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Investigating the potential of time-varying free parameters in equilibrium shoreline change models through data assimilation

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Abstract

Equilibrium shoreline change models with calibrated, time-invariant free parameters have demonstrated good skill in hindcasting shoreline evolution at sites dominated by cross-shore sediment transport. However, their performance can be biased by the specific conditions present during the calibration period. In this study, a dual parameter-state ensemble Kalman filter (EnKF) was applied to track non-stationarity in model free parameters at three sites along the west coast of Europe. Introducing time-varying parameters did not substantially improve performance relative to an already well-calibrated stationary model. Model skill improvement occurred mainly during the EnKF correction step, highlighting the potential of real-time data assimilation for maintaining model stability. Although variations in model parameters may compensate for unresolved processes and should be interpreted cautiously, incorporating climate-driven, time-varying parameters could improve extreme-event predictions at seasonally dominated sites and enhance overall model performance in regions influenced by complex, multimodal wave climates.

KEYWORDS

data assimilation, ensemble Kalman filter, non-stationary parameters, shoreline modelling, wave climate

1 | INTRODUCTION

Responding to variable wave forcing, cross-shore sediment transport dominated shorelines constantly approach a dynamic equilibrium (Wright & Short, 1984). Models based on this equilibrium concept (Davidson et al., 2013; Miller & Dean, 2004; Splinter et al., 2014; Yates et al., 2009) can effectively simulate sandy shoreline evolution over timescales ranging from days to decades (Azorakos et al., 2024; Castelle et al., 2014; Mao et al., 2025; Montañó et al., 2020; Splinter et al., 2013; Wright et al. 1985). Typically, time-invariant model free parameters are optimized over a calibration period using shoreline observations (Splinter et al., 2013, 2014), leading to shoreline predictions that can be biased by the phenomena present in the period used for model calibration (D'Anna et al., 2020; Splinter et al., 2017).

Furthermore, shoreline change models with time-invariant best fit parameters may struggle to reproduce shoreline dynamics over time scales that differ from the calibration period (Splinter et al., 2013, 2017). Introducing time-varying model free parameters is hypothesized to make shoreline change models dynamic and adaptive, allowing them to better reflect the diversity of beach response and behaviour across different temporal scales.

Splinter et al. (2017) investigated the effect of changing storm seasonality on shoreline response and best fit model free parameters at an open-coast beach exposed to a multimodal wave climate on the east coast of Australia. They found that optimal model parameters varied by an order of magnitude following a shift of the incident wave climate and shoreline response from seasonal to episodic. Ibaceta et al. (2020), Alvarez-Cuesta et al. (2021) and Vitousek, Vos, et al.

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(2023) employed data assimilation techniques to incorporate shoreline observations into their modelling applications. Ibaceta et al. (2022), working at the same site as Splinter et al. (2017), implemented a dual state/parameter ensemble Kalman filter (EnKF) to track temporal variability in model free parameters, which they found to negatively correlate with incoming wave energy. Chen et al. (2025) explored the use of time-varying model free parameters and their relationship with environmental forcing at Hasaki Beach, Japan. They showed that changes in incoming wave energy positively correlate with changes in model free parameters which differs from the findings of Ibaceta et al. (2022).

Time-varying parameters may compensate for missing processes in numerical models and should be interpreted cautiously, as site-specific links to environmental conditions may not generalize or accurately reflect system behaviour. To robustly test the hypothesis that variability in model free parameters could be linked to wave climate, it is necessary to examine multiple well-monitored cross-shore sediment transport and wave dominated sites, exposed to similar wave climates. The present work seeks to address this gap by conducting such an investigation across three sites along the Atlantic coast of Europe. An EnKF algorithm (Ibaceta et al., 2020) was applied to track temporal variability of the model free parameters in the Davidson et al. (2013) model. Improvement in model skill by the introduction of time-varying model free parameters was quantified and links between parameter variability and environmental forcing were explored. The ability of the EnKF algorithm to track the non-stationarity of the system and the potential to improve shoreline prediction is thoroughly discussed. The study sites, data used and adopted methodology are detailed in Section 6. The results are presented in Section 6 followed by a detailed discussion and conclusions in Sections 6 and 6.

