MODELLING AEOLIAN SEDIMENT ACCUMULATIONS ON A BEACH

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Abstract

This paper aims to conceptually simulate observed spatial and temporal variability in aeolian sediment transport rates, erosion and deposition on a beach. Traditional strategies of modeling aeolian sediment transport rates do not account for supply limitations that are common on natural beaches. A recently developed 1D linear advection model is used in which supply limitations are taken into account in a highly aggregated manner. It is shown that the model is able to simulate the appearance and disappearance of sediment accumulations. However, sediment accumulations alike observed in the field using ARGUS cameras behave on a different time and spatial scales.

Key words: aeolian transport, beach, numerical model

1. Introduction

The evolution of coastal dunes and beaches is governed by marine and aeolian forces. While predicting coastal evolution it is important that both are well represented in the predictive tools used. Because current knowledge on marine processes is abundant and tools to quantify marine processes are available, this paper focuses on the far less understood aeolian processes.

Most state of the art aeolian models are relevant to dune formation in desert type situations where sediment availability is abundant (e.g. Bagnold, 1954). Using process based desert models, sediment transport rates are often modeled as a function of wind speed only. Local variability in windspeeds are often calculated using complex models for wind flow introducing feedback mechanisms between local wind conditions, sediment transport rates and morphology. As a result typical desert related dune morphology can be simulated using a process based approach (e.g. Kroy et al., 2002). Alternative models to simulate dune aeolian transport and dune morphology are cellular automata models (Werner, 1995) and linear stability models (Melo et al., 2012). Apart from few exceptions, many models are generally intended to describe morphology and aeolian transport in desert situations where abundant supply is present.

In contrast to these desert type situations, aeolian processes on the beach are typically characterized by supply limited aeolian sediment transport (Davidson-Arnott and Law, 1990). In a supply limited system, the wind driven transport capacity cannot be met due to the lack of sediment supply. Traditional desert type formulations are often calibrated to fit a relationship between wind speed and sediment transport rates measured at beaches (see for example Arens, 1996). This calibration requires the introduction of parameters representing supply limitations.

Analyzing and modeling supply limited aeolian sediment transport is more complicated due to the introduction of additional variables representing supply limitations. Examples of supply limiting variables are moisture content but also sediment sorting at the sand surface layer, vegetation and salt crust formation. These variables can vary in space and time and therefore, aeolian transport rates as well as erosion and sedimentation also vary in space and time. While the range of governing parameters is large and supply limiting parameters may interact, the relationship between wind speed, supply limiting parameters, erosion/sedimentation and aeolian sediment transport is difficult to isolate in an analysis. Consequently supply limited aeolian transport is less well understood than aeolian sediment transport in desert situations.

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Variability in aeolian sediment transport rates due to varying wind speed but also due to varying supply limiting parameters in space and time influences erosion, sedimentation and the morphology of the dry beach and coastal dune area. Beach morphology is often relatively 2D (flat surface) with respect to the adjacent dune areas. This relatively flat, vegetation free, surface could be explained by the incidental influences of marine processes during storm events where waves diffuse all local irregularities at the beach surface. During periods in between storm events however, aeolian processes govern the sedimentary processes on this relatively flat beach surface. The beach surface is of particular interest because supply properties might influence or be influenced by the characteristics of the beach surface. For example, a wet beach could possibly limit the supply and abundant supply could possibly lead to desert type dune formation.

A typical observation of sedimentary processes on the dry beach are the occurrence of sand strips (Nield, 2011). These sand strips can be observed using Argus video images, Figure 1. Despite the Argus video system is designed to capture the characteristics of the surf zone (Holman and Stanley, 2007), in many of the collected Argus images large part of the beach is also present. While hourly images are generally captured, a time series of images covering beach and dune areas is available. Figure 1 shows an example of collected images at Egmond beach in the Netherlands. The flat beach surface is present and at some moment sand strips appear and disappear over a period of several days. Wind conditions during these days were measured at a nearby location (IJmuiden). Wind conditions were generally shore parallel in the direction of view (south west) and strong with daily maxima around 10-14 m/s. Some rain showers occurred at each of the days.

