

Advances in Modelling of Large Scale Coastal Evolution

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Summary

The attention for climate change impact on the world's coastlines has established large scale coastal evolution as a topic of wide interest. Some more recent advances in this field, focusing on the potential of mathematical models for the prediction of large scale coastal evolution, are discussed. The key element in this discussion is *reduction*: of inputs, models, outputs and measured data.

1. Introduction

The morphological response of low-lying coastal regions and deltaic areas to increasing sea-level rise and other climate change impacts has aroused the interest of coastal engineers (cf. De Vriend et al., 1993), physical oceanographers and geographers (cf. Terwindt and Battjes, 1990) and marine geologists (cf. Cowell and Thom, 1995). The common understanding between these various disciplines is that quantitative approaches for this particular problem involve morphological concepts of large scale coastal behaviour which differ from the traditional concepts.

The mutual interactions between hydrodynamic processes on the one hand and sediment, bed and topography dynamics on the other hand involve a broad range of time and space scales (see Fig. 1). Long term modelling suffers from the fact that most of the physical understanding and corresponding models concern scales which are significantly smaller than the scale of the phenomena in which we are interested. Because of the nonlinearity of the natural system its long term behaviour may be inherently unpredictable, but even if this is not the case it might not be the right approach for long term predictions to run small scale models for long periods of time. This is due to the lack of knowledge regarding the importance of small scale residual effects which are important on the long run.

The above problem of nonlinear multiple-scale dynamics is not unique to coastal evolution; in the applied physics area (meteorology, oceanography or structural dynamics) pioneering research has already been done and coastal morphodynamics may profit from this.

2. Data reduction

In the various stages of long term modelling data play an important role. Phenomena and mechanisms of interest are derived from observations. Associated model concepts need to be validated with data. For applications validated models need calibration and verification. Finally, operational models may be updated by assimilating data.

Because of the wide range of and complexity (e.g. stochastic character) of the physics on the space and time scales involved we need to call upon data reduction techniques to extract the

relevant information, and to exclude "noise". Some data reduction techniques of possible use to coastal morphodynamics are briefly described.

