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Modelling the Retreat of a Coastal Dune under Changing Winds

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ABSTRACT

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Coastal dunes can move in response to winds and cause serious hazard to human assets. Changes in wind patterns, potentially occurring as a consequence of climate change or variability, could affect rates of aeolian transport and migration velocity of coastal dunes. However, most of previous modeling studies were conducted assuming that aeolian bedforms are subject to constant wind velocities. This article presents a modeling of the mobility of the Dune du Pilat in Aquitaine, a coastal transverse dune exposed to winds of varying intensity. It applies well-established models and empirical formula for aeolian dune migration, including a model previously validated against measurements of real profiles of desert and coastal dunes. The average migration velocity of Pilat dune predicted by the models is about 3m/year, which is in good agreement with in-situ measurements. To test the response of transverse dune mobility to changing winds, virtual wind time series are generated using a stochastic model. Modelling experiments suggest that more frequent storms have less impacts than more intense winds. Due to the size of the Pilat Dune (altitude of about 100m), these result in moderate changes in the average dune velocity. This study shows that the approach of combining a stochastic model for winds with a morphodynamic dune model can provide valuable insight into how aeolian bedforms respond to changes in flow conditions potentially caused by climate change.

ADDITIONAL INDEX WORDS: *Coastal dunes, dune migration hazard, stochastic wind model, climate change.*

INTRODUCTION

Unvegetated mobile dunes can be associated with a significant hazard of burying assets located behind their avalanche slopes. For risk management, a most significant parameter is the rate of retreat of the dune, that is, the velocity of its avalanche slope. In existing risk assessment procedures, past rates of dune mobility are usually extrapolated to estimate the expected lifetime of assets located behind the avalanche slope. However, this approach neglects potential impacts of climate change and variability for wind regimes. This source of uncertainties remains difficult to evaluate because winds are most difficult variables to predict using climate change modeling. For example, Pryor, Nikulin and Jones (2012) show that different model-scales can generate differences in model outcome as large as the predicted changes. In this case, using winds from climate models might be less relevant than testing how plausible different winds may affect dune mobility and hazards. Hence, this paper explores an approach to evaluate the sensitivity of dune retreat to changing winds.

The approach is applied at the Dune du Pilat in South-Western France. It consists in evaluating the dune retreat using a morphodynamic dune model and simplified approaches based on the quasi-equilibrium dune hypothesis under different sets of wind time series: (1) the real time series of wind velocities; (2) other possible wind time-series representing the present climate; (3) simulations of wind time series representing plausible slightly changing wind conditions. The simulations of wind time series are generated using a wind stochastic model (Monbet, Ailliot and Prevosto, 2007; Ailliot and Monbet, 2012). Here, the modeled present dune retreat rates are compared with observations, and the uncertainties due to the variability of simulated wind time series and due to different sand flux formula are evaluated. Finally, the sensitivity of the dune retreat rates to changing wind parterns are analysed and discussed with specific attention to mobile coastal dunes management.

Site description

The site selected for this modeling study is the Pilat dune, located in south-western France in Aquitaine. In this region, high-intensity winds (velocities higher than 8m/s) originate from the west and are mostly perpendicular to the coast. The formation of dunes in Aquitaine is described by Froidefond and Prud'homme (1991): wooded parabolic dunes were formed in the XVIth century above two ancient paleosols dated from 3500 years BP to 2900 years BP. They were progressively covered by sand until the end of the 18th century, at the time of first attempts to mitigate the migration of sand through revegetalization and use of vegetation debris. Subsequently, a 80 m high transversal dune was covered by a forest of young pines, cultivated for their resin but also used for fixing the sand. By the end of the 19th century, the dune was

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buried by 20 to 30 m of sand, so that it reached a height of 115m by 1910. Today, the Pilat dune it is 2500m long and 500 m wide, and reaches a height of 107m. These rapid morphological changes are due to aeolian processes that involve sand brought to the coast by waves and currents. Because of its dimension, mobility and absence of vegetation, the dune of Pilat remains presently a geomorphological exception in south-western France (Tastet and Pontee, 1998).

