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Data-driven and hybrid coastal morphological prediction methods for mesoscale forecasting

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ABSTRACT

It is now common for coastal planning to anticipate changes anywhere from 70 to 100 years into the future. The process models developed and used for scheme design or for large-scale oceanography are currently inadequate for this task. This has prompted the development of a plethora of alternative methods. Some, such as reduced complexity or hybrid models simplify the governing equations retaining processes that are considered to govern observed morphological behaviour. The computational cost of these models is low and they have proven effective in exploring morphodynamic trends and improving our understanding of mesoscale behaviour. One drawback is that there is no generally agreed set of principles on which to make the simplifying assumptions and predictions can vary considerably between models. An alternative approach is data-driven techniques that are based entirely on analysis and extrapolation of observations. Here, we discuss the application of some of the better known and emerging methods in this category to argue that with the increasing availability of observations from coastal monitoring programmes and the development of more sophisticated statistical analysis techniques data-driven models provide a valuable addition to the armoury of methods available for mesoscale prediction. The continuation of established monitoring programmes is paramount, and those that provide contemporaneous records of the driving forces and the shoreline response are the most valuable in this regard. In the second part of the paper we discuss some recent research that combining some of the hybrid techniques with data analysis methods in order to synthesise a more consistent means of predicting mesoscale coastal morphological evolution. While encouraging in certain applications a universally applicable approach has yet to be found. The route to linking different model types is highlighted as a major challenge and requires further research to establish its viability. We argue that key elements of a successful solution will need to account for dependencies between driving parameters, (such as wave height and tide level), and be able to predict step changes in the configuration of coastal systems.

1. Introduction

Planning and development on our shorelines is increasingly undertaken within the framework of structured shoreline management plans that require the consideration of morphological change over a window of up to 100 years into the future. Methods to perform this have been scarce and predictions have been made on an ad hoc, case by case, basis. The absence of a consistent predictive framework has provided the motivation to develop morphological models that can provide useful mesoscale (of the order of 10^1 to 10^2 km length scales and 10^1 to 10^2 year timescales) estimates of coastal morphological change. The hurdles to developing such models are significant. The deterministic process models that have proved useful for predicting short-term storm response encounter difficulties when applied to mesoscale problems. Not only does the increased number of time steps required lead to an unacceptable accumulation of numerical errors, as well as huge increases in computational time, but the approach has difficulties in reliably reproducing some of the broad morphological tendencies observed in practice.

In this paper we discuss some of the methods that have been attempted to make mesoscale predictions of coastal change and then propose an alternative approach, based on using information contained in the growing amount of observational evidence gathered in coastal monitoring programmes. This approach has gained the epithet 'data-driven' modelling and is demonstrated through a number of applications to study sites from around the world. We also provide a demonstration of how data-driven methods can be combined with reduced

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complexity models as an example of how a good observational database can be combined with elements of physical understanding to form the basis of prediction. Accordingly, we argue for the importance of maintaining and extending long records of good quality observations, such as those gathered at Duck in the USA, Lubiatowo in Poland and the Channel Coastal Observatory in the UK, and the intention to expand the observational network to cover a wider range of shoreline types and exposures. Further, methods that combine the observational evidence with elements of our understanding of the key physical processes seem to show some promise, and go some way towards addressing the criticism that purely data-driven methods are based entirely on historical measurements.

One question that arises naturally from scale categorisation is whether forecasting methods can (or should) be developed at each scale, or whether the detailed process knowledge at small scales should simply be extended into the description of larger scale processes, at consequent computational cost. Section 2 provides some background to the different types of methods that have been developed for predicting mesoscale coastal morphology. Section 3 presents a range of data-driven techniques together with a selection of applications to specific sites. The merging of data-driven and mechanistic approaches in hybrid models is discussed in Section 4. The paper concludes with Section 5.