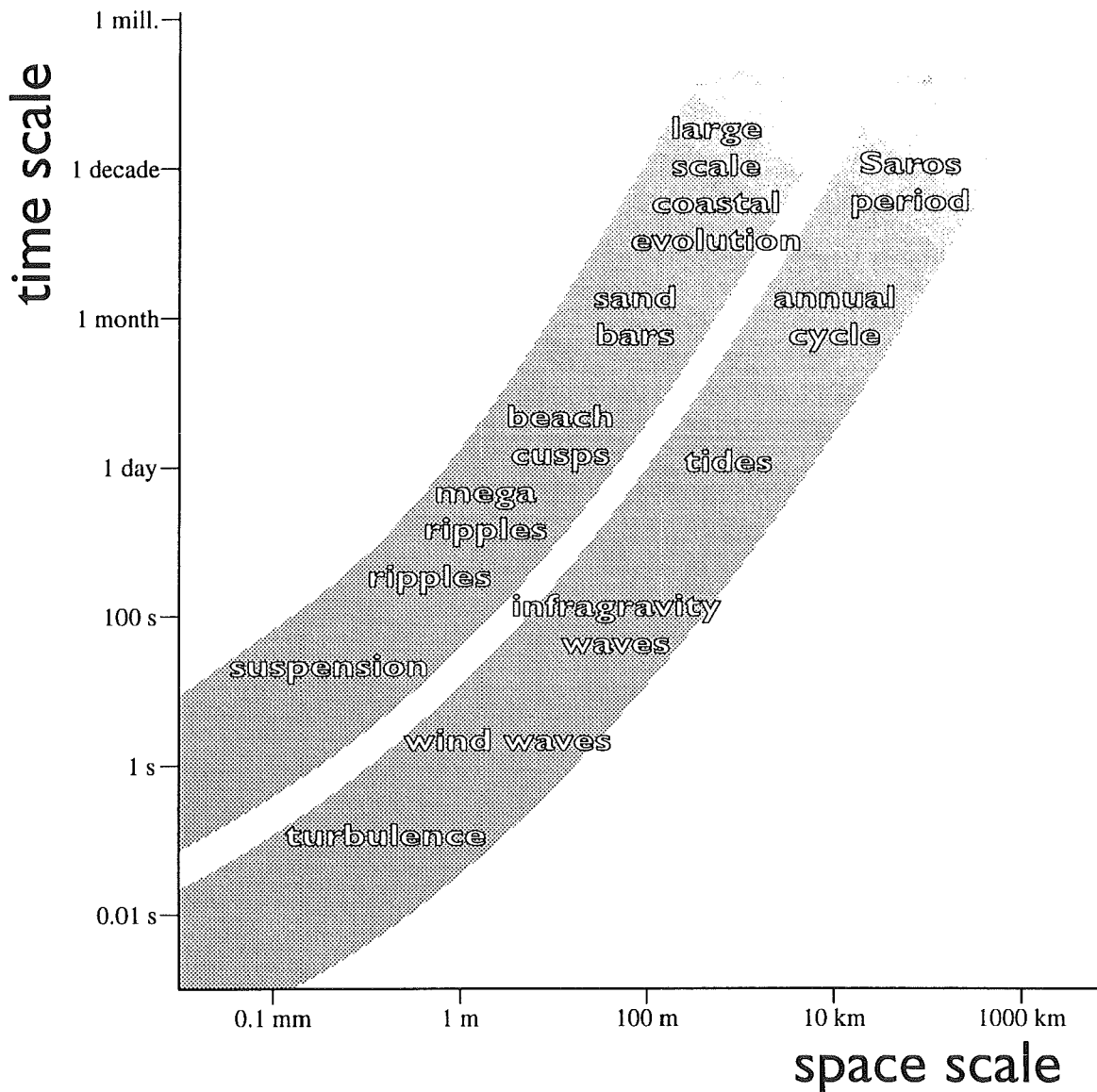


Figure 1 Time and space scales of fluid motions and bed responses in the coastal zone

Correlation

Correlation, a statistics principle, is an extreme form of data reduction: all information on the difference between two data fields, e.g. between model generated and observational data, is stored in a single index. Correlation indexes should be defined in a statistically averaged sense, because of the inherent uncertainty of the system.

Statistical analysis

As described above, temporal and spatial behaviour of coastal evolution occurs on various scales. Separation of trends for the various scales is essential both for a correct statistical extrapolation and for the determination of sampling interval. Dolan et al. (1991a, 1991b) discuss these optimizations for the temporal and spatial cases.

Empirical orthogonal functions (EOF)

The basic idea of the EOF technique is to map a dataset onto an orthogonal set of spatial functions, which are derived from the eigenfunctions of the covariance matrix (Preisendorfer and Mobley, 1988). Each spatial function has its time evolution function and a corresponding eigenvalue, which indicates the contribution to the total variance of the data. The summation of a limited number of the largest contributions, where each contribution is the product of the spatial eigenfunction, its time function and the square root of the eigenvalue, gives a best fit to the data, enabling to approximate a dataset by a limited number of space and time functions, and multiplication factors.

An interesting application of the EOF technique, addressing the analysis of large scale coastal behaviour, is Wijnberg and Terwindt (1995). They analyzed the temporal and spatial behaviour of cross-shore profiles in an alongshore moving averaging window using 27 years of data along the central Netherlands coast. Fig. 2a to 2d illustrates some of their important findings. Since stable bars are virtually absent along this coast, the second and third eigenfunctions (Fig. 2c and 2d) represent primarily the bar topography. Clearly "provinces" of different temporal behaviour are discerned. The bar behaviour appears also to be closely related to the anomalies of the + 1 m and of the 750 m offshore depth contour (Fig. 2a and b) indicating systematic undulations and the absence of trends. They concluded that the provinces cannot be explained by alongshore hydrodynamic variations, but that they are rather related to morphological constraints resulting from engineering works.

