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AEOLIAN MODELLING OF COASTAL LANDFORM DEVELOPMENT

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Abstract: In order to improve the current aeolian modeling, a process-based model is developed by implementing biological and physical processes adapted from different existing models. The current version of the model is capable of simulating barchan and parabolic dunes and the initial stage of coastal dune formation: Embryo dunes. Potentially the model can be used to determine the influence of tidal ranges, storm frequencies, armoring, salinity and precipitation on dune building processes. This will result in a greater insight in the general behavior of coastal systems and on the other hand the model can also be used for engineering purposes.

Introduction

Coastal dunes serve as a first line of protection against flooding by the sea. This primary function of dunes has been developed at many managed coastlines. In the recent past, the interest in secondary functions provided by coastal dunes has increased, such as ecological values and recreation. Due to the increased interest in these secondary functions, dune management strategies are changing at many locations over the world. Along the Dutch coastline for example, natural dynamics are reintroduced at certain areas, stimulating the return of the dynamic character of coastal systems. Instead of maintaining the foredune as a continuous ridge, the formation of blowouts is artificially stimulated. The development of such blowouts causes an increase of ecological values and it is often believed a more dynamic system is better capable of adjusting to the changing conditions, such as climate change induced sea level rise (Loffler *et al.*, 2016). Because of such shifting management strategies, uncertainties concerning coastal dune development are increasing.

Numerical models with quantitative predictive capabilities on the development of coastal dunes provide a useful tool for coastal zone managers. Recent developments have shown the added value of coupling existing models into more comprehensive models that can describe a multitude of processes (Cohn *et al.*, 2019). The aim of this paper is to improve the current aeolian modeling state of the art by implementing biological and physical processes using a combination of existing models, using a modular aeolian transport model with quantitative predictive capabilities for dune development, and demonstrate its use for engineering purposes.

Several models for aeolian sediment transport and coastal dune development are currently available. A general problem in modelling of aeolian transport is the over-prediction of actual transport rates on beaches when transport-limited situations are assumed (de Vries *et al.*, 2014). This over-prediction limits the quantitative prediction of the development of coastal dunes. Supply-limited situations can occur because of surface moisture or beach armouring. The *Aeolis* model (Hoonhout and de Vries, 2016) is a process-based model developed for the simulation of aeolian sediment transport in supply-limited situations. However, since the interaction between wind fields and morphology is not implemented, the *Aeolis* model is not capable of describing the development of dune morphology. The Coastal Dune Model (*CDM*) (Durán and Moore, 2013) is a process-based model that can describe development of dune morphology, using a transport-limited method in combination with several empirical formulations for sediment availability and vegetation zoning. DUne BEAch VEgetation (*DUBEVEG*) (de Groot *et al.*, 2011) is a cellular automaton with a probabilistic approach on the formation of dune and vegetation growth. The *DUBEVEG* approach is computationally fast, but the approach limits the quantitative predictive skills.

Method

We have combined model formulations of three aeolian transport and dune models *Aeolis*, *CDM* and *DUBEVEG* into a single model. The aeolian transport of sediment is the main driver of dune development. The supply-limited approach and the modular structure from *Aeolis* are combined with the dune development processes and general formulas for vegetation growth and their influence on the shear stresses from *CDM*. Vegetation parameters as vertical growth, sediment burial tolerance, germination and lateral expansion are adapted from *DUBEVEG*. To reproduce the influence of the sea, marine sediment supply in the intertidal zone and the mechanical erosion of sediment and vegetation during extreme events are implemented as well. In order to demonstrate the potential of the model, three landforms have been simulated: Barchan dunes, parabolic dunes and embryo dune fields.

Implementation of processes

Gradients in wind velocity cause sedimentation and erosion, initiating the development of dunes. The interaction between the wind field and morphology is described by the implementation of the analytical perturbation theory for turbulent boundary layer flow (Weng *et al.*, 1991). Since the solution is only valid parallel to the wind direction, an overlaying grid is implemented which rotates along with the changing wind direction in time. In order to make the method suitable for situations where flow separation occurs, flow separation is described by a separation bubble (Sauermann *et al.*, 2001). Within this separation bubble the shear stress is assumed to be zero, resulting in a deposition of all the sediment where flow separation is initiated.