2 | STUDY SITES, DATA AND METHODOLOGY

2.1 | Study sites

Three study sites were selected along the west coast of Europe, namely, Perranporth in SW England; Porsmilin in Brittany, NW France; and Truc Vert in Nouvelle-Aquitaine, SW France (Figure 1). All three sites are exposed to a wave climate generated in the north Atlantic ocean, consist of medium quartz sand ($0.32 \leq d_{50} \leq 0.35$ mm) and are predominantly cross-shore sediment transport dominated. Perranporth and Porsmilin are macrotidal beaches while Truc Vert is a meso-macrotidal beach with a spring tidal range of 6.3, 5.7 and 3.7 m, respectively. Long-term monitoring programmes have been in place at all three sites since between 2003 and 2006, with publicly available datasets described in detail in McCarroll et al. (2023), Bertin et al. (2022) and Castelle et al. (2020).

2.2 | Wave and shoreline data

The Perranporth wave time series (Figure 1i) is recorded at 30-min intervals by a Datawell Directional Waverider Mk III buoy moored at ~ 18 m depth, offshore of the study site (50.352° N, -5.174° E). Data

gaps caused by buoy failure during extreme events were filled using records from the more reliable Bideford Bay buoy, located ~ 100 km up the coast (51.058° N, -4.277° E). Both datasets and associated metadata are freely available through Southwest Coastal Monitoring (<https://southwest.coastalmonitoring.org/>). The Porsmilin wave time series (Figure 1j) is extracted at hourly intervals from hindcasts produced using the Wavewatch III (WW3) model (Version 4.11), at a depth of ~ 14 m (48.347° N, -4.681° E). The time series is a product of two databases developed and curated by Ifremer, namely, the HOMERE database (Accensi & Maisondieu, 2015) covering 1994 to 2023 and the NORGAS-UG database (Ardhuin & Accensi, 2012), which spans from 2008 to present. The Truc Vert wave time series (Figure 1k) is extracted at hourly intervals from the ERA5 global reanalysis dataset (Hersbach et al., 2023) at a depth of ~ 54 m (44.5° N, -1.5° E). These offshore wave conditions were subsequently shoaled and refracted to breaking-wave parameters using the formulation proposed by Larson et al. (2010).

For the three sites, shoreline position time series are obtained by topographic surveys performed during spring low tide, using an RTK-GNSS with a vertical accuracy between 3 and 10 cm introducing a horizontal uncertainty between 3 and 10 m depending on beach slope. Shoreline proxies were defined as the horizontal position of the +0 m elevation above Ordnance Datum Newlyn (ODN) in Perranporth and the +2 and +1.5 m elevation above mean sea level (AMSL) in Porsmilin and Truc Vert, respectively. At Perranporth and Truc Vert, the beach profile is averaged alongshore to filter out three-dimensional beach features (e.g., cusps and megacusps). In contrast, a single profile at the centre of the beach is monitored at Porsmilin. Prior to 2012, the alongshore extent surveyed at Truc Vert was less than 1000 m and varied between surveys. However, complete filtering of megacusp at this site requires a minimum alongshore extent of 1400 m (Azorakos et al., 2024). The normalized shoreline positions, $X/\sigma(X)$, where $\sigma(X)$ is the standard deviation of the time series, are shown in Figure 2a-c.

The following analysis considers seasonal shoreline changes over winter (December–March, plotted in blue) and the remainder of the year (plotted in black). Figure 2d-i presents the seasonal shoreline change against the corresponding average wave forcing and the shoreline position at the beginning of each season. To enable quantitative comparison between the three sites, wave height has been normalized. At Perranporth and Truc Vert, seasonal shoreline variations are nearly identical and strongly governed by wave forcing. Shoreline position appears to reflect a weighted moving average of wave energy, as almost all winter and non-winter periods exhibit clear erosion–accretion cycles, suggesting that shoreline change may be interpreted as a convolution process (Vitousek et al. 2025).

Porsmilin behaves somewhat differently, with mild winters occasionally leading to accretion and increased scatter during summer. This may partly reflect planform dynamics such as rotation or breathing (Blossier et al., 2017; Castelle et al., 2020), given that only a single profile is monitored. Nevertheless, the erosion–accretion cycle remains largely controlled by the shoreline position at the start of each season (X_0), as accreted shorelines tend to erode and vice versa, largely independent of season. Despite these site-specific differences, all three beaches exhibit similar responses to high-energy winters and nearly identical behaviour during the extreme winter of 2013–2014.

