Press, San Diego, pp. 50–58.

Murray, A.B., Paola, C., 1994. A cellular model of braided rivers. Nature 371, 54–57.

Murray, A.B., Paola, C., 1996. A new quantitative test of geomorphic models, applied to a model of braided streams. Water Resour. Res. 32, 2579–2587.

Murray, A.B., Ashton, A., 2013. Instability and finite-amplitude self-organization of large-scale coastline shapes. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 371, 20120363.

Murray, A.B., Lazarus, E., Ashton, A., Baas, A., Coco, G., Coulthard, T., Fonstad, M., Haff, P.K., McNamara, D., Paola, C., Reinhardt, L., 2008. Geomorphology, complexity, and the emerging science of the Earth's surface. Geomorphology 103, 496–505.

Murray, A.B., Coco, G., Goldstein, B., 2014. Cause and effect in geomorphic systems: complex systems perspectives. Geomorphology 214, 1–9.

Narayan, S., Hanson, S., Nicholls, R.J., Clarke, D., Willems, P., Ntegeka, V., Mobaliu, J., 2012. A holistic model for coastal flooding using system diagrams and the source-pathway-receptor (SPR) concept. Nat. Hazards Earth Syst. Sci. 12, 1431–1439.

Nicholas, A.P., 2009. Reduced-complexity flow routing models for sinuous single-thread channels: intercomparison with a physically-based shallow-water equation model. Earth Surf. Process. Landf. 34, 641–653.

Nicholas, A.P., Quine, T.A., 2007. Crossing the divide: representation of channels and processes in reduced-complexity river models at reach and landscape scales. Geomorphology 90, 318–339.

Nicholls, R.J., 2011. Planning for the impacts of sea level rise. Oceanography 24, 144–157.

Nicholls, R.J., Bradbury, A., Burningham, H., Dix, J., Ellis, M., French, J.R., Hall, J.W., Karunarathna, H.U., Lawn, J., Pan, S., 2012. iCOASST — integrating coastal sediment systems. Coastal Eng. Proc. 33, 100 (sediment).

Nicholls, R.J., Townend, I.H., Bradbury, A.P., Ramsbottom, D., Day, S.A., 2013. Planning for long-term coastal change: experience from England and Wales. Ocean Eng. 71, 3–16.

O'Neill, E.G., DeAngelis, D.L., Waide, J.B., Allen, T.F.H., 1986. A Hierarchical Concept of Ecosystems. Princeton University Press, Princeton (253 pp.).

Oreskes, N., 2004. Beyond the ivory tower: the scientific consensus on climate change. Science 306, 1686–1690.

Oreskes, N., Scrader-Frechette, K., Belitz, K., 1994. Verification, validation, and confirmation of numerical models in the earth sciences. Science 263, 641–646.

Orford, J.D., 2011. Gravel-dominated coastal-barrier reorganisation variability as a function of coastal susceptibility and barrier resilience. Coastal Sediments '11. In: Wang, P., Rosati, J.D., Roberts, T.M. (Eds.), Proceedings of the International Conference on Coastal Sediments 2011. CD-ROM published by World Scientific Publishing Corp. and East Meets West Productions, Corpus Christi, Texas, pp. 1257–1270.

Orford, J.D., Anthony, E.J., 2011. Extreme events and the morphodynamics of coastal gravel barriers: strengthening uncertain ground. Mar. Geol. 290, 41–45.

Orford, J.D., Carter, R.W.G., Jennings, S.C., 1996. Control domains and morphological phases in gravel-dominated coastal barriers. J. Coast. Res. 12, 589–605.

Orford, J.D., Forbes, D.J., Jennings, S., 2002. Organisational controls, typologies and time-scales of paraglacial gravel-dominated coastal systems. Geomorphology 48, 51–85.

Orford, J.D., Jennings, S.C., 2007. Variation in the organisation of gravel-dominated coastal systems: evidence from Nova Scotia and Southern England. Coastal Sediments '07. New Orleans. American Society of Civil Engineers vol. 1, pp. 434–448.

Paola, C., 2002. Quantitative models of sedimentary basin infilling. Sedimentology 41 (Suppl. 1), 121–178.