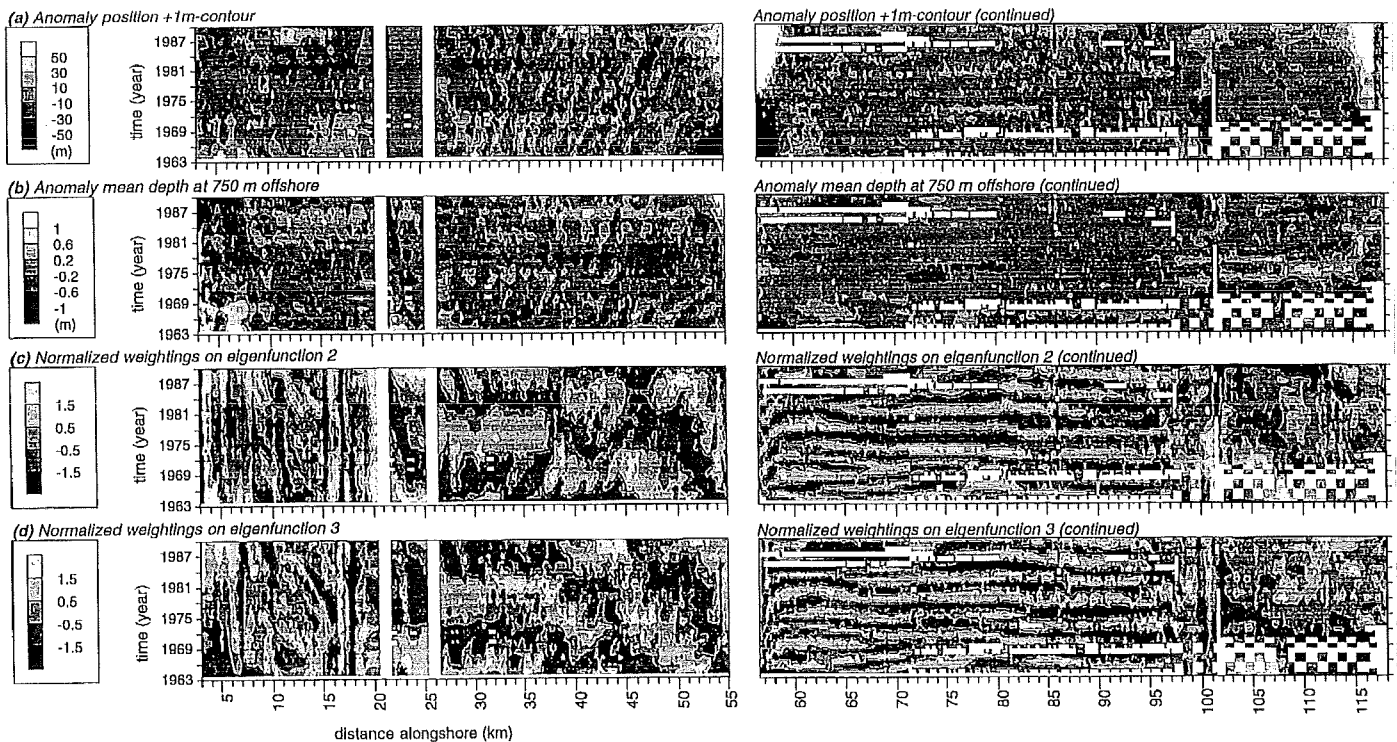


Figure 2 Alongshore coherence in the temporal behaviour of the shoreline and the profile shape (with courtesy after Wijnberg and Terwindt, 1995). (a) Cross-shore shifting of the + 1 m depth contour. (b) Deviations from the local mean depth at 750 m from the shoreline based on the weightings on the local first eigenfunctions. (c) Secondary morphological features (e.g. bars) represented by weightings on the second empirical eigenfunctions. (d) Secondary morphological features represented by weightings on the third empirical eigenfunctions.

Contour analysis

When stepping from one to two horizontal dimensions data reduction techniques involve significantly more work, while the interpretation is difficult. However, when focusing only on the time evolution of topographical patterns, coastal morphodynamics may benefit from the image processing and pattern recognition techniques developed in various other disciplines.

Video-imaging of surfzone morphology with the ARGUS system (cf. Lippmann and Holman, 1990), now employed at five different coastal sites, produces the type of data that would require contour analysis techniques.