Morphological models that include sediment transport rates, supply limitations and surface evolution, such as the appearance and disappearance of temporary morphology (e.g. sand strips), are currently not available. Nield (2011) present a numerical model, based on a cellular automate approach by Werner (1995), that can reproduce the appearance of sand strips where supply magnitude is varied. The disappearance of sand strips, wind fluctuations and actual quantities of aeolian sediment transport rates remain unadressed.

In an effort to analyze and explain supply limited aeolian sediment transport rates an alternative model approach is proposed by de Vries et al. (submitted). This proposed model takes supply limitations explicitly into account in an extension to using traditional sediment transport formulations. As a result, variability in rates of aeolian transport are governed by variability in wind speed and variability in supply magnitude. In the remainder of this paper it is hypothesized that this model can be used to explain the occurrence temporal sediment accumulation on the dry beach surface.

Figure 1. Snapshots of Argus images with and without aeolian accumulations at Egmond aan Zee, Netherlands. The images were taken one or two days apart each time. (a) 28-09-2005 (b) 30-09-2005 (c) 1-10-2005 (d) 2-10-2005.

2. Model and Setup

The applied model is described in detail in de Vries et al. (submitted). Below a summary is given. The 1D linear advection model simulates aeolian sediment transport in which the source can be supply limited thereby affecting the simulated sediment transport dynamics. The model uses an implementation of a conventional Bagnold (1954) type formulation to calculate wind driven equilibrium transport concentrations ($C_u(u(t))$). To allow for supply limitations a maximum is set to the sediment which can be ejected from the bed into transport at any location ($S_s(x)$). As a result, the actual sediment concentration ($C_c(x,t)$) and sediment transport rate ($Q(x,t)$) is calculated. Also, for each time and location an amount of erodible sediment at the bed ($S_e(x,t)$) is calculated. The increase or decrease in erodible sediment at the bed ($S_e(x,t)$) is governed by the ejection rates (($S_s(x)$ in the supply zone) and the erosion/sedimentation due to wind fluctuations. The total set of equations reads:

$$\frac{\partial C_c}{\partial t} + u\frac{\partial C_c}{\partial x} = \frac{\min\left(C_u - C_c, S_e/h\right)}{T} \tag{1}$$

where:

$$\frac{\partial Se}{\partial t} = S_s - \frac{\min\left(C_u - C_c, S_e/h\right)}{T} \tag{2}$$

and:

$$C_u = u^2 \tag{3}$$

Here h is the height of the transport layer which, for simplicity, is assumed to be 1 m. T is the timescale for adapting sediment concentrations to wind conditions set to T = 1 s. The sediment velocity (u = wind speed) is set to fluctuate randomly between 0-10 m/s. Model parameters T, u and h (and others) are set to values within the physical range. However, no effort has been taken at this stage to specify and calibrate to exact physical values. As a result, the variability in transport, erosion and sedimentation induced by supply and wind fluctuations is only analyzed conceptually.

The (1D) spatial domain is 1 km and divided into a zone of supply at the upwind side and a zone of no supply downwind (see Figure 2). This spatial domain is inspired by a somewhat extreme interpretation of the work by van der Wal (1998). Van der Wal (1998) illustrates that in situations where (aeolian) armoring processes have limited the sediment supply at the upper beach, the intertidal zone can be an important source for aeolian transport. Therefore a spatial variability in the cross shore distribution of the sediment source is suggested where supply is largest at the intertidal beach and smaller at the upper beach. In this academic case it is chosen to consider an explicit supply and no supply zone to account for extreme variability in supply.

The characteristics of the supply zone are defined by parameters α and $S_s(x)$ where α specifies the extent of the supply area with respect to the total domain. $S_s(x)$ represents the sediment ejection rate [kg/m^2s] in the supply zone. The magnitude of the ejection rate is defined manually and covers the extent of the supply limitation. All physical supply limiting effects, such as moisture and sediment sorting at the bed, are aggregated in the model by quantifying and varying the ejection rate. An overview of the definitions of model variables is given in Table 1.