Vegetation can initiate and stimulate dune development. It acts as a roughness element, resulting in the reduction of shear stress and the deposition of sediment. With the assumption that the effective shelter area of vegetation is proportional to its basal area, the remaining shear stress acting on the sediment is given by a formulation from Raupach *et al.* (1993). The establishment of vegetation consists out of the dispersion and germination of seeds and rhizomes. The establishment of vegetation is implemented following a probabilistic approach, with a spatially uniform probability of occurrence. The establishment of vegetation is expressed by a probabilistic value (Keijsers, 2015). Once established, vegetation starts growing locally and in lateral direction. A main characteristic of dune building species is that they are tolerant to sediment burial and moreover, are often driven by sediment burial. The local change in vegetation cover is described by a modified version of the vegetation growth formulation by Durán and Herrmann (2006), which relates vegetation growth to sediment burial. The lateral propagation of vegetation is, similar to vegetation establishment, implemented as a spatially uniform probabilistic value.

The shoreline influences dune development in several ways. Erosion during extreme events and the marine activity in the intertidal zone are both represented by a function that relaxes the bed towards its initial shape. This approach is only suitable for situations with stable shorelines and the assumption that marine processes are dominant in the intertidal area. For the description of the hydrodynamic influence on the morphology it is assumed that the beach profile is dominated by the marine zone and that the shoreline is stable. The hydrodynamics relax the beach profile towards initial profile within the area affected by hydrodynamics. Besides, once vegetation is under wave attack, it is assumed to get destroyed. This influence of the wave on vegetation is a dynamic, process-based limitation to the vegetation growth. Vegetation dies during extreme weather events under the influence of stresses inserted by waves in combination with the resulting high salinity concentration.

Simulation of landforms

In order to demonstrate the model, several landforms are simulated using the same model code: Barchan, parabolic and embryo dunes. Barchan dunes are formed under limited sediment transport and without the influence of vegetation or the shoreline. When wind approaches an isolated sand pile, the wind starts accelerating and an erosive trend occurs at the windward side. Due to the separation of flow at the brink line, the shear velocity drops, particles are deposited and consequently the dune starts migrating. The speed of this process migrating process is faster for smaller heights and therefore the sides of the dune move faster than the central part of the body: the horns start to grow. At the central part of the dune, the developed separation bubble causes a steep slope at the slip face. Avalanches occur when the slope of the slip face exceeds the angle of repose (Hersen, 2004). The formation of a barchan dune is schematized in Fig. 1. Since barchan dunes are a result of aeolian processes only, without the influence of vegetation and hydrodynamics, it is an ideal landform to evaluate the implementation of aeolian sediment transport, wind fields and avalanching.

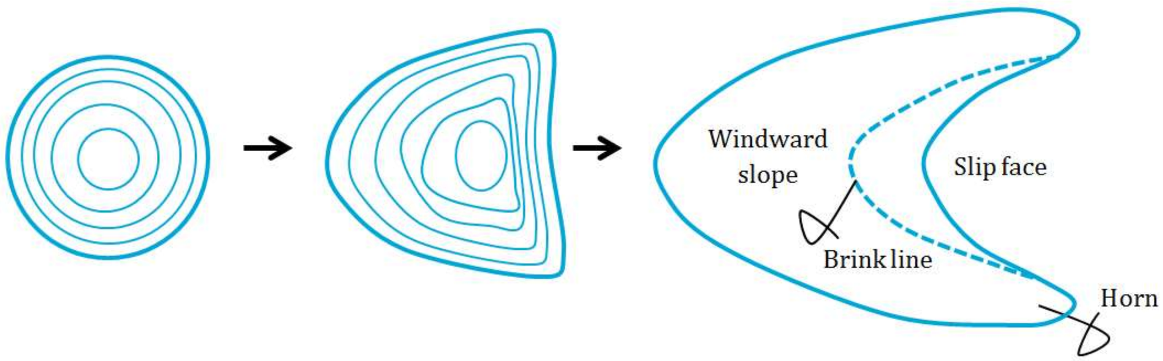

Fig. 1. Top view of barchan dune development.