3. Long term modelling approach

As described above (see also Fig. 1) coastal behaviour is the result of interactions between hydrodynamic and bed boundary processes on a wide range of time and space scales. It is commonly assumed (see Fig. 3; also see De Vriend, 1991) that the bed and topography response scales are related to the underlying hydrodynamic processes on similar space and time scales. The dynamic interactions take place over one to three decadal time scales between the hydrodynamic and bed process bands of Fig. 1 at the same space and time scale, because of the residual effects. Variations on much smaller scales are considered as noise, while variations on much larger scales are considered as due to extrinsic conditions (e.g. sea level rise). This is the justification for long term model concepts to avoid details of processes on scales either smaller or larger than those of interest, at the same time allowing for techniques such as scale separation and perturbation methods.

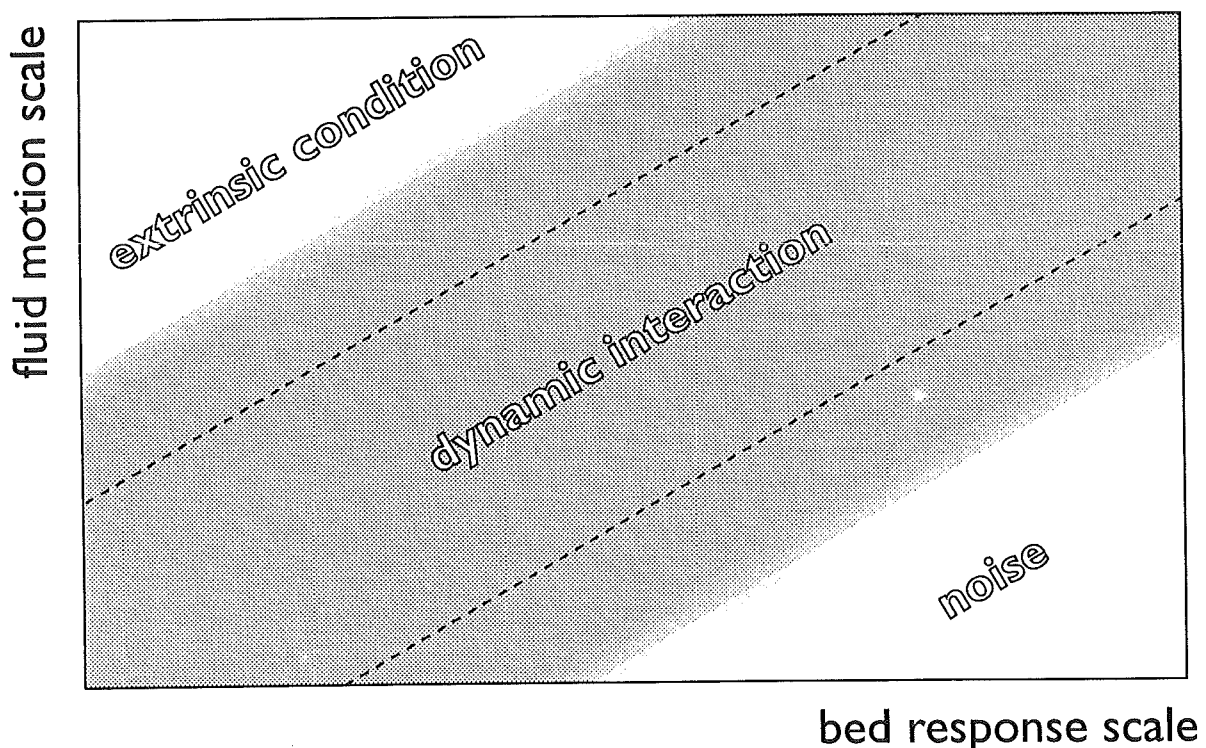


Figure 3 Dynamic interaction range between fluid motion and bed response scales (modified after De Vriend, 1991)

One of the key elements in long term modelling is reduction of information. This involves essentially four levels, which concern the input, the physical system or its model, the output and the interpretation or generalization (cf. De Vriend et al., 1993). They are reflected in the various approaches to long term modelling, viz. input reduction, model reduction and behaviour oriented modelling, which are briefly outlined below.

