Response to reviewers

Reviewer(s) 1: Robert Guza & Kilian Vos

Comment 1. Tidal aliasing. Figs 1,2 (below) show the authors statement that aliasing only "effects periods of a few weeks, rather than producing coherent oscillations at multi-month or interannual timescales" is wrong. The aliased sampling redistributes tidal energy broadly over frequencies (periods from a few months to a few years). Fig 4 (below, from the manuscript) shows results from Oregon and Washington where spring tides are 3+m, almost double the San Diego tides and with a similar increase is aliasing.

Response: We thank the reviewers for providing this illustrative example. We agree that, in the San Diego tide gauge case, subsampling induces tidal aliasing and redistributes high-frequency tidal energy across the resolved frequency band. This effect was already acknowledged in our previous response: *"We would argue that subsampling tidal signals at ~8-day intervals can indeed redistribute high-frequency tidal energy through aliasing. However, such aliasing typically produces broadband spectral leakage rather than coherent low-frequency oscillations."* This statement is consistent with the reviewers' Fig. 2, where subsampling results in an overall increase in spectral energy due to the folding of high-frequency tidal components into lower frequencies. Importantly, however, this redistribution does not generate new spectral peaks, and in particular does not produce a distinct interannual one. We also note that the reviewers do not provide a statistical significance framework (e.g., AR(p)-based significance levels), which makes it difficult to assess whether the apparent low-frequency energy increase is statistically meaningful or simply reflects redistributed variance.

To further assess this point, we reproduced the same analysis at the San Diego location using the FES2022 tidal reanalysis (1.5-hour resolution) over a 30-year period (1993–2023). The signal was then subsampled at 8-day intervals to mimic CoastSat sampling. In addition, and following the reviewers' own remark that *"aliasing details depend on the overpass time and local tides"*, we systematically varied the subsampling offset to represent all possible sampling phases relative to the tidal cycle. The resulting spectra (Fig. 1) show the expected frequency folding associated with subsampling while the amount and distribution of aliased energy depend on the subsampling offset. Critically, while aliasing can project energy into lower frequencies, it does not generate a persistent or coherent interannual signal across sampling configurations. This demonstrates that tidal aliasing alone cannot explain the spatially coherent interannual variability identified in our analysis.

We further emphasize that, in the present discussion, the focus is oriented toward a simplified and limiting scenario in which the satellite-derived shoreline would behave as a direct proxy of the tidal signal alone. As stated in our previous response: *"tides represent only one component among many that modulate water level. The waterline (used here as a dynamic proxy for shoreline position) integrates multiple contributions, including tides, wave runup, and sea-level variability."* In reality, the satellite-derived shoreline composite reflects the combined effects of these processes, each characterized by distinct temporal scales and dynamics. As a result, no tidal signal remains isolated. Instead, it is embedded within a mixed signal. Consequently, the argument presented by the reviewer; and in this response (based on a purely tidal input) represents a conservative upper-bound test of tidal aliasing. If aliasing alone does not produce a robust interannual feature under purely tidal forcing, it is unlikely to do so in the real system, where additional processes further dilute the tidal signal.

Finally, to provide direct empirical verification, we repeated the analysis using the dataset of Graffin et al. (2025) along the north-west American coast. This dataset explicitly corrects for tidal effects, meaning that the shoreline positions are not affected by tidal aliasing. This was also found locally using direct, *in-situ* surveyed data at Torrey Pines beach. The results remain unchanged: the spectral peak in the biennial band persists and exhibits spatial coherence along the coastline (Fig. 2).
This demonstrates that the observed remaining interannual peak within residual shoreline signal cannot be attributed to tidal aliasing.

Comment 2. Bispectral methods. As noted in our review, bicoherence with records including relatively few cycles (~8) of the 30mo signal are statistically noisy. The 95 % significance level for zero bicoherence with 16 dof =0.61 (Haubrich, 1965 and many others). The authors acknowledge that noise is an issue and do not claim statistical significance of Torrey Pines results. However, they say "the core results rest entirely on the observational evidence and the in situ validation at Torrey Pines".