Parabolic dunes are a characteristic landform resulting from the interaction between stabilizing by vegetation, wind fields and morphology. The growth of vegetation is related to sediment burial: Vegetation is not likely to grow in areas that are prone to high erosion or sedimentation. Therefore, the windward side of the barchan will not be grown, because it is subject to a strong erosive trend. In areas with low bed level changes, such as the horns and the brinkline, vegetation is able to grow. As a result, the middle part of the barchan will migrate in windward direction, while the horns are stabilized (Durán and Herrmann, 2006). This process is schematized in Fig. 2. Besides the influence of vegetation, the model configuration is the same as for the barchan dune simulations. Therefore, the parabolic dune is an ideal landform to evaluate the influence of various vegetation parameters on the shape of the landform.

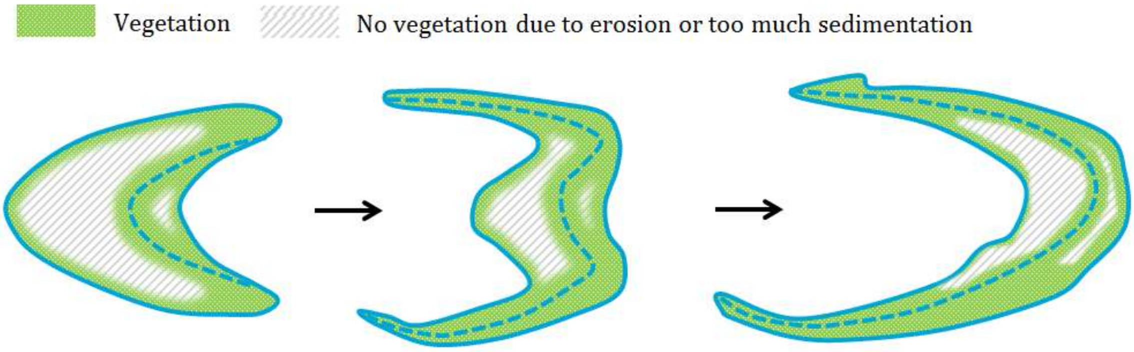

Fig. 2. Top view of parabolic dune development.

Embryo dune are the initial stage of coastal dune development. The main difference between the development of parabolic dunes and coastal dunes is the influence of the presence of the shoreline, which limits the growth of vegetation and can cause dune erosion. The aim of the simulation of embryo dune fields is to get a better understanding on the influence of different processes on embryo dune development and to see if the model results show comparable behaviour as measured in the field (Goldstein *et al.*, 2017; van Puijenbroek *et al.*, 2017). The shape of embryo dunes is less characteristic when compared to the somewhat academic barchan and parabolic dunes and can be found more often along coastlines and it is easier to measure entire fields instead of one single dune. Therefore, during the simulation of embryo dunes the focus will not only be on the shape and development of a single dune, but also of the distribution of multiple dunes and their location in an embryo dune field.

Results

The capabilities of the model are demonstrated by comparing the model results with field measurements and model results from *CDM*. The shear stress profile, resulting morphology and vegetation patterns are evaluated. The evaluation of the implemented flow perturbation theory is performed by comparing the simulated shear stress over a one-dimensional Gaussian shaped hill with an analytical solution of the theory (Kroy *et al.*, 2002). In Fig. 3, both the analytical and the numerical results are shown. At the top of the hill and at the downwind side, the amplitude of the numerical solution is somewhat larger. Besides the phase difference at the top compared to the bed level is larger for the numerical solution. The development of the morphology of barchan dune simulation is shown in Fig. 4.