Input reduction

Input reduction is based on the idea that we can describe long term residual effects (e.g. water or sediment transport fields) with models based on the description of small scale processes, if we can find the representative inputs to drive them. In this context we may distinguish between tidal input, wave input and combined wave and tide input filtering approaches.

Although the astronomical tide is deterministic and can be predicted accurately, it exhibits significantly longer term modulations (spring-neap, year, nodal), which makes the real-time representation of the tidal motion in a long term model prohibitively expensive. Therefore, we need to find a way to represent the tidal motion by a small number of unmodulated tides. The idea behind tidal input filtering is to take a complete tidal record over the period of interest and compute the mean absolute transport in a number of salient points of the model domain. Subsequently, a small number or even a single representative tide is selected, such that in these points the reference quantity is reproduced. This approach was elaborated by Latteux (1987) for tides only and by Steijn (1989, 1992) for tides in combination with waves. They both find that the representative tide is somewhat (7% to 20%) higher than the mean tide, depending on the magnitude of the power of the sediment transport formula and on the adopted threshold for sediment motion.

Further analysis and testing of the above approaches reveals (De Vriend et al., 1993) that automatic procedures for tidal input filtering are not yet available. Much depends on the specific properties of the tide in the area of interest. The availability of sufficient data on the tidal velocities in that area is therefore of vital importance.

The overall wave conditions in an area vary with a certain randomness, i.e. stochastically, with time. At the scale of the morphological evolutions of interest, randomness has to be taken into account via the boundary conditions. The objective of wave input filtering is to represent the wave climate by a small number of representative conditions, with which we can drive the wave module in our deterministic model system in order to estimate long term mean transports and bed evolutions. Different approaches have been developed, viz. a multiple (Steijn 1989, 1992) and a single (Chesher and Miles, 1992) representative wave approach (MRW and SRW). The typical complications that one encounters in both approaches is that it is difficult to choose representative weighting factors because of simultaneous and usually mutually exclusive requirements to comply with different physical processes, such as bulk longshore drift, sediment stirring, rippled bed or sheet flow transport.

This illustrates the inherent limitation of these approaches: if the schematization is correct for one point or one transport mechanism, it is not necessarily so for all others.

In the case of simultaneous occurrence of wave and tide induced transport, it is usually not possible to consider them separately. First, there will be interactions, e.g. due to tidal water

level variations on the wave-induced sediment stirring. Second, the relative importance of waves and tides will vary in space (channels vs. shoals) and time (extreme wave events vs. calms). In order to take such effects into account, a single representative tide in combination with a single representative wave per direction sector may not be enough. For complex topographies, we should rather think of two tides (neap or mean and spring) and three representative wave conditions (calm, mean, storm) per sector.

Model reduction

Model reduction is based on the idea that, by using more or less formal analysis and integration methods, the model can be reformulated at the scale of interest without describing the details of smaller scale effects. The topographic scale of interest is usually that of the "mean" flow. Non-linearities due to advection, bottom friction and propagation therefore act over the whole model domain, such that we have to use a fully non-linear flow module in morphodynamic models. Especially in horizontally 2D morphodynamic models, the flow module is usually by far the most expensive constituent in computational terms. Some principal approaches to reduce the physical model formulation and thereby the computational efforts are:

- reduction of the number of calls to the expensive modules by increasing the effective morphological time step;
- introduction of simple updating methods for the flow and wave fields after small bed changes;
- semi-empirical averaging over the smaller space and time scales; and
- formal model reduction and analysis.

All these reduction methods make use of the difference in time scale between the hydrodynamic and bed response processes (cf. De Vriend et al., 1993). The first three of these methods contain intuition and or empirical assumptions. Here, we will only describe a recent result (Hulscher, 1995) which was established by formal model reduction. It is based on a linear stability analysis, which is discussed without going into the mathematics.

The formal reduction method, originally developed in river morphodynamics, makes use of the time scale difference between the relevant hydrodynamic and morphodynamic processes. The first step consists of scaling the constituent equations, after which characteristic scales for all variables are introduced, so that a non-dimensional form of the equations result. Depending on the situation considered, some of the terms in the non-dimensional equations are small, thereby allowing us to apply perturbation methods to derive simplified equations.