An important feature is that sediment exchange with the bed is simulated providing the possibility to model erosion and deposition based on supply and wind fluctuations only. At this stage, no spatial variability in wind velocities are taking into account. This implies that wind and wind driven equilibrium transport are constant in space and no feedback between morphological evolution and the imposed wind field is present. As a result, accumulations of sand on the bed can only develop and migrate from spatial transport gradients associated with supply limitations in the current model.

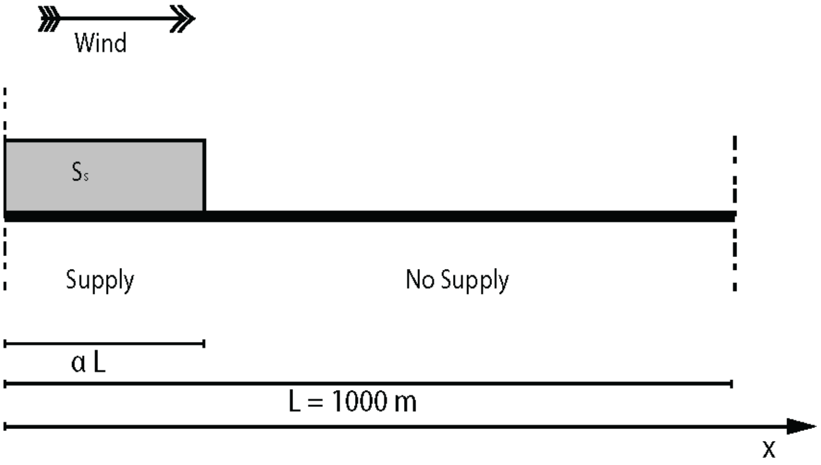

Figure 2. Spatial domain of the 1D model. Supply zone is indicated where ejection rate (S_s) is a local constant in space and time.

$C_c(x,t)$	Sediment transport concentration	kg/m^3
h	Height of the transport layer	m
u(t)	Sediment velocity	m/s
$C_u(t)$	Equilibrium concentration	kg/m^3
$S_e(x,t)$	Amount of erodible sediment at the bed	kg/m^2
$S_s(x)$	Ejection Rate at the bed	kg/m^{2}s
T	Timescale for adapting sediment concentrations	s
α	Spatial fraction of the supply zone (between 0-1)	-

Table 1 List of symbols

In the next section 2 model cases are presented:

- In **Case I** the variability in accumulation and erosion of sediment at the bed within the spatial domain is described as a function of wind fluctuations.
- In **Case II** the supply zone is extended to account for supply induced fetch effects and its implications on the spatial variability of the accumulation and erosion of sediment at the bed.

3. Results

In the presented cases wind forcing is identical. Winds are set to fluctuate randomly between 0-10 m/s on a time interval of 2 s. Characteristics of the supply zone are varied.

3.2 *Case I - Formation and disappearance of sand accumulations*

In Case I a small supply zone of 20 m (α = 0.02) is adopted with S_s set to 6 kg/m^{2}s. This value of S_s is selected to guarantee supply limited conditions with respect to the wind capacity. The results of the supply limited model are summarized in Figure 3. The left panel of Figure 3 shows a timestack image of the amount of erodible sediment at the bed. The erodible sediment at the bed generally increase when wind velocities decrease after a period of strong wind velocities.

The right panels shows snapshot images at a certain time. The top right panel shows the presence of some spatial variability of deposition. Moreover, it is shown that while a spatial variability of deposition is present, wind driven transport capacity (C_u) is reached throughout the entire spatial domain.

The bottom right panel shows that several time steps later, wind speed is larger. As a result, the temporal deposits have been picked and no erodible sediment (S_e) is present at the bed. This sediment is picked up and brought into transport (C_c) in downwind direction with the sediment speed (u). It is also shown that the wind driven transport capacity (red dash-dotted line) is not reached.

