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Non-stationary Model Free Parameter in Equilibrium Shoreline Modelling

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Abstract. The state-of-the-art equilibrium shoreline model proposed ShoerFor [1] is used to hindcast shoreline evolution. A similar approach to the work of Ibaceta et al. (2022) [2] is adopted, where they introduced non-stationary model free parameters to improve long term shoreline change predictions. An Ensemble Kalman Filter (EnKF) is implemented to track the temporal variability in model free parameters and explore if their evolution can be linked to the environmental forcing. A correlation between the winter wave energy and the model free parameter ϕ (beach memory) is identified where high energetic winters are followed by an increase in the parameter suggesting such time variation in beach memory can be parametrized.

Keywords: Equilibrium shoreline modelling · Data assimilation · Kalman filter · Non-stationary model parameters

1 Introduction

Sandy shorelines are very dynamic environments constantly adjusting due to a variety of physical processes spread over a wide spatiotemporal range. Our ability to understand and accurately predict the evolution of sandy coasts will enable effective management of coastal ecosystems. Current generation of reduced complexity shoreline evolution models have proven skillful and efficient, especially when simulating timescales extending up to several decades (~ 010 years). Most simplified shoreline evolution models are based on time invariant model free parameters determined using a specific period for their calibration. Not resolving all the processes involved in shoreline evolution explicitly can render these models biased to the period used for their calibration.

At the present study a similar approach to the work of Ibaceta et al. (2022) [2] has been adopted where they introduced non-stationary model free parameters to improve long term shoreline change predictions. A dual parameter/state Ensemble Kalman Filter (EnKF) has been implemented to track the temporal variability in model free parameters and explore how their evolution can be linked to the environmental forcing. This study is focused on the remote site of Truc Vert beach, where equilibrium shoreline models have been proven successful in reproducing it's seasonal and interannual dynamics [3].

2 Methodology

A 20-year timeseries of alongshore averaged +1.5 m above mean sea level (AMSL) shoreline proxy has been derived from in-situ RTK DGPS surveys at the remote cross-shore transport dominated site of Truc Vert beach (France, Atlantic coast). Truc Vert beach is a high energetic, meso- macrotidal, double barred exposed beach, backed by tall and wide coastal dunes. Tide is semi-diurnal with an annual mean spring tidal range of ~ 3.7 m and largest tidal range of ~ 5 m. The wave climate is seasonally modulated with monthly average significant wave height H_s and peak wave period T_p ranging from 1.11 m and 9 s in July, with a dominant west-northwest direction, to 2.4 m and 12.8 s in January with a dominant west direction [4, 5] (Fig. 1).