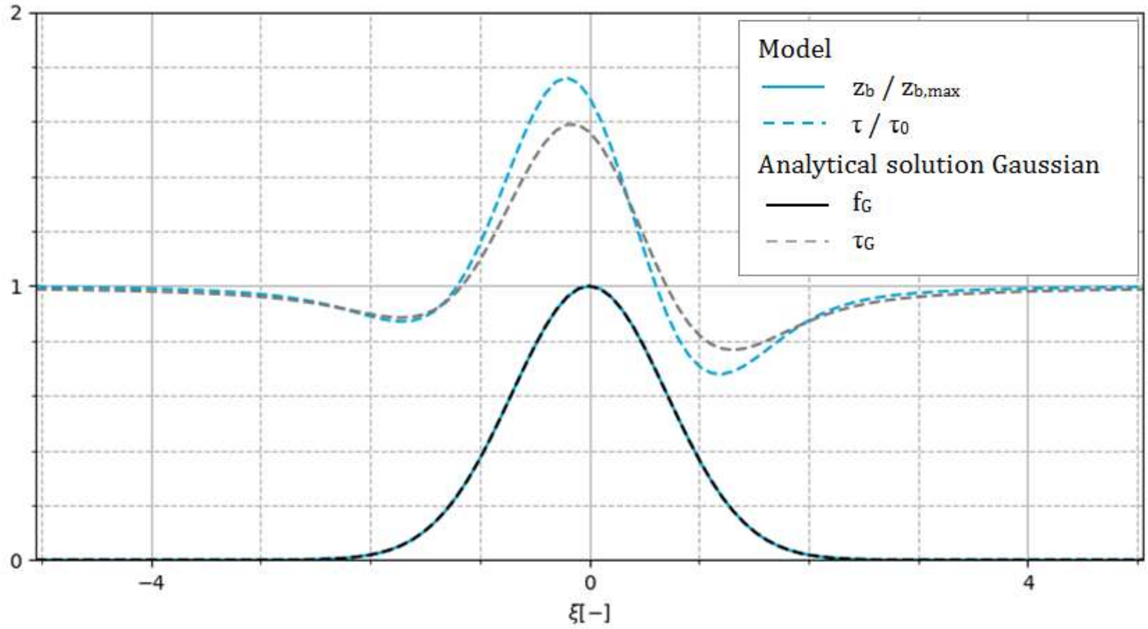

Fig. 3. Normalized surface shear stress profile (τ) over a Gaussian shaped hill (z_b) from a solution by Kroy *et al.* (2002) and model simulations.

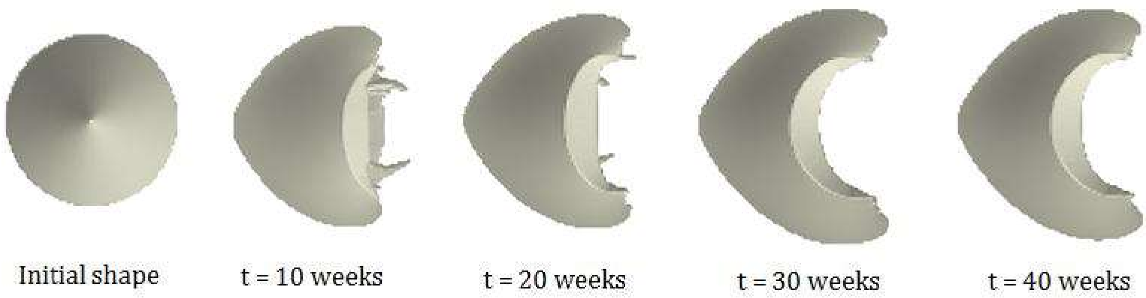

Fig. 4. Formation of a barchan dune from a cone-shaped topography with wind velocity of 6 m/s.