Payo, A., Hall, J.W., French, J.R., Sutherland, J., van Maanen, B., Nicholls, R.J., Reeve, D.E., 2015. Causal Loop Analysis of coastal geomorphological systems. Geomorphology. http://dx.doi.org/10.1016/j.geomorph.2015.07.048.

Pedersen, J.B.T., Bartholdy, J., 2007. Exposed salt marsh morphodynamics: an example from the Danish Wadden Sea. Geomorphology 90, 115–125.

Peyronnin, N., Green, M., Richards, C.P., Owens, A., Reed, D., Chamberlain, J., Groves, D.G., Rhinehart, W.K., Belhadjali, K., 2013. Louisiana's 2012 Coastal Master Plan: overview of a science-based and publicly informed decision-making process. J. Coast. Res. Spec. Issue 67, 1–15.

Phillips, J.D., 2012. Synchronization and scale in geomorphic systems. Geomorphology 137, 50–58.

Phillips, J.D., 2014. State transitions in geomorphic responses to environmental change. Geomorphology 204, 208–217.

Pilkey, O.H., Young, R.S., Riggs, S.R., Smith, A.W., Wu, H., Pilkey, W.D., 1993. The concept of shoreface profile of equilibrium: a critical review. J. Coast. Res. 9, 255–278.

Pilkey, O.H., Young, R., Cooper, J.A.G., 2013. Quantitative modeling of coastal processes: a boom or bust for society? In: Baker, V.R. (Ed.), Geological Society of America Special Paper 502. Rethinking the Fabric of Geology, pp. 135–144.

Roelvink, D., Reniers, A., 2012. A Guide to Modeling Coastal Morphology. World Scientific, New Jersey (292 pp.).

Sayers, P.B., Hall, J.W., Meadowcroft, I.C., 2002. Towards risk-based flood hazard management in the UK. Proc. Inst. Civ. Eng. 150, 36–42.

Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. In: Morisawa, M. (Ed.), Fluvial Geomorphology. State University of New York Publications, Geomorphology, Binghampton, pp. 299–310 (Binghamton, New York).

Schumm, S.A., Lichty, R.W., 1965. Time, space, and causality in geomorphology. Am. J. Sci. 263, 110–119.

Schwartz, M., 1967. The Bruun theory of sea-level rise as a cause of shore erosion. J. Geol. 75, 76–92.

Simon, H.A., 1962. The architecture of complexity. Proc. Am. Philos. Soc. 106, 468–482.

Singh Chauhan, P.P., 2009. Autocyclic erosion in tidal marshes. Geomorphology 110, 45–57.

Slott, J.M., Murray, A.B., Ashton, A.D., Crowley, T.J., 2006. Coastline response to changing storm patterns. Geophys. Res. Lett. 33, L18404.

Stive, M.J.F., Roelvink, D.J.A., de Vriend, H.J., 1991. Large-scale coastal evolution concept. Proceedings of the 22nd International Conference on Coastal Engineering. American Society of Civil Engineers, New York, pp. 1962–1974.

Stive, M.J.F., Capaobianco, M., Wang, B., Ruol, P., Buijsman, M.C., 1998. Morphodynamics of a tidal lagoon and adjacent coasts. 8th International Conference on Physics of Estuaries and Coastal Seas. The Hague. Rotterdam, Balkema, pp. 397–407.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), 2013. IPCC, 2013: climate change 2013: the physical science basisContribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (1535 pp.).

Storlazzi, C.D., Griggs, G.B., 2000. Influence of El Nino-Southern Oscillation (ENSO) events on the evolution of California's shoreline. Geol. Soc. Am. Bull. 112, 236–249.

Syvitski, J.P.M., Kettner, A., 2011. Sediment flux and the Anthropocene. Philos. Trans. R. Soc. Lond. A Math. Phys. Eng. Sci. 369, 957–975.

Tebbens, S.F., Burroughs, S.M., Nelson, E.E., 2002. Wavelet analysis of shoreline change on the Outer Banks of North Carolina: an example of complexity in the marine sciences. Proc. Natl. Acad. Sci. U. S. A. 93 (Suppl. 1), 2554–2560.