Response: We thank the reviewer for this comment and for encouraging a more detailed assessment of the nature of the nonlinear interactions discussed in the manuscript.
First, the reviewers refer to the work of Haubrich (1965), which is based on classical Fourier bispectral analysis and indeed shows that bicoherence estimates based on records containing relatively few cycles (e.g., ~8 cycles of a ~30-month signal) are statistically noisy, leading to high significance thresholds (e.g., ~0.61 for 16 degrees of freedom, as reported in Haubrich, 1965). As already noted in our previous response, this framework is inherently designed for stationary signals and relies on statistical averaging over multiple independent realizations. In this context, Haubrich also emphasizes that a high bicoherence value does not necessarily imply a true nonlinear interaction, as it can arise from strong spectral structure or non-stationarity in the signal itself. This constraint reflects the limitations of bispectral methods based on FFT approaches in short, non-stationary records as they implicitly assume stationarity, such that a sufficient number of

independent realizations is required to obtain stable estimates. This point has already been acknowledged and justified in our previous response: *"...we acknowledge that classical bispectral analysis is a widely used tool for diagnosing nonlinear triadic interactions in stationary signals."*

In order to explicitly address this limitation related to non-stationarity, we have, in our previous response, complemented the analysis by computing a cross-wavelet bicoherence at Torrey Pines (Fig. 6; previous response). This formulation extends the classical bispectral framework to the time–frequency domain, thereby relaxing the strict stationarity assumption. The result shows a clear and robust bicoherence maximum ($b^2 \approx 0.83$–0.93) at the expected triadic combination ($T_1 \approx 4.94$ months, $T_2 \approx 6.08$ months, $T_3 \approx 26.30$ months), consistent with the interaction identified in the manuscript, and a local bicoherence $b^2(t)$ that remains persistently elevated throughout the record, suggesting that the interaction is not confined to a single transient episode. Here, the wavelet bicoherence evaluates whether the complex amplitudes of the three components are coherent in the time–frequency domain. Formally, it involves a quantity of the form: $W_1(f1,t)\,W_2(f2,t)\,W_3^*(f3,t)$, where $Wi(f,t)$ denotes the complex wavelet coefficient of signal x_i at frequency f and time t; which is averaged over time (and often across neighboring frequencies), resulting in a product that mixes both amplitude and phase information. If this product remains coherent, the bicoherence takes high values. Hence, the method responds very strongly as soon as three well-defined spectral components are present and energetically correlated, even if their phase relationship is not organized in time, primarily testing a third-order spectral coherence rather than phase organization.

Hence, the bicoherence remains strongly controlled by the presence of coherent spectral components and by the narrow admissible frequency geometry imposed by the triadic constraint $f3 = f1 - f2$. In the present case, where $f1 \approx f2$ and f3 lies in a much lower-frequency band, the available frequency space is extremely restricted, which makes the estimation highly sensitive to smoothing choices and reduces the effective degrees of freedom of the test. As a consequence, the null distribution becomes poorly constrained and the diagnostic loses its ability to robustly discriminate between true phase-organized interactions and configurations where similar spectral content exists without phase coupling. Even in its wavelet formulation, the method remains tied to spectral amplitude consistency rather than to the temporal organization of phases.

This is precisely the point that motivates the use of complementary phase-based diagnostics. The mere coexistence of frequencies is a necessary but not sufficient condition for triadic interaction to emerge. It also requires the existence of a stable phase relation $\phi_1 - \phi_2 - \phi_3 \approx$ const, allowing for appropriate energetic transfers to happen. This perspective is not new and builds on a large body of work on phase synchronization and phase coherence in nonlinear systems (e.g., Rosenblum et al., 1996; Tass et al., 1998; Lachaux *et al.*, 1999), where the focus is placed on the organization of phase rather than on spectral energy alone. What we implement here is a direct extension of this framework to triadic interactions, adapted to a geophysical context. The metric R evaluates the circular concentration of $\Delta\phi$, while Rw introduces an amplitude-weighted formulation that selectively emphasizes dynamically energetic intervals, together with a permutation-based significance test that does not rely on stationarity assumptions; to operate in a regime where bicoherence are known to be less reliable (Haubrich, 1965): short, noisy, and non-stationary records with intermittent interactions.

Hence, the wavelet bicoherence (Fig. 6; previous response) provides a consistent spectral indication that the expected triadic combination is present, but its statistical interpretation remains limited in this configuration. The phase-based metric R (or Rw by extension), by contrast, directly tests the defining property of the interaction and remains sensitive to its intermittent nature.