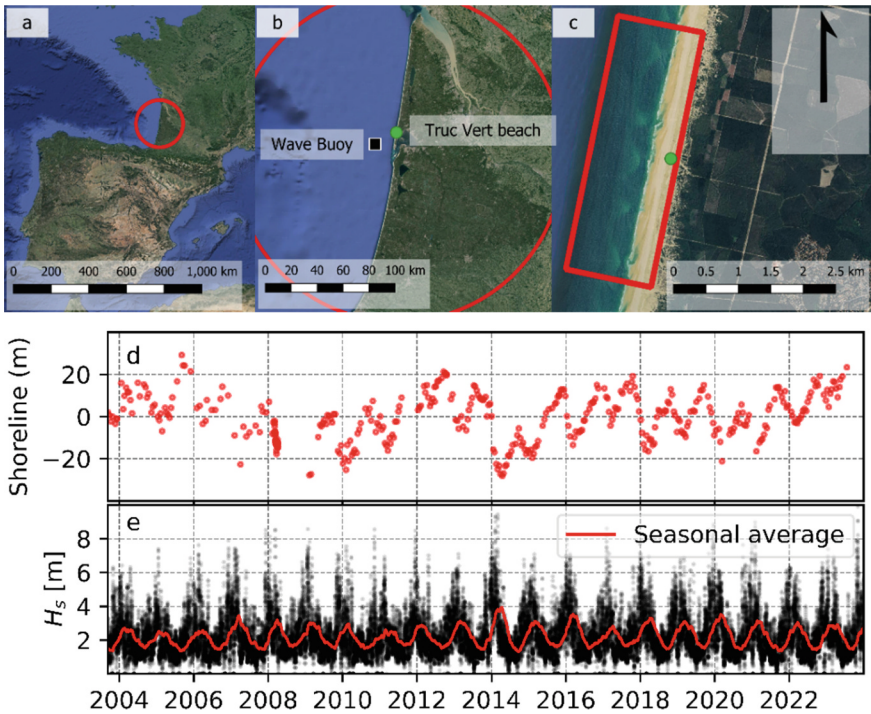


Fig. 1. (a) Overview of the area (b) Location map of Truc Vert beach, southwest France indicating the position of the CANDHIS wave buoy (Cap Ferret wave buoy 03302). (c) Survey zone at Truc Vert beach. (d) Alongshore averaged in-situ shoreline position. (e) Offshore wave height extracted at the location of the buoy from the ERA 5 reanalysis dataset.

The state-of-the-art equilibrium shoreline model, proposed by Davidson et al. (2013) [1] was used to simulate shoreline evolution, forced by the freely available ERA5 wave dataset described in Hersssbach et al. (2024) [6].

2.1 Shoreline Model

The shoreline displacement in the model is defined as a function of the nearshore wave power and a disequilibrium state of the beach, with the rate of shoreline change being defined as:

$$\frac{dx}{dt} = c^{\pm} P^{0.5} (\Omega_{eq} - \Omega) \tag{1}$$

The model’s forcing term is the product of the incident wave power P (W) computed using linear wave theory, and the model free parameter c^{\pm} representing the response rate of the shoreline with units of velocity per measure of incident wave power. The parameter c^{\pm} is separated into accretion c^+ when $\Omega_{eq} > \Omega$ and erosion c^- when $\Omega_{eq} < \Omega$ components, accounting for the fact that accretion and erosion are observed to evolve at different rates. The formulation of Davidson et al. (2013) [1] included an additional term b , accounting for linear trends stemming from longer term processes that are not explicitly addressed in the model. In the present work this term is disregarded due to the relatively small trend. The term inside the parenthesis in Eq. (1) is a disequilibrium term which is based on the premise that shoreline state and morphological change are inter-related. Ω is the dimensionless fall velocity defined as:

$$\Omega = \frac{H_s}{T_p w_s} \tag{2}$$

H_s and T_p are the instantaneous significant wave height and peak wave period respectively and w_s is the fall velocity of the beach’s median grain diameter d_{50} calculated using Stoke’s law. The time varying equilibrium condition Ω_{eq} is a weighted average of the antecedent dimensionless fall velocity Ω defined as:

$$\Omega_{eq} = \sum_{j=0}^{2\varphi} \Omega_j 10^{-j/\varphi} \left[\sum_{j=0}^{2\varphi} 10^{-j/\varphi} \right]^{-1} \tag{3}$$

where j is the number of days prior to the present time and the memory decay φ is a model free parameter indicating the number of days it takes for the weighting to reach 10%, 1% and 0.1% of the instantaneous value at φ , 2φ and 3φ days prior to the present. The formulation used in the present work incorporates all past beach state information for the past 2φ days, yielding a minimum weighting factor of 1%.

3 Results

Using the EnKF algorithm proposed by Ibaceta et al. (2020) [7], the shoreline timeseries has been assimilated to the model, tracking the variability of the free model parameter φ , while the rest of the model free parameters have been kept fairly constant. In Fig. 2 the results obtained using the EnKF data assimilation method are depicted. For comparison the results of a calibrated model with time-invariant parameters [4] are also plotted in the figure.