Similar as for barchan dunes, the validation of parabolic dunes has the objective to validate the influence on dune development of various processes separately. The simulations of parabolic dunes start with an initial hill without the presence of vegetation. Once the simulation starts, vegetation growth is initiated. Since vegetation growth is negatively affected by erosion and accretion, growth will be maximum at the sides of the dune and thus these areas will stabilize first. While this process continues, the vegetation will grow towards the middle of the dune, until the entire dune is stabilized. The simulation results are shown in Fig. 5.

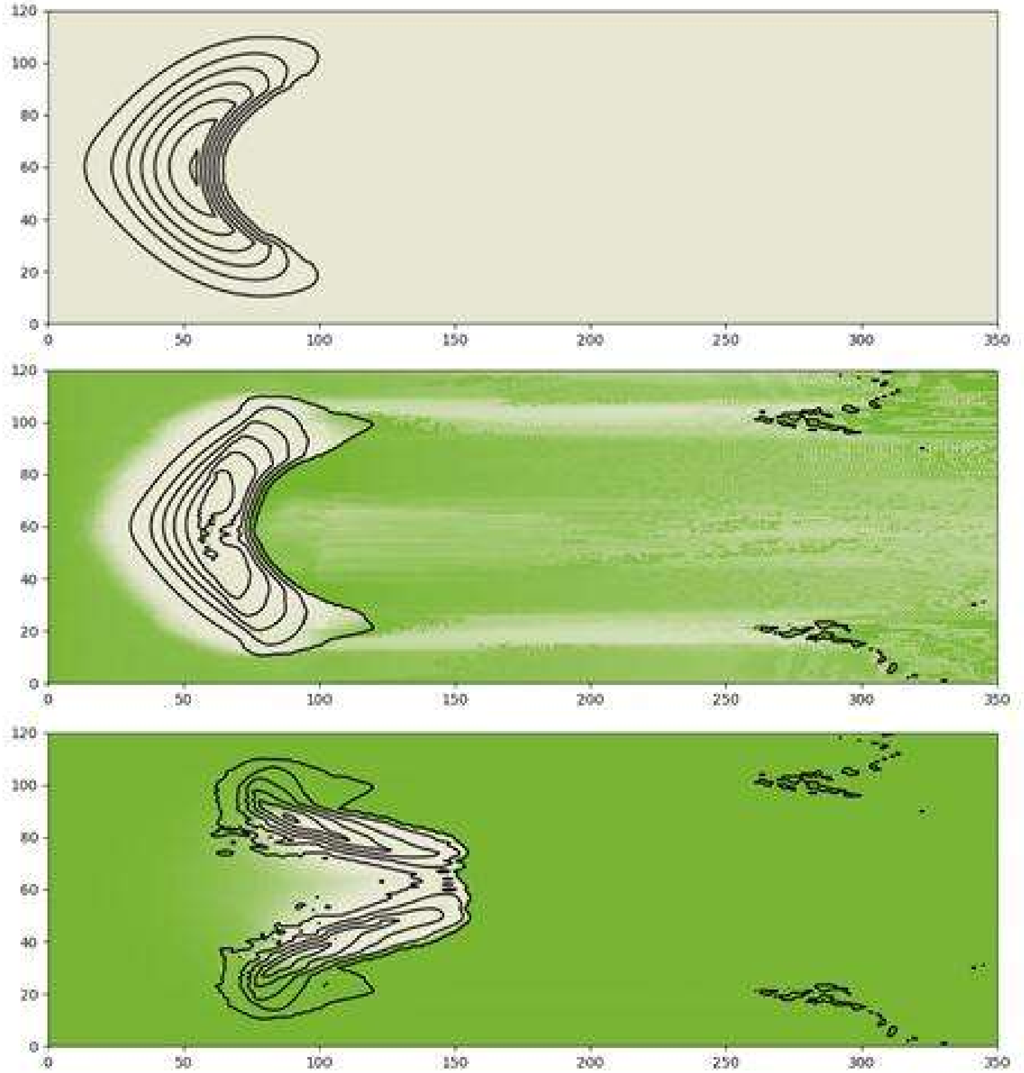

Fig. 5. Simulation of the development of a parabolic dune, with vegetation indicated in green.