To provide objective validation of this approach in our case, we have conducted a series of controlled synthetic experiments designed to isolate the observable signatures of triadic interactions and to evaluate how our diagnostic responds under identical spectral conditions but different phase organizations. We consider two configurations sharing identical spectral content and satisfying the same triadic frequency relation f1 - f2 = f3, but differing in their phase organization. In the first configuration, the three signals contain the relevant frequencies but their phases evolve independently, such that no phase locking is present (Fig. 3 - Case A). In the second configuration, the same frequencies are present but a triadic phase relation $\phi1-\phi2-\phi3$ is intermittently enforced over selected time intervals, mimicking a non-stationary and episodic interaction (Fig. 4 - Case B).

In the absence of phase locking, the obtained $\Delta\phi$ distribution remains broad and does not exhibit any preferential orientation, indicating the absence of phase organization (Fig. 3). Although the raw coherence values R and Rw remain elevated due to the quasi-periodic nature of the signals, the permutation test correctly identifies the lack of structure ($p = 0.456$), and the circular histogram confirms the absence of a preferred phase. In contrast, in the intermittent triad configuration, the obatined $\Delta\phi$ distribution becomes sharply peaked, the permutation test yields a significant result ($p = 0.011$), and the circular histogram shows a well-defined mean angle (Fig. 4). The time evolution of $\Delta\phi$ further reveals that this organization is intermittent, consistent with the imposed structure. These results indicate that the metric R detects phase organization when present, while remaining insensitive to purely spectral coincidences.

As previously stated, the phase-based metric (R) used here is not entirely new in its conceptual basis. It builds upon established phase-coherence diagnostics developed in nonlinear dynamics and geophysics, including phase-locking value measures and circular statistics applied to Hilbert-transformed signals (e.g., Rosenblum, 1996; Tass, 1998). The present study thus applies these concepts to triadic interactions by introducing an amplitude-based selection of energetic events to focus on physically relevant intervals, and by implementing a permutation-based statistical test adapted to this configuration.

The additional threshold ($Rw > 0.5$) is not intended as a theoretical criterion, but as a pragmatic effect-size filter to retain only locations exhibiting both statistical significance and a non-negligible level of phase organization, as this indicator remains a proxy (derived directly from the observational signals) of the extent and persistence over the time window during which phase locking satisfies the relation $\phi1 - \phi2 - \phi3$.

We acknowledge that the presentation of the phase-based metric in the manuscript may give the impression that it was developed specifically for this study without sufficient connection to existing approaches. We therefore commit, once the public discussion phase is concluded and that we prepare the final response to all reviewers together with a revised version of the manuscript, to better position this metric within the broader methodological framework, clarify its assumptions, and explicitly discuss its strengths and limitations relative to other methods.

Finally, the reviewer suggests that weak triadic coupling may be associated with aliasing or other artifacts. We have shown independently that tidal aliasing redistributes energy through frequency folding, with a magnitude that depends on the sampling offset, but does not generate a consistent phase organization of the form observed here. Since the proposed metric is based on phase organization rather than spectral energy alone, it is not expected to respond to broadband aliasing effects in the same way as spectral methods. This point is further reinforced by applying the phase-based metric Rw to the tidal-corrected dataset of Graffin et al. (2025), which is, by construction, free from tidal contamination. The resulting estimates exhibit comparable magnitudes and spatial coherence along the North American west coast (Fig. 6; this response), indicating that the observed phase organization cannot be attributed to tidal aliasing. The consistent performance of the phase-based metric across independent datasets, reflected in similar ranges of Rw, strengthens confidence in its reliability, and suggests that the observed phase organization is not dataset-specific but captures a robust and reproducible feature of the underlying dynamics. In this context, while we agree that weak coupling must be interpreted cautiously, the combination of phase organization, statistical significance, and consistency across independent analyses does not support the interpretation that the observed signal is solely the result of aliasing or other sampling artifacts.

To conclude, we do not state that the core results rest “entirely on the observational evidence and the in situ validation at Torrey Pines.” This interpretation does not reflect the structure of the study and we regret if we have given this impression to the reviewers and will tone down the manuscript accordingly. The central result of the manuscript is the identification of a globally recurrent near-biennial mode emerging from triadic phase coupling, based on satellite-derived shoreline observations spanning 7.4×10^4 km of coastline, along with a mechanism explanation for the semi-annual components of wave and shoreline signals. The *in situ* dataset at Torrey Pines is not used as a foundational element of the analysis, but as an independent comparison step, confirming that the same frequency and phase-organization signatures can be observed in a long-term field record.