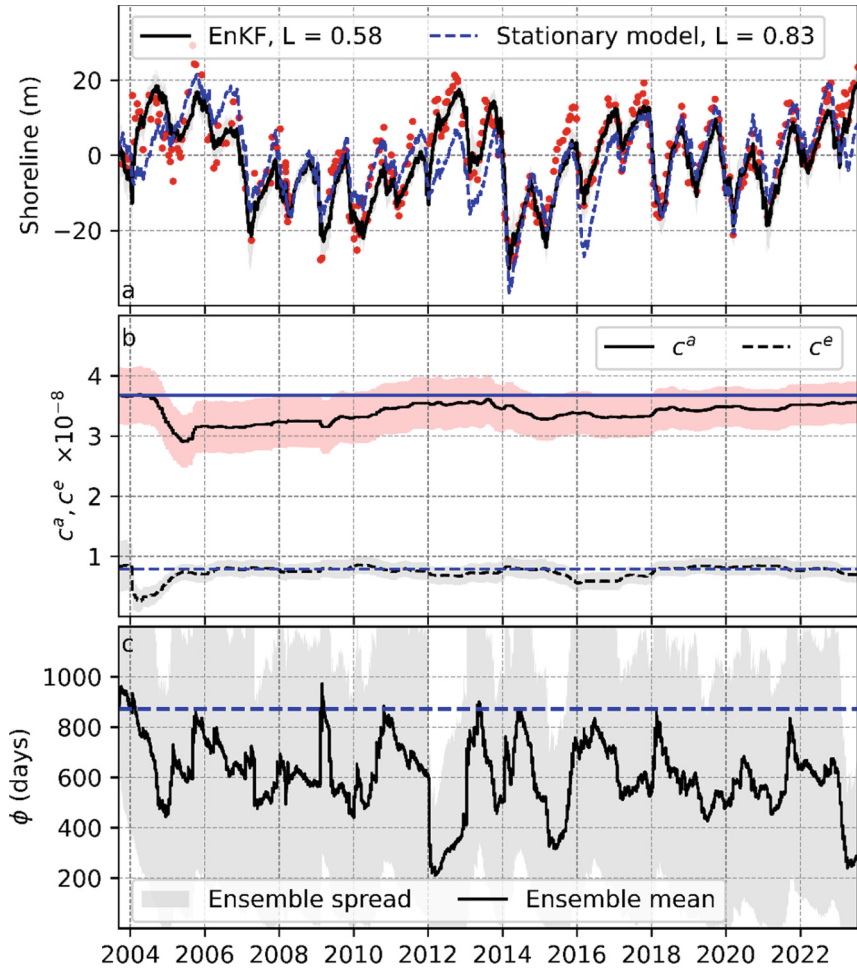


Fig. 2. (a) Model hindcasts of a stationary (blue dashed line) and non- stationary (black solid line) model parameters. (b) accretion/erosion rate parameter. (c) Beach memory parameter ϕ .

The Loss function used to evaluate the model’s performance is expressed as:

$$L = \sqrt{(0 - RMSE_{Norm})^2 + (1 - R^2)^2 + (1 - STD_{Norm})^2} \tag{4}$$

where the root mean square error (RMSE) and the standard deviation (STD) of the simulated shoreline timeseries are normalized with the standard deviation of the observed shoreline timeseries. The full metrics of the model are summarized in Table 1.

An ensemble of 500 simulations was implemented in the Kalman filter. The grey areas in Fig. 2 indicates the spread of the ensemble while the solid lines indicate the ensemble mean. All metrics were calculated on the ensemble mean.

Table 1. Model metrics compared to the observation

	Loss	RMSE, (m)	$RMSE_{Norm}$	R^2	STD, (m)	STD_{Norm}
Ensemble Kalman Filter	0.58	6.0	0.52	0.75	10.24	0.89
Stationary model	0.83	8.0	0.70	0.56	9.94	0.86

4 Discussion

The introduction of the non-stationary model free parameter using the EnKF algorithm significantly improves model results as indicated by the reduction in the Loss function L . The stationary model fails to capture the extreme values of the timeseries, while the non-stationary approach indicates that a time varying ϕ could address this shortcoming of the model. The model free parameter ϕ can be interpreted as a beach memory, indicating the amount of days prior to today the wave conditions can influence the shoreline response. A cluster of storms for example will erode the sand from the upper part of the profile and deposit it offshore creating a sandbar, which will make the beach harder to erode as larger wave conditions would be needed. This is simulated by an increase in the beach memory parameter ϕ , meaning that the cluster of storms will influence the shoreline response for a longer period. As the model moves further away from the storm period and mild wave conditions prevail, the beach memory parameter drops simulating the decreasing influence of the past storm conditions.

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