Due to wind fluctuations, some of the spatial variability in the sediment concentration results in spatial variability in deposition and vice versa. The deposited sediment re-mobilizes when wind increases and deposit when wind decreases. As a result from this intermittent behavior, distinct sediment accumulations appear and migrate during the erosion/deposition cycle. This is illustrated in particular in the left panel of Figure 3. The migration speed of these sediment accumulations is some fraction of the imposed sediment speed.

Based on our model results, no rhythmic spatial patterns are found to be present at first sight. Rhythmic spatial patterns could be expected because winds fluctuate with a constant interval of 2 seconds. However, the assumed random character in time of these fluctuations do not allow organized patterns to emerge. Using a specific periodic dependent wind signal (such as a sinusoid), migrating rhythmic bed forms could however be simulated.

3.3 *Case II - Supply limited fetch conditions and bed forms*

The previous example has shown a small supply area and a relatively large no supply area where in the no supply area, temporal deposits occur. In Case II a specific focus is on the role of the supply area. Therefore the spatial domain is adjusted in towards a relatively large supply area: $\alpha = 0.4$ and $S_s= 0.3$, keeping the total sediment supply of Cases I and II identical. Wind conditions are identical to case I.

The left panel of Figure 4 shows again the temporal and spatial development of the sediments at the bed for Case II. A similar picture is shown with the exception that because the upwind side of the supply area is significantly larger (with smaller supply magnitude), a supply induced fetch effect is present. In the supply zone there is hardly any sediment at the bed at any time while sediment transport concentrations are generally low due to the small upwind supply. This indicates that any sediment which is available for transport in this zone is quickly mobilized for transport in downwind direction.

The right panels show snapshots of erodible sediment at the bed, sediment transport concentrations and the wind driven sediment transport capacity. The sediment transport concentrations (C_c) and erodible sediment at the bed (S_e) increase with increasing fetch length at both considered moments (top and bottom panel). The top right panel shows that after some distance in downwind direction, sediment transport capacity is reached and in more downwind directions deposition accumulates at the bed (as erodible sediment). The bottom right panel shows a snapshot a couple of timesteps later where all sediment is re-mobilised and in transport concentration (C_c).

3.4 *Interpretation*

In both cases I and II sedimentation is spatially and temporally variable. In Case I it is shown that spatial variability in transport shows an intermittent signal in time where at some moment sedimentation occurs and another moment the sediment is re-mobilized and transported in the downwind direction. Alongside this intermittency, explicit sand accumulations migrate with time trough the spatial domain.

When comparing case II with case I, migrating sediment accumulations are less pronounced in case II. This is especially clear when comparing the timestack images of the left panels of Figures 3 and 4. The smaller but more active (larger ejection rates) supply zone in case I leads together with the wind fluctuations (that are kept identical between cases) to more distinct features than a larger less active supply zone.

Looking back at the images in Figure 1, a comparable variability is shown where bed forms appear and disappear over a period of several days. The presented model results are of much different spatial en temporal scale but the concept of supply limitations governing temporary sand accumulation could possibly relate to the observed variability. Focusing on the zone around the waterline in Figure 1b the sediment bed appears to be free from bed forms. This could be explained by the limited sediment supply in this zone (due to large moisture content) in line with the modeled results showing no accumulation of sand in the zone of limited supply.