As stated in the Discussion/Conclusion of the manuscript, the present work does not provide a direct proof of a dynamical resonance mechanism in the strict sense (i.e., explicit demonstration of energy transfer within a fully resolved dynamical system). Rather, it identifies a set of robust observational signatures that are consistent with triadic phase coupling. In natural geophysical systems, where the governing equations are not fully accessible and forcing is broadband and partly stochastic, such inference necessarily relies on indirect evidence. The combination of frequency matching, phase organization, statistical significance, persistence after removal of linear forcing, and spatial coherence provides a set of constraints that is difficult to reconcile with trivial or artifact-driven explanations.

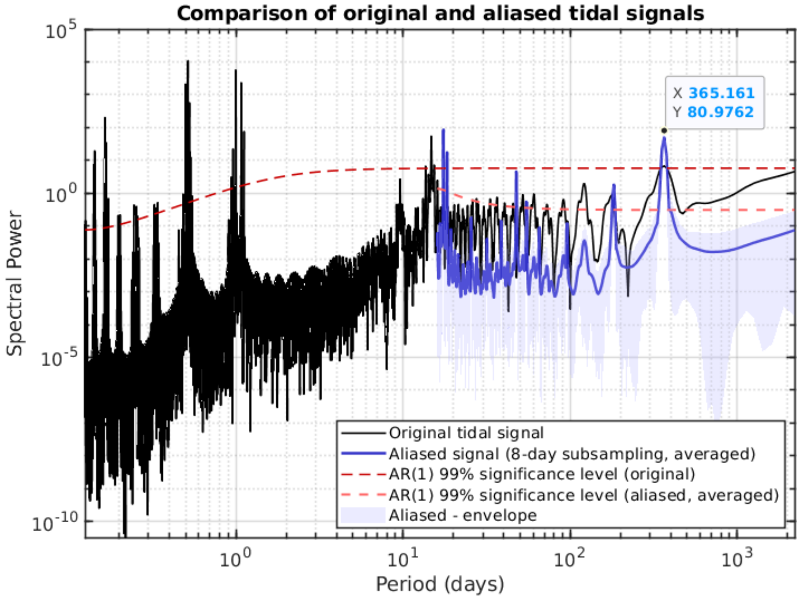

Figure 1. Comparison between the original tidal spectrum (black) and spectra obtained after 8-day subsampling (blue), using FES2022 tidal reanalysis at the San Diego location (1993–2023). *The dark blue line shows the mean spectrum across all subsampling offsets, while the shaded area represents the full envelope (min–max) over all possible sampling phases. Red dashed lines indicate AR(1)-based 99% significance levels for both original and subsampled signals. Here, no robust or significant spectral peak emerges beyond the annual timescale, demonstrating that tidal aliasing does not produce a persistent interannual signal.*