Although the initial vegetation and stabilization pattern from the simulation is as expected, the resulting shape of the parabolic dune deviates from simulations done with *CDM*. It seems that the simulation results depend on parameters related to the implementation of the separation bubble. Additionally, during the simulation the model becomes unstable, leading to increased simulation times and causing the simulation to stop. Probably, these problems could be solved by simulating with a finer computational grid.

The embryo dune field simulations are shown in Fig. 6, where the cross-shore distance is in x-direction and the longshore distance in y-direction. The beach profile has a slope of 1:50 and the bed level z_b is 0 m NAP at x = 0. Since the mean of the water elevation is approximately 0 m NAP, the cross-shore location of the shoreline is assumed to be at x = 0. The general growth pattern is as expected, with initially a few small dunes which start to grow and followed by coalescing. For smaller dunes, behind the embryo dune a "tail" develops along the wind direction, which can also be seen at real world embryo dune fields.

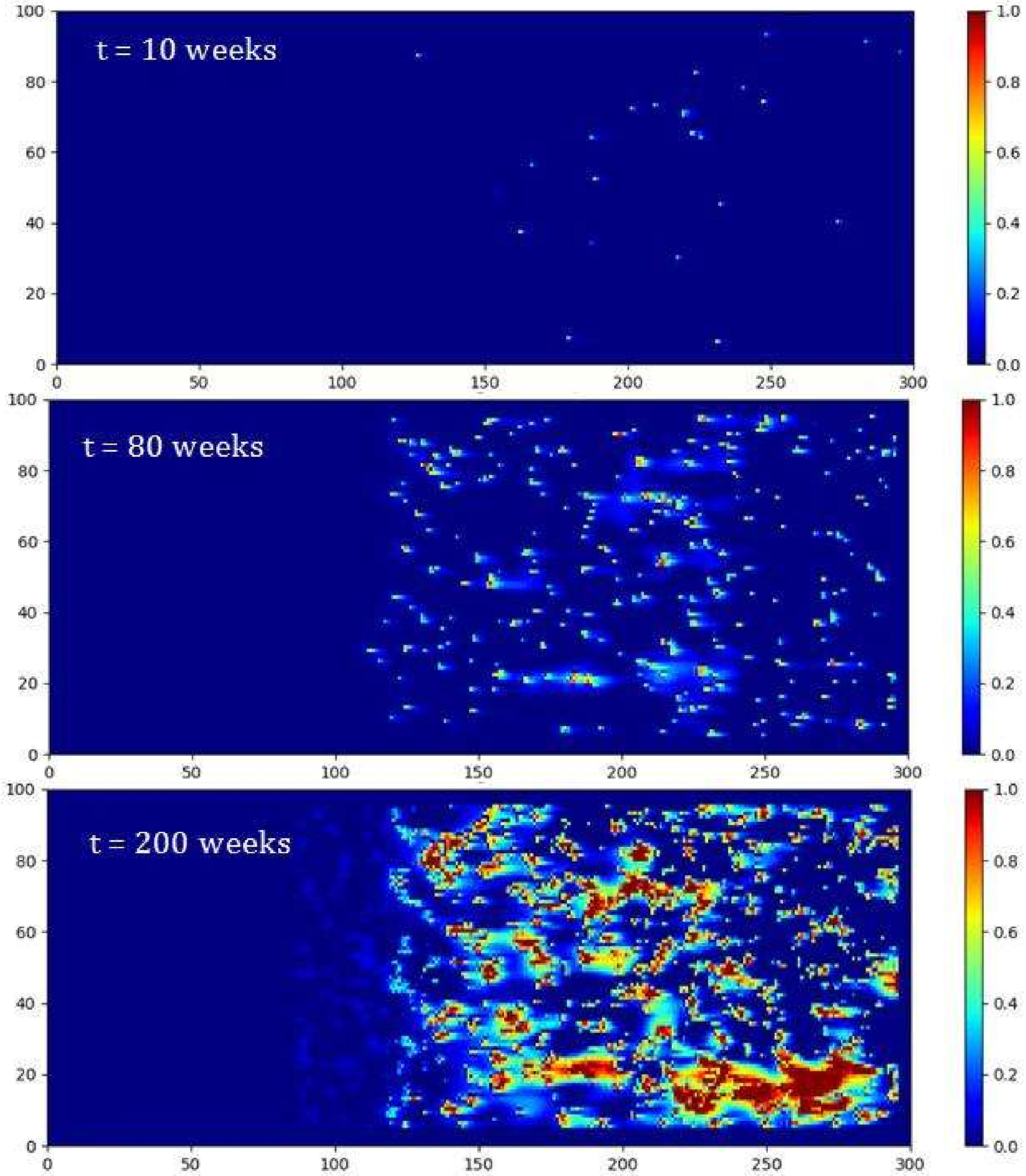

Fig. 6. Bed level change Δzb [m] over the simulation of an embryo dune field.

In Fig. 7, the characteristic height of an embryo dune is plotted against the dune radius from the model simulations and the data by van Puijenbroek *et al.* (2017). Despite the fact that the measurements from van contain more dunes and that the spread in data is wider, it can be stated that the overall embryo dune shape and the linear proportionality between the both dimensions is reproduced well by the model.

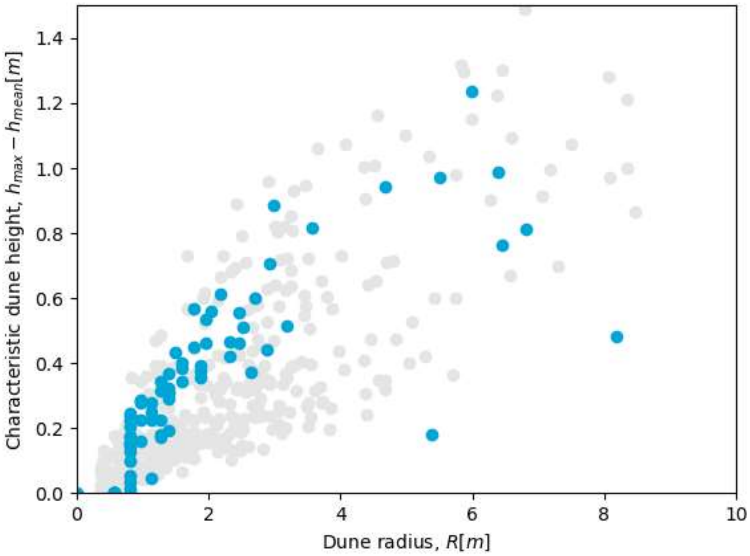

Fig. 7. Characteristic embryo dune height plotted against dune radius from simulation results (blue) and measurement data (gray) (van Puijenbroek *et al.*, 2017) at t = 80 weeks.

Conclusion

Combing the capabilities of several numerical models has contributed to a more comprehensive process-based description of aeolian, biological and marine processes and potentially a better quantitative prediction of coastal dune development.

The combination of a supply-limited approach and the interaction between wind fields and topography is the most significant improvement for the coastal dune modelling state, since it has become possible to simulate dune development with a quantitative approach to sediment transport. Consequently, several new situations are potentially reproducible by the model, such as dune development in areas subject to beach armouring and the influence of tidal ranges or storms on the formation and growth of dunes.

The model reproduces the establishment and lateral propagation of vegetation due to the addition of a probabilistic approach on germination and lateral expansion. Consequently, the model can describe the formation of embryo dunes and the corresponding characteristics such as growth, zonation and coalescing into foredunes.

The addition of the destruction of vegetation under the influence of water level elevation and wave run-up, a dynamic vegetation limit, is a more process-based approach on the general development of coastal dunes. It is possible to simulate the influence of conditions such as the tidal range, storm intensity, sediment characteristics and beach slope on dune development.

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