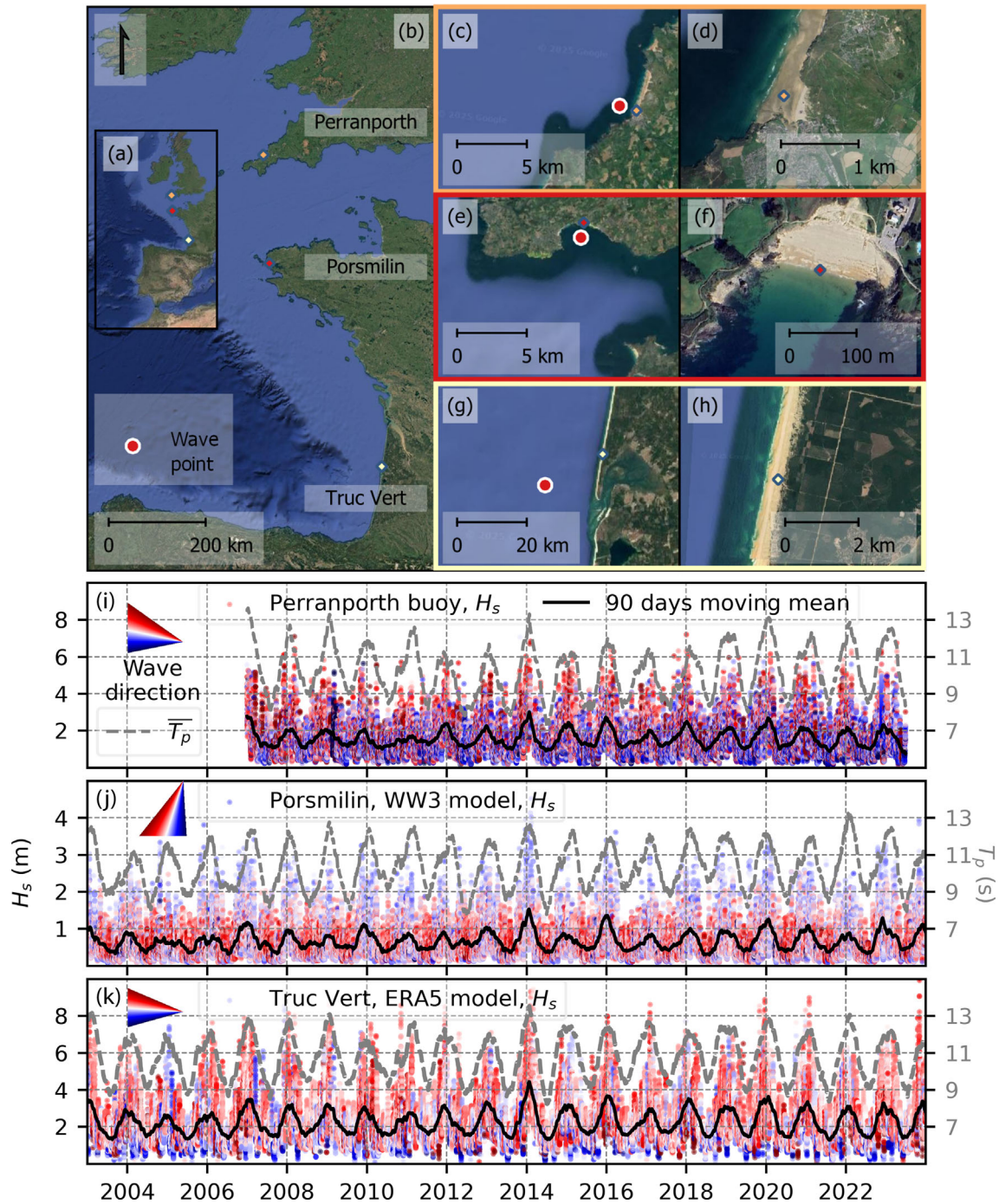


FIGURE 1 (a,b) Location of the three study sites along the west coast of Europe. (c) Perranporth beach and the wave buoy location (red dot). (d) Overview of the monitored area of Perranporth beach. (e) Porsmilin beach and the wave extraction grid point location (red dot). (f) Close-up view of Porsmilin beach. (g) Truc Vert beach and the wave extraction grid point location (red dot). (h) Close-up view of the monitored area at Truc Vert. (i–k) Available wave conditions at the three sites. Wave height (H_s) measured/extracted is indicated by the coloured dots together with the 3-month moving mean \bar{H}_s (black solid line) and \bar{T}_p (grey dashed line, plotted in the right axis). Red and blue colours indicate the incoming wave direction.

Overall, the analysis confirms and extends previous studies on the influence of the North Atlantic wave climate on beach response along the western European coast (Bertin et al., 2022; Castelle et al., 2017, 2024; Dodet et al., 2019; Masselink et al., 2023; McCarroll et al., 2023). Wave conditions are found to dominate shoreline change not only at the exposed beaches of Perranporth and Truc Vert (Masselink et al. 2023) but also at the more sheltered Porsmilin site. Furthermore, the initial shoreline position at the start of each season emerges as a key factor modulating seasonal response, particularly at Porsmilin (Dodet et al., 2019).