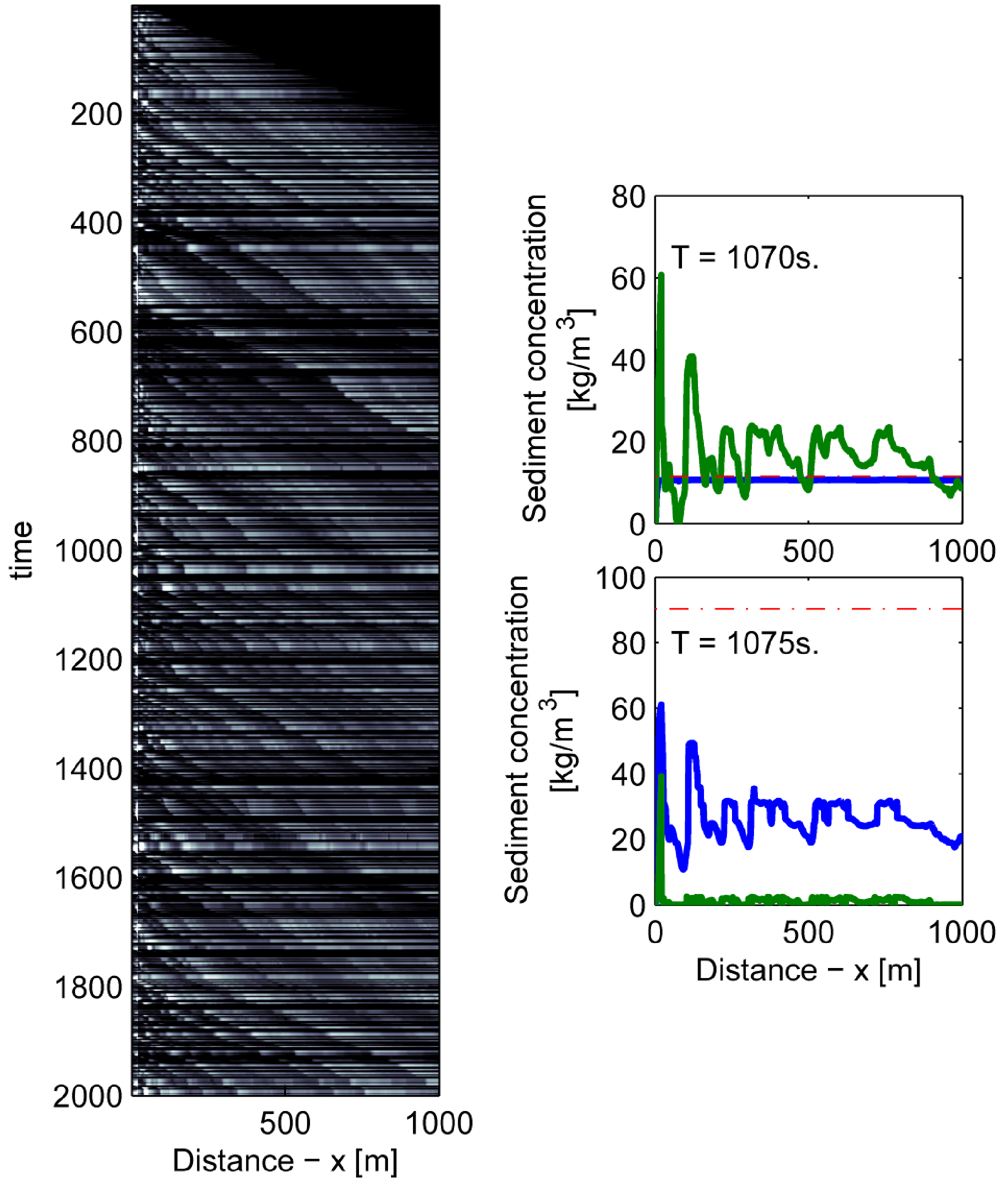

Figure 3: The Left panel shows a timestack of accumulated sediment at the bed (S_e). The right panels show snapshots of two arbitrary moments where the blue line indicates the sediment in transport (C_c) and the green line indicates the sediment at the bed (S_e). The red dash dotted line indicates the momentary sediment transport capacity (C_u).