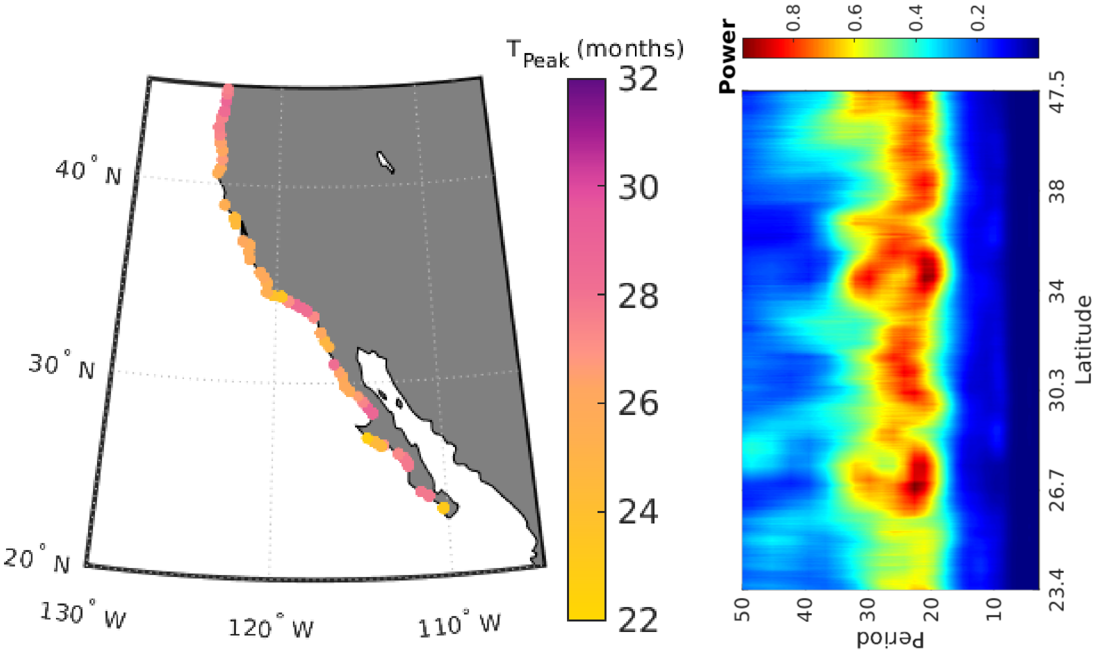

Figure 2. Cross-EOF methodology applied to the tide-corrected satellite-derived shoreline dataset (HRTC) from Graffin et al., 2025 over the common transect shared with the GlobC dataset (no micro-tidal filter). *(Left) spatial distribution of the dominant peak period* T^{peak}*(months) extracted from the shoreline residuals along the coastline. (Right): corresponding wavelet scalogram as a function of latitude, showing the concentration of energy in the interannual band and the spatial coherence of the signal along the coast.*

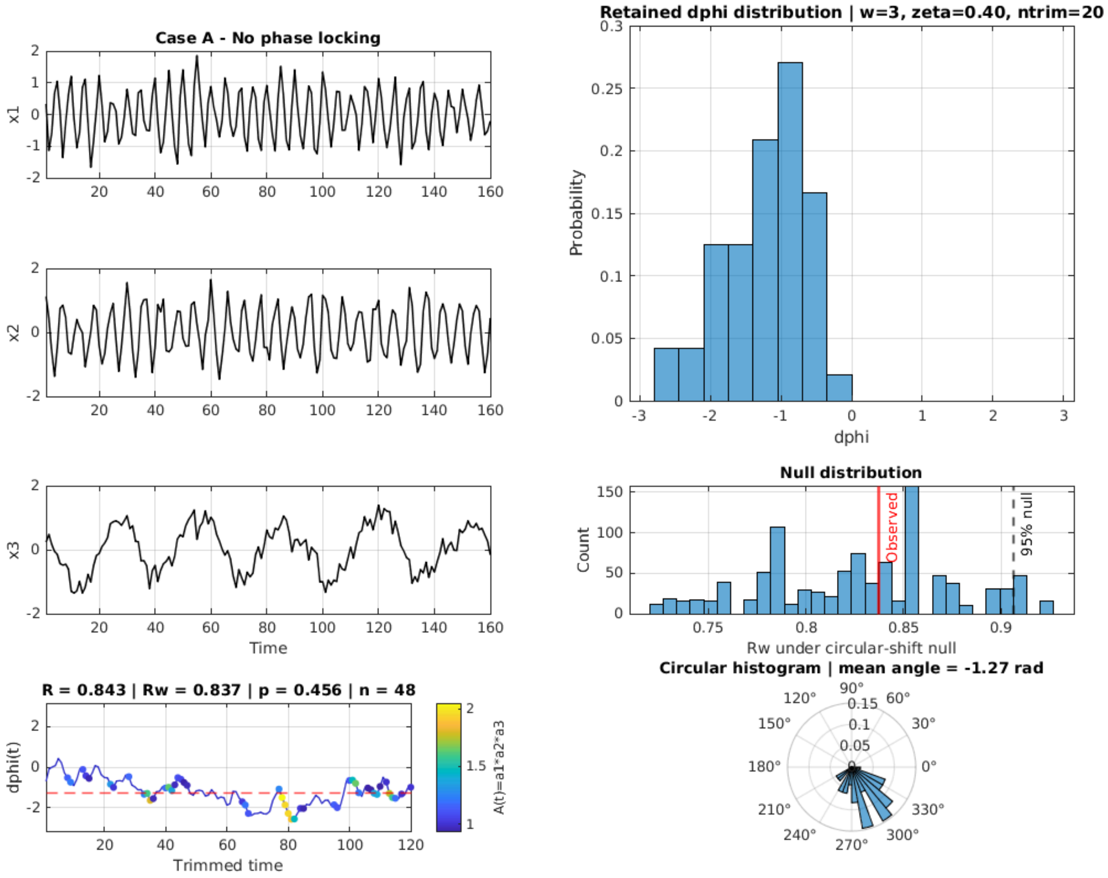

__Figure 3. Controlled synthetic experiments illustrating the behavior of the phase-based metric under identical spectral conditions but different phase organization.__ Case A (no phase locking): three signals share the same triadic frequency relation but evolve with independent phases. Despite high raw coherence (R, Rw), the retained phase difference Δϕ remains broadly distributed, the permutation test is not significant (p = 0.456), and the circular histogram shows no preferred angle, indicating absence of phase organization.