2.3 | Equilibrium shoreline model

The rate of shoreline change dx/dt (m/s) is calculated based on the Davidson et al. (2013) model as

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

where 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} , which represents the response rate of the shoreline

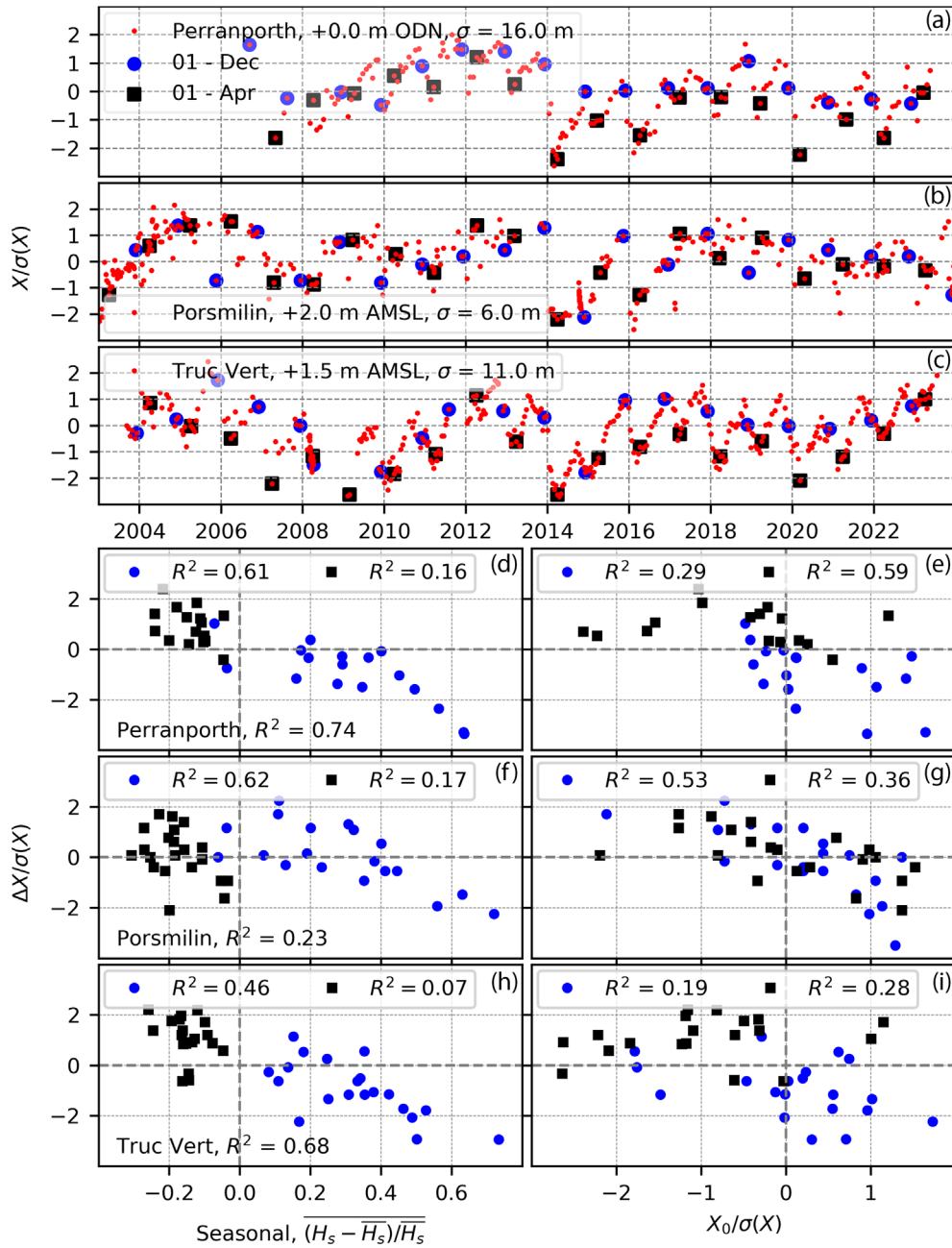


FIGURE 2 Normalized time series of shoreline fluctuation around the mean position $X/\sigma(X)$ in Perranporth (a), Porsmilin (b) and Truc Vert (c). The shoreline proxy, vertical datum used at each site, and standard deviation of shoreline position $\sigma(X)$, are indicated in the legend. The start (1 December) and end (1 April) of winter are marked by blue circles and black squares on the nearest observations, respectively. (f) Normalized shoreline change $\Delta X/\sigma(X)$ in Perranporth versus seasonal normalized wave height fluctuations around the mean $(H_s - \bar{H}_s)/H_s$ depicted in blue dots for the winter period and black squares for the rest. (e) Seasonal $\Delta X/\sigma(X)$ versus the shoreline position at the beginning of the season $X_0/\sigma(X)$ in Perranporth. (f–i) depict the same results for Porsmilin and Truc Vert. The seasonal and total coefficient of determination R^2 are indicated in each panel.