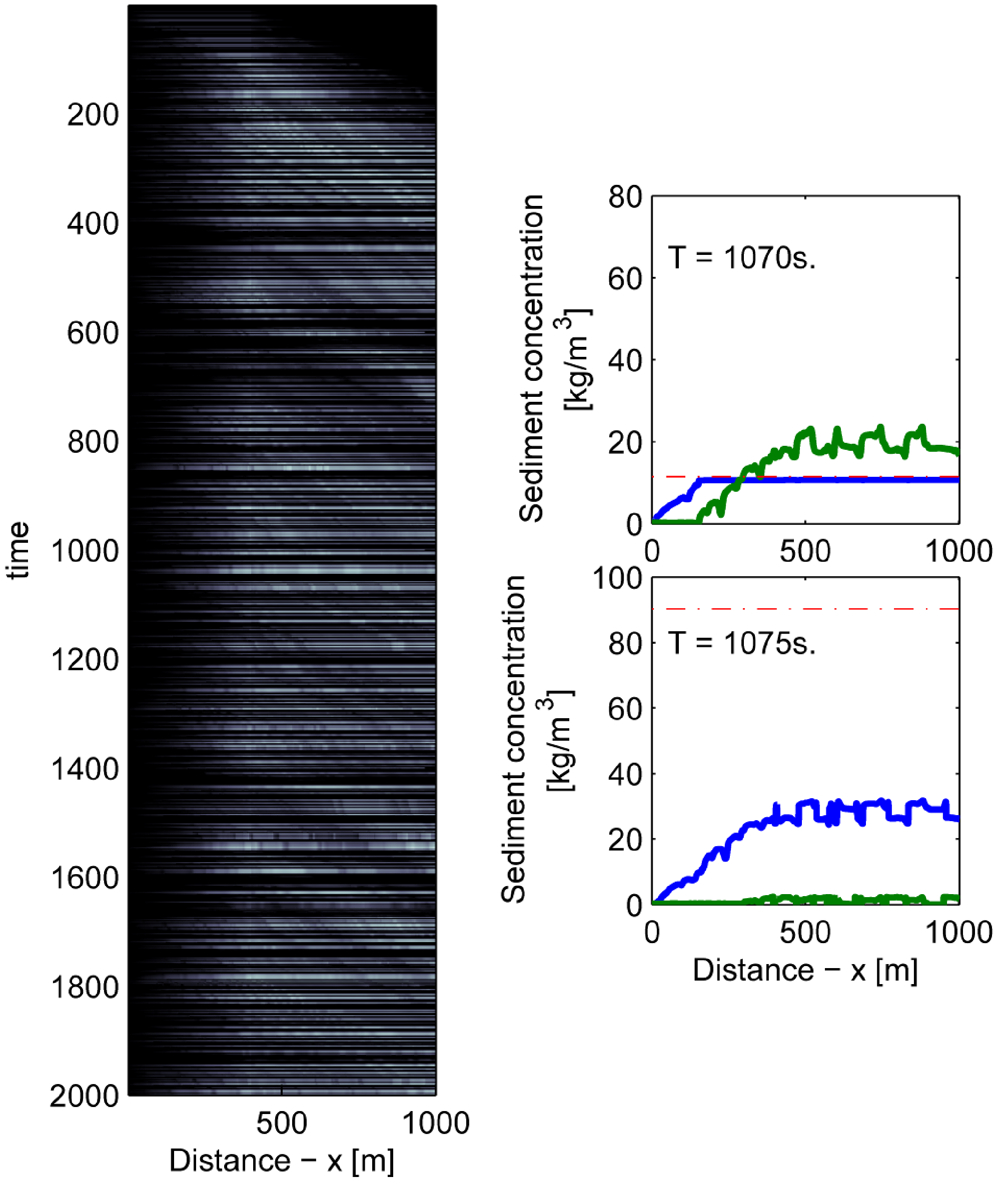

Figure 4: The Left panel shows a timestack of accumulated sediment at the bed (S_e). The right panels show snapshots of two arbitrary moments where the blue line indicates the sediment in transport (C_c) and the green line indicates the sediment at the bed (S_e). The red dash dotted line indicates the momentary sediment transport capacity (C_u).

4. Discussion

In the presented model it is assumed that modeled fluctuations in sediment transport rates are governed by supply magnitude and fluctuations in wind speed only. Both wind and supply magnitude vary in space and time on different scales. Currently, supply magnitude is assumed constant in time in the presented model. The validity of this assumption is very dependent on scale. Some studies suggest that supply varies on several timescales where Short and Hesp (1982) describe the effect of supply on a geographical timescale and de Vries et al. (2012) show measurements of a possibly fluctuating supply on an hourly timescale. At present a pragmatic choice regarding the modeled time and space scale is made. However, with supply and wind conditions vary on a large range of timescales the model might be extended towards a larger range of scales.

