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

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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

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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 multi-decadal 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