with units of velocity per incident wave power. The response rate 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 disequilibrium term $(\Omega_{eq} - \Omega)$ is expressed in terms of the dimensionless fall velocity Ω , defined as

$$\Omega = \frac{H_s}{T_p w_s}, \quad (2)$$

where H_s and T_p are the instantaneous significant wave height and peak wave period, respectively, and w_s is the terminal 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

$$\Omega_{eq} = \sum_{j=0}^{2\phi} \Omega_j 10^{-j/\phi} \left[\sum_{l=0}^{2\phi} 10^{-l/\phi} \right]^{-1}, \quad (3)$$

where j is the number of days prior to the present and the memory decay ϕ is a model free parameter indicating the number of days it takes for the weighting to reach 1% of the instantaneous value at 2ϕ days prior to the present.

The original formulation by Davidson et al. (2013) and most subsequent variants include a linear trend term b in Equation (1). Given the absence of significant linear trends at all three sites, this term was excluded under the assumption that the model's remaining free parameters—accretion/erosion rates c^\pm and ϕ —can sufficiently represent the system dynamics.

For model calibration and quantitative comparison, the root mean square error (RMSE), bias included, Pearson correlation coefficient R and standard deviation σ are integrated into the loss function L , Equation (5). Combining all three statistical parameters in one metric is believed to quantify model skill rather than just model error (Mao et al., 2025; Taylor, 2001), allowing for a more holistic approach in model calibration and comparison. RMSE and σ of the simulated shoreline are divided by the σ of the observation, ensuring that all three statistical parameters are normalized.

$$RMSE_{\text{norm}} = \frac{RMSE}{\sigma_{\text{Obs}}}, \sigma_{\text{norm}} = \frac{\sigma_{\text{Pred}}}{\sigma_{\text{Obs}}}. \quad (4)$$

The loss function L is defined as

$$L = \sqrt{RMSE_{\text{norm}}^2 + (1 - R)^2 + (1 - \sigma_{\text{norm}})^2}. \quad (5)$$

Best fit stationary model free parameters have been calibrated over a 12-year period (2012–2024) using a simulated annealing nonlinear optimization algorithm (Bertsimas & Tsitsiklis, 1993). A total of 10^6 iterations were performed to minimize the loss function. The process was repeated 10 times, resulting in an ensemble of simulated shorelines trajectories, to account for the stochastic nature of the calibration algorithm.

2.4 | Data assimilation

The EnKF algorithm of Ibaceta et al. (2020) separates the data assimilation process into two steps, namely, the parameter and state update. Using an initial set of model parameters, an ensemble of $n = 500$ simulated shorelines is generated. In the first step (parameter update), simulated shorelines are compared with observations, and if model-data discrepancy exceeds the observation uncertainty, the model parameters are adjusted to reduce the error. In the second step (state update), a new ensemble of simulated shorelines is calculated using the updated parameters, which is further corrected if the residual error remains larger than the observation uncertainty. Throughout this work, observation uncertainty was set to 3 m for all three sites. A process noise magnitude is defined to inflate the parameters during the first step that can be considered as the 'search step' within the 'parameter space'. Although process noise is commonly treated as a site-specific parameter (Alvarez-Cuesta et al., 2024), in the present work, it was kept constant to preserve the regional framework. For a detailed description of the EnKF algorithm implementation, the reader is referred to the work of Ibaceta et al. (2020). The time-varying model free parameters obtained during the first step (parameter update) are referred to as the non-stationary model throughout this work.

3 | RESULTS

In Figure 3a–c, simulated shorelines from the stationary (S) and non-stationary (NS) models are compared with observations over the 12-year period from 2012 to 2024. Shoreline data prior to 2012 were excluded due to their limited and spatially variable alongshore coverage at Truc Vert. The reduced model skill observed at Perranporth during winter 2013/2014 likely results from a buoy failure and the subsequent substitution of measurements with data from Bideford Bay. Introducing non-stationary parameters significantly improved model performance at Perranporth, had little effect at Truc Vert and reduced skill at Porsmilin. Adjusting model free parameters at each observation step yielded only marginal gains overall. The temporal evolution of the non-stationary parameters, normalized by the corresponding stationary value, is shown in Figure 3e–g. To illustrate wave climate variability, Figure 3h presents the ERA5 offshore wave height time series for Truc Vert (Hersbach et al., 2023), with winter seasons indicated by shaded areas.