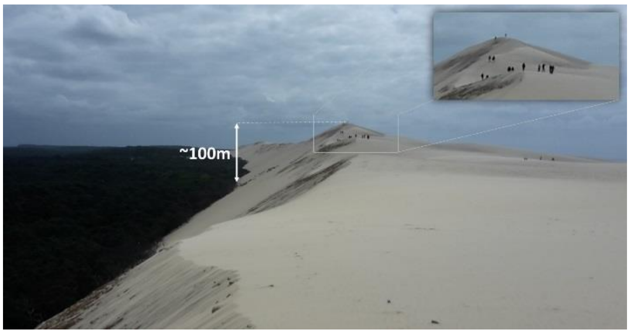

Figure 1. Avalanche slope of the dune (north-eastern side, May 2015).

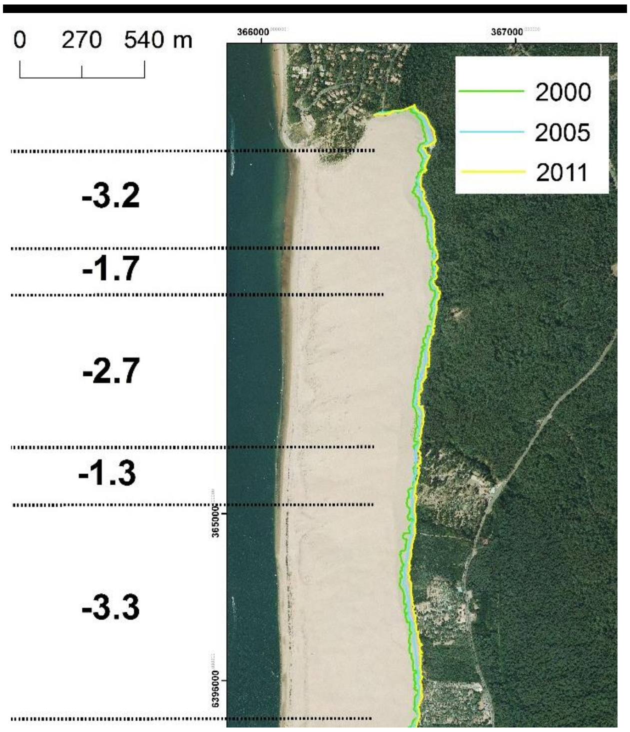

Figure 2. Mean dune retreat rates per dune sector (in m/yr) according to a DSAS (Thieler *et al.*, 2009) analysis of three aerial images from 2000 to 2011. The marker used here is the dune/forest limit.

The eastern side of the dune is characterized by an avalanche slope (Figure 1). Its velocity can be evaluated using different methods: aerial photographs (2000, 2005 and 2011) allow digitalizing the permanent vegetation limits, leading to mean rates of 3.3m/yr (Figure 2). Furthermore, historical maps of the French Geographic Institute (IGN) and their metadata show that from 1965 to 1995, the dune retreat varies from 60m to 120m (averaged displacement along the entire dune: 100m). Hence, at these timescales, the observed dune retreat ranges from 2 m/year to 4 m/year (mean of 3.3m/year). Finally, additional information has been made available through an in-situ survey undertaken from 1935 to 1992 by Henri Ferradou, a private individual (www.dune-pilat.com), who measured the distance between the foot of characteristic trees and the foot of the dune: his results gave a global displacement of 280 m during 57 years, *i.e.* 4.9 m/year in average, and a discontinuous migration with yearly speed varying between 0 and 10 m/year.

METHODS

To test the response of the dune to different wind conditions, virtual wind time series are generated using the stochastic model shown in Figure 3. Then, observed and simulated wind time series are used to calculate the retreat of the dune.

Wind stochastic model

Previous works have proposed stochastic models able to reproduce realistic wind time series (Monbet, Ailliot and Prevosto, 2007; Ailliot and Mombet, 2012). The wind stochastic model used for this study is a Gaussian Markov Switching Auto-Regressive (G-MSAR) model for wind time series (G-MSAR) (Guerber, Le Cozannet and Pedreros, 2008):

$$Y_t = N(a^{(s_t)}Y_{t-1} + b^{(s_t)}, \sigma^{(s_t)}) \qquad (1)$$

where Y is the observed wind time series intensity,S is the hidden state chain and N(μ,σ) the Gaussian distribution with mean μ and standard deviation σ. The time series of non-observable hidden S control Y, and a and b are state dependent parameters.