A particularly successful approach now consists of investigating free instabilities of the morphodynamic system, in order to explain rhythmic morphological features. After the model simplification, the basic state is described, which is a solution of the simplified model in the absence of morphological features. For this basic state a linear stability analysis is conducted by investigating the evolution of infinitesimally small perturbations with a priori arbitrary wave numbers and orientations. The wave numbers and orientation refer to the length scale and orientations of the bottom perturbations. This results in a dispersion relationship for the complex frequency as a function of the wave number and basic model parameters. The real part of this frequency gives the exponential growth rate of the perturbations. If this rate is positive for a certain range of wave numbers, the basic state is unstable with respect to perturbations which belong to that class. The rate intensity indicates which modes are the initially fastest growing, which should be detectable in field observations.

Contributions to the basic effort along this line of approach to explain tidal sand banks in offshore areas based on the depth-integrated shallow water wave equations (Huthnance, 1982a), have been made by Huthnance (1982b) and De Vriend (1990). Recently, the extension of this approach as started by Hulscher et al. (1993) by introducing in the flow model a vertical structure of the flow, including velocity veering due to Coriolis forces, has resulted (Hulscher, 1995) in a relative complete mapping of the regions instable to initial, arbitrary perturbations of the bed as a function of Coriolis, viscous effects, and bed slope (see Fig. 4). It appears that, besides a flat bottom region, three different types of initially most unstable modes can be identified: tidal sand banks, sand waves and tide parallel ridges. These findings seem to be well in accordance with observations.

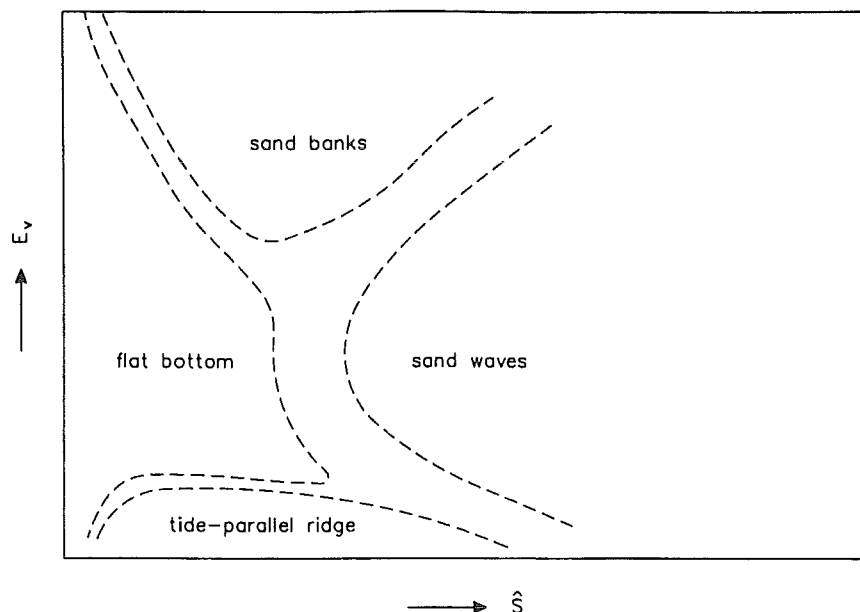


Figure 4 Characteristic bed forms predicted by the three-dimensional shallow water model as a function of the nondimensional bottom slip parameter S and nondimensional viscous depth parameter E_v (with courtesy after Hulscher, 1995).

Behaviour oriented modelling

When applying behaviour oriented modelling one attempts to describe the physical phenomena without formally going into the underlying processes.

An example of such an approach is found in Stive and De Vriend (1995). They describe the behaviour of coastal stretches which have some form of superstructure like a dune preventing overwash, and which are not interrupted by inlet systems nor constrained by underlying or nearby geology. Furthermore, it is assumed that this coastal stretch is approximately uniform in the longshore direction both as far as it concerns the profile form, loose-sediment substrate characteristics and extrinsic hydrodynamic conditions. Effectively, this implies that they consider the average shoreface profile evolution of coastal stretches or cells of several kilometres in length, which are part of an uninterrupted coastline with small curvature.