In Perranporth and Truc Vert, all three non-stationary parameters seem to fluctuate around their stationary values. This is not the case for ϕ in Porsmilin, however, especially between 2017 and 2021 when it drops to almost 10% of its stationary value, ϕ_{ST} , which is in the order of 10^3 days at all three sites. ϕ exhibits the largest and most frequent fluctuations, hinting that there might be a seasonal/interannual signal. The accretion/erosion rates c^\pm show smaller and longer fluctuations, suggesting that these might be affected by long-term patterns in the wave forcing and/or alongshore sediment transport processes. Some similarities in the temporal variability of all three parameters can be identified between the three sites. However, the correlation, although statistically significant, is very weak. For instance, the strongest correlation was found in the variability of the erosion rate c^- between Truc Vert and Porsmilin, with $R^2 = 0.3$ ($p \approx 0.00$).

The high frequency fluctuations in ϕ and especially the response to high-energy winters, prompted some further investigation into the drivers behind this variability. Changes in the normalized ϕ over the winter period have been calculated and compared with winter mean wave height, which seems to describe 37% to 58% of winter $\Delta\phi$ (see Figure 4). Some scatter is observed during average winters, when $(H_s - \overline{H_s})/\overline{H_s} \approx 0.36$, whereas above average winters almost never result in a significant decrease of the parameter. Across all three sites, the most and least energetic winters correspond to large increases and decreases in ϕ , respectively.

4 | DISCUSSION

To the best of the authors' knowledge, this is the first study to examine whether temporal variability in model free parameters across multiple sites exposed to similar wave climates reflects changes in environmental forcing. Inter-site comparisons of parameter variability reveal only weak linear correlations, suggesting that subtle seasonal or interannual fluctuations in wave climate exert a minor influence along the Atlantic coast of Europe. At all sites, however, the ϕ parameter increased significantly in response to the most energetic winter on record (2013–2014). This observation aligns with (Ibaceta et al., 2020; Splinter et al., 2017), who demonstrated that, at an open-coast beach