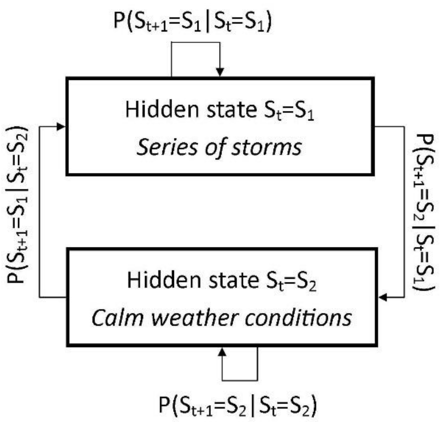

Figure 3. hidden states of the wind stochastic models and the related transient probabilities and their physical meaning.

The stochastic model is fitted to observed SeaWinds wind time series covering 9 years from 2000 to 2008. These satellite observations are in good agreement with shorter in-situ wind measurements acquired by Météo-France. The fitting procedure uses an expectation-maximisation algorithm, which estimates the parameters of equation 1 together with state switching probabilities (Monbet, Ailliot and Prevosto, 2007). Here, to preserve the seasonality of wind regimes, the G-MSAR model parameters are estimated for two distinct periods (winter from October to March, and summer from April to September). This data fitting provides the baseline stochastic model, representing the wind time series (here at 6h timesteps) in the current climate conditions. Finally, by modifying the stochastic model parameters in equation (1) or the state transient probabilities, it becomes possible to generate new time series representative of slightly different wind climates.

Aeolian dune retreat calculations

Following previous works on the formation of barchans and transverse dunes, the sand transport direction is assumed essentially constant over time (Kroy, Sauermann and Hermann, 2002; Hersen *et al.*, 2004; Katsuki, Kikuchi and Endo, 2005; Pelletier, 2009; Zheng, Bo and Zhu, 2010). This approximation is realistic here, because the direction of winds able to generate saltation is mostly perpendicular to the coastline.

The wind shear velocity u_* is computed at each 6h time step of the wind time series (Bagnold, 1941; Pye and Tsoar 1990). To compute the dune velocity from the wind data time series, two approaches are used: the first approach considers that the dune size changes more slowly than its position, and that the velocity of transverse dunes is proportional to the average transport rate divided by the dune height (Bagnold 1941; Pye and Tsoar 1990; Parteli, Andrade and Hermann, 2011; Parteli *et al.*, 2014); the second approach is an adaptation of a well-established aeolian dune morphodynamic model (Sauermann, Kroy and Hermann, 2001). This dune model combines a quantitative description of the turbulent wind field over the topography with a continuum model for the motion of the saltating particles and the evolution of the sand surface. In the latter approach, time series of u_* allow to calculate the sand flux q_s, which are estimated here following classical formula (Bagnold, 1941; Iversen and Rasmussen, 1999; Lettau and Lettau, 1978; Sorensen, 1991; Sauermann, Kroy and Hermann, 2001) as well as empirical formula developed for the specific case of Aquitaine beaches (Pedreros, 2001). Finally, the dune migration velocity v_d can be calculated following the approach of Elbelrhiti, Claudin and Andreotti (2005).

RESULTS

Figure 4.A shows one of the wind time series used for fitting the stochastic model parameters and figure 4.B shows one of the simulated wind time series. A quantile-quantile comparison of simulated and observed time series shows comparable statistics for high winds intensities. Conversely, winds lower than 5m/s are under-represented in the simulations. This does not impact the results as the aeolian transport is negligeable in these conditions.

The simulations of the dune retreat between 2000 and 2008 are provided in Figure 5. Most of the classical formulas overestimate the dune displacement, which is found at about 3m/yr (Figure 2). However, the Pedreros (2000) formula underestimates the dune velocity. One possible explanation is that the Pedreros formula underestimates the sand flux for wind shear velocities close to the threshold shear velocity, while it better fits observed sand flux in Aquitaine in other wind conditions. Finally, Sauermann's formula is the closest to the observations, whether used in the complete morphodynamic model or within the simplified approach.

To test the ability of the wind stochastic model to produce dune migration rates compatible with the observations, 1,000 virtual time series are produced using the G-MSAR model, each representing one year of the present climate. The model results are very close to each other (Figure 6): each simulation leads to retreat rates ranging between 0 and 5m/year. Only 15% of the simulations fall outside the range of 2.5-3.5 m/year. The average dune retreat value is of 3.16 m/year and the median value of 3.1m/year. 47% of the simulations lead to retreat rates of 3±0.25m/year. The dune retreat rates calculated using the sand-flux formula provide mean retreat rates ranging from 1.36m/year (Pedreros formula) to 3.48m/year (Bagnold formula).