2. Background

Our coastlines change as a consequence of the aggregation of forces due to winds, waves and tides and the consequent movement of sediments. The net result of continual sediment transport is an alteration of the shape or morphology of the shoreline. De Vriend et al. (1993) concluded over 20 years ago that understanding this process was one of the most challenging issues confronting coastal engineers and managers. Despite improvements in process understanding, computational power and monitoring techniques, our understanding of coastal morphodynamics remains limited. Unfortunately there are practical limitations to simply expanding the process models that have worked quite well for short-term prediction to the mesoscale problem. These arise partly through the potential for errors associated with the numerical approximation of derivatives to accumulate and eventually dominate the procedure, rendering the solution useless (e.g. Lilly, 1965). There are theoretical arguments that suggest there may be an inherent uncertainty or limit of predictability in the equations used for coastal process modelling due to their strong nonlinearity. In practical terms this means that the computations for very similar starting conditions will at some point diverge to very different, but equally valid, solutions. This type of behaviour has been termed “chaos” after the pioneering work of Lorenz (1963) into dynamical systems. The consequence of apparently deterministic equations of motion supporting chaos is that even if our set of morphological prediction equations are solved perfectly, we cannot be sure that our predictions will be perfect because of the limited accuracy of the initial conditions. Both Baas (2002) and Southgate et al. (2003) discuss a number of methods developed in the discipline of nonlinear processes and explain how these can be applied in the context of coastal engineering. To date, it has not been established whether the equations for morphodynamic evolution support chaos or not. From a pragmatic point of view, it seems only prudent to assume that uncertainties in initial conditions, measurement errors and numerical errors are likely to limit the period over which useful predictions can be obtained through deterministic process modelling. Some progress has been made using the ‘brute force’ approach of running process models over areas of several square kilometres and for periods up to 5 years or so as reported by Lesser (2009). The primary computational constraint is that the hydrodynamic and morphodynamic time scales are quite different. The currently preferred technique for addressing this is the morphodynamic acceleration method, in which the bed level changes that occur during a single hydrodynamic time step are multiplied by a factor so that the morphodynamic updating step does not have to be computed for each short hydrodynamic step. Detailed discussion of the technique in a range of applications can be found in Lesser et al. (2004), Jones et al. (2007), van der Wegen and Roelvink (2008), Roelvink et al. (2009), Ranasinghe et al. (2011) and Dissanayake et al. (2012) amongst others. Thence, there is good motivation to find alternative means to make mesoscale predictions that are required to inform coastal planning.

Coastal management, design of coastal structures, and flood risk all depend upon our understanding of how the shoreline changes, especially at decadal and longer timescales. Engineered structures such as groynes, artificial headlands and detached breakwaters are used as means to control the movement of sediment on the beach or near the coast. Despite such measures, changes in the prevailing conditions can lead to dramatic variations in coastal morphology and hence flood and erosion risks. Gaining insight into the physical processes that govern mesoscale morphological evolution (French et al., in this issue; van Maanen et al., in this issue), is crucial for the successful design of coastal defence systems and formulation of shoreline management strategy. From a forecasting perspective, various classes of approach are possible:

a) Process-based modelling: These models include explicit representations of physical processes to describe the complex interaction between waves, tides, sediment transport, coastal defence structures and the resulting morphological and shoreline changes. This approach can be successful for short-term forecasting, such as single or multiple storm events, often at a limited spatial scale associated with specific engineering schemes. It becomes less feasible for longer term simulations and larger domains for the reasons already mentioned above. Nevertheless, process-based modelling is capable of providing valuable insights into complex processes, thus improving the level of understanding of those processes, as demonstrated in the reviews by de Vriend et al. (1993), Nicholson et al. (1997), Roelvink (2006), Pan et al. (2010) and others.
b) Data-driven modelling: This relatively new class of approach is discussed in detail in Section 3, so only a brief outline is given here. In essence, data-driven models use measurements of past conditions at a site, together with sophisticated statistical techniques, to identify patterns of behaviour that are then extrapolated into the future to form a forecast.
c) Hybrid Modelling: This covers models in which simplifications to the governing equations or the forcing, or both, are made in order to make mesoscale forecasting tractable. Such approaches have also been termed ‘reduced complexity methods’ or ‘behaviour-oriented’ models. This class also includes approaches that combine two or more modelling concepts to form hybrids, such as combining empirical equilibrium models with wave sequences to introduce an evolutionary element (e.g. Yates et al., 2009; Splinter et al., 2014). In some situations information from complex process models is used to provide parameterised data to simpler models, such as one-line or N-line models, in order to retain the primary coastal processes. An example of this type of approach includes the use of Unibest-CL+ with parameterizations derived from a number of simulations using the model suite Delft3D reported by van Koningsveld et al. (2005). Huthnance et al. (2008) provide a brief survey of hybrid models developed for estuary and coastal inlet morphology prediction with a range of complexity, including the Analytical Emulator described by Manning (2007), the Hybrid Regime model of HR Wallingford (2006), the SandTrack approach of Soulsby et al. (2007), ASMITA described by Wang (2005), and the inverse techniques of Karunarathna et al. (2008), that have demonstrated applications with encouraging results.
d) Probabilistic modelling: This class of modelling is used to quantify uncertainties and is included as a separate approach because the input data and output quantities are distinct from those of deterministic models. Specifically, descriptions of the probability distribution functions and correlation properties of the drivers are required as