Thieler, E.R., Pilkey, O.H., Young, R.S., Bush, D.M., Chei, F., 2000. The use of mathematical models to predict beach behavior for U.S. coastal engineering. J. Coast. Res. 16, 48–70.

Thorn, C.E., Welford, M.R., 1994. The equilibrium concept in geomorphology. Ann. Assoc. Am. Geogr. 84, 666–696.

Thornhill, G., French, J.R., Burningham, H., 2015. ESTEEM — a new 'hybrid complexity' model for simulating estuary morphological change at decadal to centennial scales. In: Wang, P., Rosati, J.D., Cheng, J. (Eds.), Proceedings Coastal Sediments 2015. World Scientific (13 pp.).

Townend, I.H., Wang, Z.B., Rees, J.G., 2006. Millennial to annual volume changes in the Humber estuary. Proc. R. Soc. A 463, 837–854.

Urban, D.L., 2005. Modeling ecological processes across scales. Ecology 86, 1996–2006.

Urban, D.L., Acevedo, M.F., Graman, S.L., 1999. Scaling fine-scale processes to large-scale processes using models derived from models: meta-models. In: Mladenoff, D., Baker, W. (Eds.), Spatial Modelling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge, pp. 70–98.

Valentine, J.W., May, C.L., 1996. Hierarchies in biology and paleontology. Paleobiology 22, 23–33.

Van Koningsveld, M., Davidson, M.A., Huntley, D.A., 2005. Matching science with coastal management needs: the search for appropriate Coastal State Indicators. J. Coast. Res. 213, 399–411.

Van der Kreeke, J., Hibma, A., 2005. Observations on silt and sand transport in the throat section of the Frisian Inlet. Coast. Eng. 52, 159–175.

Van Maanen, B., Nicholls, R.J., French, J.R., Barkwith, A., Bonaldo, D., Burningham, H., Murray, A.B., Payo, A., Sutherland, J., Thornhill, G., Townend, I.H., van der Wegen, M., Walkden, M.J.A., 2016. Simulating mesoscale coastal evolution for decadal coastal management: A new framework integrating multiple, complementary modelling approaches. Geomorphology. 256, 68–80.

Van Rijn, L.C., 2011. Coastal erosion and control. Ocean Coast. Manag. 54, 867–887.

Villaret, C., Hervouet, J.-M., Kopmann, R., Merkel, U., 2013. Morphodynamic modelling using the Telemac finite-element system. Comput. Geosci. 53, 105–113.

Voinov, A., Gaddis, E.J.B., 2008. Lessons for successful participatory watershed modeling: a perspective from modeling practitioners. Ecol. Model. 216, 197–200.

Voinov, A., Shugart, H.H., 2013. 'Integronsters', integral and integrated modelling. Environ. Model. Softw. 39, 149–158.

Warner, J.C., Perlin, N., Skyllingstad, E.D., 2008. Using the Model Coupling Toolkit to couple earth system models. Environ. Model. Softw. 23, 1240–1249.

Werner, B.T., 1999. Complexity in natural landform patterns. Science 284, 102–104.

Werner, B.T., 2003. Modeling landforms as self-organized, hierarchical dynamical systems. In: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology: Geophysical Monograph 135. American Geophysical Union Press, Washington, D.C., pp. 133–150.

Wolinsky, M.A., Murray, A.B., 2009. A unifying framework for shoreline migration: 2. Application to wave-dominated coasts. J. Geophys. Res. 114, F01009. http://dx.doi.org/10.1029/2007JF000856.

Woodroffe, C.D., Murray-Wallace, C.V., 2012. Sea-level rise and coastal change: the past as a guide to the future. Quat. Sci. Rev. 54, 4–11.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol. 56, 93–118.

Wright, L.D., Thom, B.G., 1977. Coastal depositional landforms: a morphodynamic approach. Prog. Phys. Geogr. 1, 412–459.

Young, R.S., Pilkey, O.H., Bush, D.M., Thieler, E.R., 1995. A discussion of the Generalized Model for Simulating Shoreline Change (GENESIS). J. Coast. Res. 11, 875–886.