The modeled erosion and deposition are governed by supply magnitude and wind fluctuations as well. In contrast to an aeolian model where gradients in wind speed are governed by local morphology inducing morphological feedback, supply has a governing, in some cases possibly an overshadowing, effect on morphological development. Hence based on the presented supply limited model, large deposits which can grow into desert type aeolian dunes due to morphological feedback are unlikely to form in a supply limited area at any scale.

In the presented model the wind speed is spatially constant and is equal to the sediment speed. Due to the lack of a more detailed description of the (wind) forcing, local interactions with the sediment bed and therefore possible feedback mechanisms are not taken into account. There is no interaction with the bed morphology. When actual sediment supply is smaller than wind driven sediment demand, interaction with the bed is expected to be limited while all available sediment erodes. During periods of heavy rain this is evidently the case where surface moisture stabilizes the sediment surface and wind is not able to mobilize any sediment at all. During dry periods with limited winds it could well be that sediment supply exceeds wind driven sediment demand. During these periods with abundant supply interaction with the bed is likely to be important especially when spacing and amplitude of bed forms are of interest. In these cases traditional models (Werner, 1995; Nield, 2011; Melo et al., 2012; Kroy et al., 2002) might be used to predict the characteristics of the bed forms. Possibly the presented supply limited model could be combined with traditional models to incorporate both supply limiting effects to account for a wider range of processes.

In the presented academic cases, there are distinct supply and no supply zones. This implies that erodible and non erodible surface layers are present on the beach. Current evidence is illustrative at best where morphological measurements show that sub-aerial beaches are relatively static with very limited sedimentation and erosion (de Vries et al., 2011). Moreover, the upper beach can have a non erodible surface due to bed stabilizing processes such as sediment sorting at the bed surface. In the intertidal beach no aeolian sediment sorting processes occur due to the mixing as a result of marine processes. With limited erosion and sedimentation assumed, the aeolian beach is assumed to function as a transfer area for aeolian transport only rather than a general source area for sediment.

Sediment transport rates are assumed to be governed by wind conditions and supply magnitude however, the relative importance of the two remains unaddressed. While many available transport formulations based on wind forcing, the quantification of sediment supply and its governing parameters is poorly understood. Effects of supply limitations are however evident. In general cases where modeling of coastal evolution including the beach and dune morphology is of interest the quantification of sediment supply to the aeolian domain needs to be taken into account. The analysis of time series of collected Argus images at different coastal locations (examples shown in Figure 1) could provide a large and useful source of data for analyzing supply limited aeolian transport.

5. Conclusion and Recommendations

It is concluded that:

- The adopted model shows the potential capability of modeling spatial and temporal varying aeolian sediment transport as a function of sediment supply and varying wind conditions. The appearance and disappearance of sand accumulations at a relatively non erodible bed can be simulated. However, the model is lacking proper implementation of temporal and spatial scale. Therefore the model results can be used conceptually only.

- Supply limitations can govern aeolian sediment transport rates to an extend that despite fluctuations in wind very limited sand accumulates at the bed. Therefore the potential for aeolian bed forms to appear is small. This is especially relevant for upwind areas where fetch effects play a significant role.
- Whether the simulated variability could result in realistic bed forms is not confirmed at this stage. Temporal and spatial scales need to be specified. Moreover, morphological feedback is lacking it and it is not expected that the often observed spatial rhythmicity in migrating bed forms could appear in the present model. However, specific assumptions on wind fluctuations and supply characteristics could lead to spatially rythmic an migrating bed forms.
- Sediment supply is an important model parameter. For the model to be applicable to real life cases, the actual magnitude of sediment supply needs to be determined. This magnitude is likely to be governed by parameters such as moisture content, sediment sorting but also fetch effects
- The model is lacking spatial wind fluctuations. For a proper implementation of spatial wind fluctuations, an assumption on how fast sediment moves with respect to wind is needed

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