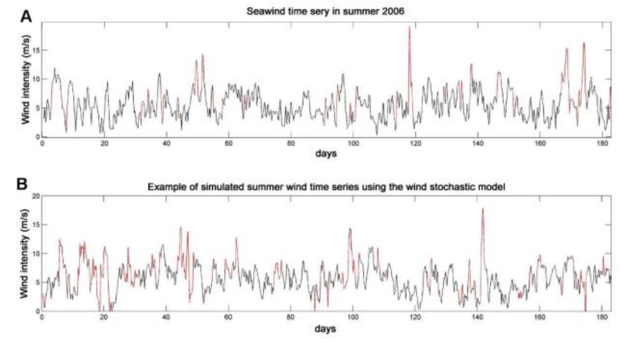

Figure 4. seawinds time series in summer 2006 (A, above) and one of the summer wind time series simulated using the wind stochastic model (B, bellow) (see section 3.3). The two states of the hidden Markov chain can be identified by the colours (red and dark) of the time series.

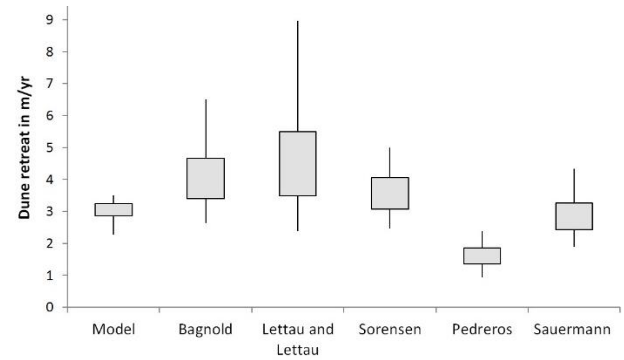

Figure 5. Dune retreat over 2000-2008, obtained using Seawinds winds data. The boxes represent the standard deviation of the yearly dune retreat rates (interannual variability). The lines represent the maximum and minimum yearly dune retreat rates over 2000 to 2008.

Collectivly, these results suggest that there is a good agreement between (1) the observed dune retreat (values ranging from 1.3 to 4.9m/yr depending on the observation exact location, period and methods) (2) the dune retreat as calculated from the dunes' physical model forced by observed winds (yearly mean values ranging from 1.6 to 4.5m/year) and (3) the dune retreat as calculated from the dunes' physical model forced by winds from the stochastic model (mean values ranging from 1.4 to 3.5m/year). However, the results presented above combine two different sources of uncertainties: (1) those due to the use of several models; (2) those related to the internal variability of observed wind time series. A variance-based sensitivity analysis (Saltelli *et al.*, 2008) shows that assuming equal confidence in each modeling approach, the influence of the variability of wind time series is found much lower (about 20%) than the influence of the variability of models outcome (about 70%). The influence of the combined effects of the two input parameters is estimated at about 10%. Other important sources of uncertainties not quantified here include: (1) the estimation of dune retreat rates from observations, including digitalization errors as well as differences due to the use of different dune toe indicators; (2) differences between the probability distributions of real and MSAR simulated wind time series; (3) the fact that all sand transport formula take as input parameter winds averaged in time (6h here), therefore not taking into account the full dynamics of wind transport processes.

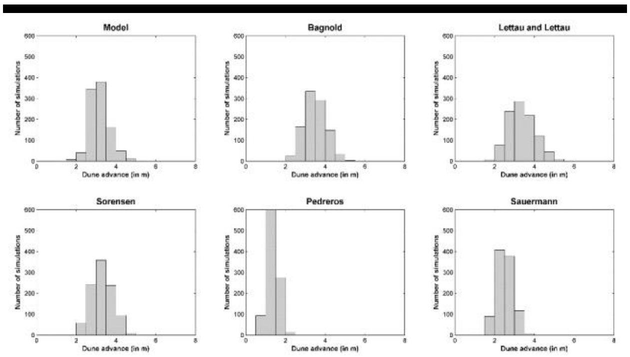

Figure 6. histogram of the dune retreat based on the 1,000 simulations from MSAR for different dune retreat modelling approaches. The abscissas represent the retreat in m/year, with a graduation of 0.5m.