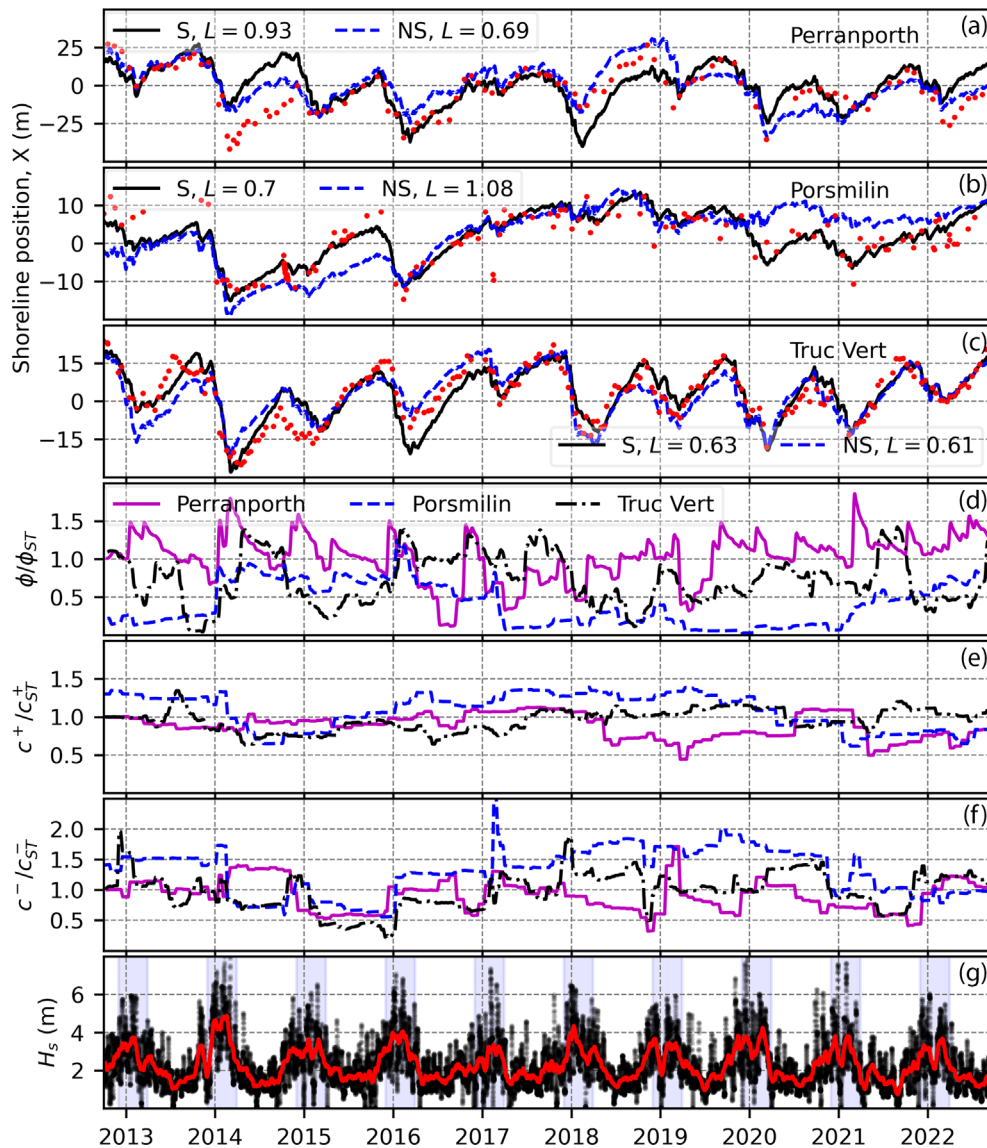


FIGURE 3 (a–c) Simulated shoreline time series produced by the stationary S (solid black line) and non-stationary NS model (dashed blue line) depicted together with the shoreline observations (red dots) at all three sites. Model skill (loss function) is indicated in the legend as L . (e–g) Time series of non-stationary model free parameters for Perranporth (magenta solid line), Porsmilin (blue dashed line) and Truc Vert (black dashed/dotted line). Non-stationary parameters have been normalized using the value of the corresponding stationary model free parameter. (h) ERA5 time series of instantaneous (black dots) and monthly averaged (red line) H_s extracted offshore of Truc Vert. Winter period (December–March) is illustrated by the shaded background.

exposed to multimodal wave climate and interannual storm regime shifts, pronounced changes in forcing can significantly affect best fit model parameters, particularly ϕ . Conversely, Vitousek et al. (2025) demonstrate that the Davidson et al. (2013) model, when implemented with a time-varying memory decay function (Equation 3 with varying ϕ), can yield a non-zero mean even in the absence of trends in the forcing due to a correlation between the equilibrium condition $\Omega_{eq} - \Omega$ and the forcing $P^{0.5}$ in Equation (1) (see fig. S2 in Vitousek et al., 2025). In this context, the observed variations in ϕ may partly compensate for, or counteract, fluctuations in incoming wave energy, acting as an adaptive mechanism that maintains model stability and performance. Nevertheless, these findings underscore the potential of time-varying free parameters to improve model predictions of shoreline response during extreme events, which was identified as an important limitation in the benchmarking studies of Montaña et al. (2020) and Mao et al. (2025).

The stationary models achieved skill levels among the highest reported in the literature for comparable environments (Azorakos et al., 2024; Mao et al., 2025; Montaña et al., 2020; Splinter et al., 2013, 2014). Consequently, incorporating non-stationary parameters may offer limited improvement when baseline model performance is already near its practical limits. Furthermore, the ability of the EnKF framework to reproduce the skill of the stationary model suggests it may also serve as a viable alternative for model calibration (Alvarez-Cuesta et al., 2021; Vitousek, Vos, et al., 2023).

The ability of the EnKF algorithm to accurately track system non-stationarity declines with increasing observation error and/or decreasing sampling frequency (Alvarez-Cuesta et al., 2024; Ibaceta et al., 2020). The poor performance of the non-stationary model at Porsmilin may therefore be partly attributed to the irregular observation frequency (Bertin et al., 2022). Additionally, unresolved three-dimensional beach processes likely further impact EnKF