On the shoreface of such a coastal cell a variety of hydrodynamic and sediment-transport processes are interacting with the bed, as indicated in Figure 8. The nature of the hydrodynamics (waves, currents and circulation) in the surf zone is different from that on the remainder of the shoreface. In the surf zone the processes are strongly depth controlled and

largely driven by the associated loss of momentum and the dissipation of wave energy. Wave propagation, circulation and currents on the remainder of the shoreface are influenced by the shoaling water depths and shoreline position, but in this coastal boundary layer many external forces, such as friction, pressure gradients and geostrophic effects and baroclinic forces, are driving circulation and currents, while density differences may also play an important role.

Their starting hypothesis is that, in line with the above hydrodynamic differentiation, two distinct morphodynamic regimes may be distinguished in the long-term morphological evolution of the shoreface profile, viz. (1) the upper shoreface which includes the dune face, beach, inner and outer surfzone, and where the effects due to wave energy dissipation are predominant, and (2) the lower shoreface through to its inner-shelf foot where the mixed action of shoreface currents and shoaling and refracting waves is predominant. The upper shoreface, often called the 'active zone' in the literature on short-term profile evolution, is assumed to obey more or less the assumption of invariance of the profile relative to the mean sea level (cf. Bruun, 1962). This implies that the morphodynamic adaptation of the profile is assumed to be relatively fast. The lower shoreface in contrast undergoes relatively slow adaptations to the changes of the currents and waves caused by such things as changes of the mean sea level. The transition zone between these regimes, the middle shoreface, is assumed to adapt itself to the changes imposed by the upper and lower shoreface behaviour.

An overview of the general behaviour and possible displacements of the several cross-shore profile zones and of the steering processes is as summarized in Table 1.

PROFILE ZONE	BEHAVIOUR AND DISPLACEMENT
Upper shoreface	■ Steady profile form (yearly averaged) ■ Upward profile displacement with sea-level rise ■ Shoreward horizontal profile displacement due to: - upward profile displacement with sea-level rise - aeolian transport over first dune row - positive alongshore transport gradient (alongshore loss) - downwelling transport on shoreface ■ Seaward horizontal profile displacement due to: - wave asymmetry and upwelling transport on shoreface - negative alongshore transport gradient (alongshore gain)
Middle shoreface	■ Inclining or declining depending on: - horizontal upper shoreface displacement - declining or inclining lower shoreface
Lower shoreface	■ Declining (and eroding) in case of: - dominance of wave asymmetry and upwelling transport - negative alongshore transport gradient ■ Inclining (and accreting) in case of: - dominance of downwelling transport - positive alongshore transport gradient
Inner shelf	■ Steady average level

Table 1 Large-scale evolution of a coastal stretch

Based on the above analysis Stive and De Vriend (1995) conclude that on a large time scale the whole shoreface profile is "active", but that the dynamic profile response takes place at different time scales. Observations suggest time scales of hours around the waterline (e.g. Lippmann and Holman, 1990) to millennia near the inner shelf (e.g. Niedoroda and Swift, 1991). This has an important consequence for the intrinsic shoreface behaviour: since near-equilibrium behaviour only applies where the dynamic response scale is fast relative to the time scale of changes in the extrinsic (driving) conditions (such as mean sea level, wave and current climate, sediment supplies), shoreface evolution is transient by definition. This implies that the idea is rejected that shoreface profiles may be assumed to have a fixed shape which only depends on mean sediment and wave climate characteristics. This shape invariance may hold well for the upper region of the shoreface where the dynamic adaptation is fast relative to the driving conditions.

4. Discussion and conclusion

Clearly, long term coastal modelling is still in an early stage of development, although the fact that knowledge and models based on first physical principles are being brought together with empirical knowledge is certainly an important achievement.

A key element in the analysis and prediction of long term coastal behaviour is reduction, of inputs, models, outputs and measured data. We have shown that a reduction of models and data does not make sense, unless it is intrinsically coupled to an objective. This implies that we have to specify beforehand which aspects of the coastal behaviour we wish to focus on, and which we consider as unimportant.

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