DISCUSSION

The good agreement between the various simulation and the observations suggest that the modeled yearly mean retreat rates can be used for a first estimate of dunes retreat velocities. Such results have useful implications for coastal management and climate change adaptation. In the current recommended practice of the coastal risk prevention plans in France, hazards due to dune mobility are taken into account in the following way: the analysts extrapolate the observed rates of dune retreat L_{mean} and consider the potential of an extreme event $L_{extreme}$, thus adding the two terms $L_{mean}+L_{extreme}$ to map the hazardous areas at different time hozizons. Given the timescale considered in these scenarios (several decades), one important question is to know whether this approach is suitable in the context of climate change, in particular because L_{mean} may change in the future. In the particular case of the Dune du Pilat, significant touristic assets are present behind the dune of Pilat: the road of Biscarosse is situated along 1 km between 200 and 300 m from the foot of the dune, and three camping sites spread out from the foot of the dune until the road. Consequently, with an average displacement rate of 3m/year, the first segment of the road should be cut by 2070 approximately, and the camping sites will be progressively buried. For a timely planning of relocation, there is a need to better understand to which extent the observed retreat values can change in the future.

Such results can be easily obtained by simulating changes in wind time series, that is, by modifying the parameters of the G-MSAR model. Comparing the response of the dune with two different wind climates, it appears that increasing the wind intensity by 15% in the storm weather generates an increase of the dune velocity of 9%. As expected, reducing the residence time in state S_2 (Calm weather; Figure 3) leads to increasing of the dune velocity. Changing the residence time in the "calm" weather regime leads to moderate changes in the dune retreat rates: the dune velocity increases by less than 5% for a reduction of 33% of the residence time of 2.2 days, and by 15% for a reduction of 55%. This suggests that for this particular dune, increased storm intensity have more impacts than more frequent storms. Indeed, observations undertaken from 1935 to 1992 suggest that the interannual variability of dunes retreat velocity can be large on a single location. For the assessment of dune retreat hazard in the Pilat dune, this means that $L_{extreme}$ values should be expected to remain significantly larger than any realistic change of L_{mean}. This result is not necessarily transportable to other coastal dunes.

In addition to the uncertainties discussed above, several limitations must be mentioned: first, in the case of the Pilat dune, the evolution processes are supposed to be mainly due to aeolian processes. While this approximation seems realistic, other processes affecting the dune morphology should be mentionned: human impacts (trampling) and coastal erosion seawards. Secondly, for the more general aspect of aeolian dunes risk management, this paper addresses the case of unvegetated mobile dunes. Another important issue is the coastal management approach toward local-scale wind erosion landforms, which may create breaches or initiate movement of smaller dunes (e.g. Arens *et al.*, 2013). In Aquitaine, the current management practice is a soft approach, which consists in maintaining the vegetation and, when wind erosion appears, in adding vegetation debris or wind obstacles. Therefore, a model computing geomorphic changes of dunes in the presence of vegetation and wind obstacles would be extremely useful to evaluate the impact of different management strategies. However, this requires an appropriate modeling of the competition between vegetation growth and aeolian sand transport. Nevertheless, irrespective the details of the model and setting parameters, these results illustrate how the combination of a stochastic model of forcing factors (such as winds) with a physical model of landform evolution (here unvegetated aeolian coastal dune) may help in understanding potential impacts of changing climate or weather conditions on dune mobility.

CONCLUSIONS

While the effects of climate changes on sand dunes patterns have been discussed over geological timescales (e.g. quaternary, Tsoar *et al.*, 2009), the evolution of dunes in response to contemporary anthropogenic climate change remains largely uncertain. This paper proposes an approach to evaluate the impact of changing winds on dune mobility related hazards and applies it to the Pilat Dune in France. The approach consists (1) in incorporating randomly generated stochastic wind time series into dunes evolution models (2) in evaluating the sensitivity of dune mobility rates to slight changes in wind regimes such as the mean wind speed during storms or the duration of stormy weather regimes. When applying this approach to past data at the Dune du Pilat, the result presented above show that: (1) the observations of dune mobility rates agree with the simulation, whether performed using real past wind data or simulated stochastic wind time series; (2) the variability of the dune mobility rates simulated with stochastic wind time series is more influenced by the different possible models than by the stochastic wind time series. The future evolution of landforms in the context of climate change depends on the physical patterns of coastal dunes. Model experiments such as those presented in this paper can provide insight to these issues. To transport this approach to other types of landforms, it would be required to further develop appropriate stochastic models to represent the relevant forcing factors.

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