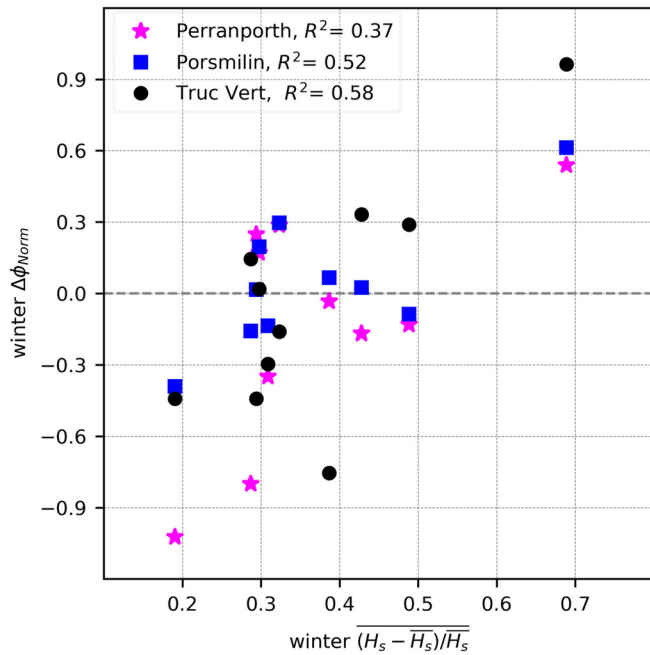


FIGURE 4 Changes in normalized beach memory ϕ/ϕ_{ST} between April and November plotted against winter normalized H_s .

performance—particularly at Porsmilin, where only a single profile is measured (Bertin et al., 2022), and at Truc Vert prior to 2012, when the spatial extent of observations was limited and inconsistent (Castelle et al., 2020). The single-profile and irregular observations at Porsmilin may also explain why the initial conditions of the non-stationary model deviate significantly from the stationary value compared with the other sites.

Pre-season beach state influences seasonal shoreline response at all sites—most notably at Porsmilin—while its exclusion from the model likely contributes to the reduced performance there. Overall, the ability of the algorithm to capture non-stationarity depends strongly on both the quality and properties of the dataset, as well as on the degree to which the governing equations represent the dominant processes. Because models remain simplified descriptions of complex physical systems, variations in non-stationary parameters should be interpreted with caution, as they may compensate for processes not explicitly included in the model structure.

Finally, the correction step of the EnKF algorithm ensures that modelled shorelines remain within observational uncertainty, regardless of the accuracy of the parameter tracking. This property provides a flexible and efficient mechanism for incorporating observational information into reduced-complexity morphodynamic models while maintaining numerical stability and physical coherence.

5 | CONCLUSIONS

Models with time-invariant free parameters demonstrate strong performance in sites exposed to seasonal, mostly unimodal, wave climate. Introducing time-varying free parameters shows great potential in improving prediction of extreme events in long-term simulations and overall model performance at sites exposed to more complex wave conditions (Ibaceta et al., 2022). Links between free-parameter variability and wave forcing are more complex than expected, requiring accurate system representation for proper identification. Future research

should consider multiple sites exposed to multimodal wave climates to further explore the relationship between environmental forcing and model free-parameter variability. Data assimilation applications can be very useful in keeping models aligned with observations and/or projected long-term trends. Considering the computational efficiency, relatively easy implementation and ability to converge even with low quality datasets (Alvarez-Cuesta et al., 2024), the EnKF algorithm is an efficient way to incorporate data in modelling applications. As coastal sciences are transformed to a data rich field of studies by the emergence of global datasets (Calkoen et al., 2025; Vitousek, Buscombe, et al., 2023), data assimilation becomes a necessary tool enabling the integration of data into our models, compensation for processes not accounted for and quantification of model error in real time.

AUTHOR CONTRIBUTIONS

Georgios Azorakos is credited with conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—reviewing and editing and visualization. Bruno Castelle is credited with conceptualization, funding acquisition, methodology, investigation, resources, supervision and writing—reviewing and editing. Déborah Idier is credited with conceptualization, methodology, supervision and writing—reviewing and editing. Vincent Marieu is credited with methodology, investigation, resources, supervision and writing—reviewing and editing. Raimundo Ibaceta is credited with software and writing—reviewing and editing. Kristen D. Splinter is credited with writing—reviewing and editing. Stéphane Bertin is credited with writing—reviewing and editing. Gerd Masselink is credited with writing—reviewing and editing. Timothy Scott is credited with writing—reviewing and editing.

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CONFLICT OF INTEREST STATEMENT

None of the authors have a conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

All the time series used in this study—namely, measured and modelled wave data as well as shoreline observations—were obtained from

publicly available datasets. Observed wave data and associated metadata for Perranporth are freely accessible via the Southwest Coastal Monitoring Program (<https://southwest.coastalmonitoring.org/>). Modelled wave data for Porsmilin, curated by Ifremer, can be downloaded from the HOMERE and NORGAS-UG databases (Accensi & Maisondieu, 2015; Ardhuin & Accensi, 2012). The Truc Vert modelled wave data were sourced from the ERA5 global reanalysis dataset (Hersbach et al., 2023). Shoreline observation time series for all three sites are available through their respective publications (Bertin et al., 2022; Castelle et al., 2020; McCarroll et al., 2023).

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