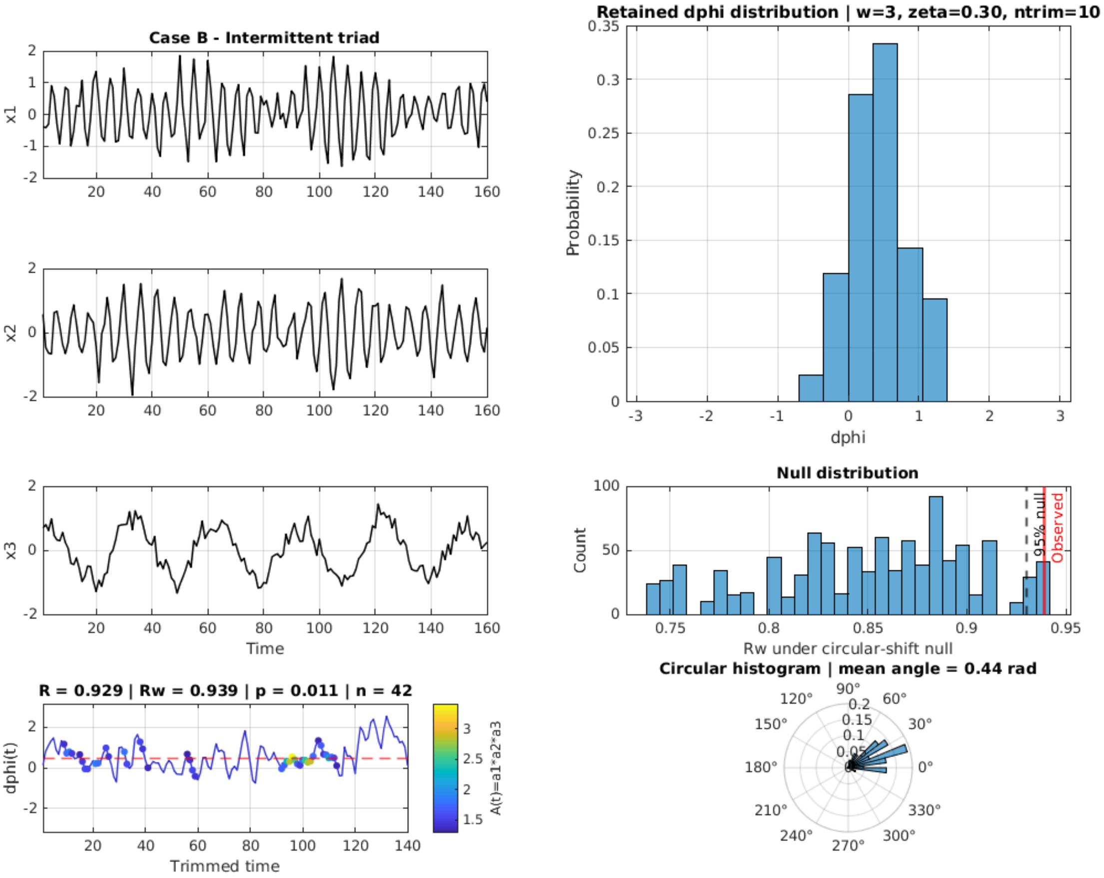

Figure 4. Controlled synthetic experiments illustrating the behavior of the phase-based metric under identical spectral conditions but different phase organization. *Case B (intermittent triadic coupling): the same frequencies are present but a phase relation* $\phi_1 = \phi_2 + \phi_3 + const$ *is intermittently enforced. This produces a sharp concentration of* $\Delta\phi$*, a significant permutation test (*$p = 0.011$*), and a well-defined mean phase angle. The* $\Delta\phi(t)$ *time series highlights the episodic nature of the coupling. These results demonstrate that the metric specifically detects phase locking, even when non-stationary, and does not produce false positives in the absence of coupling.*

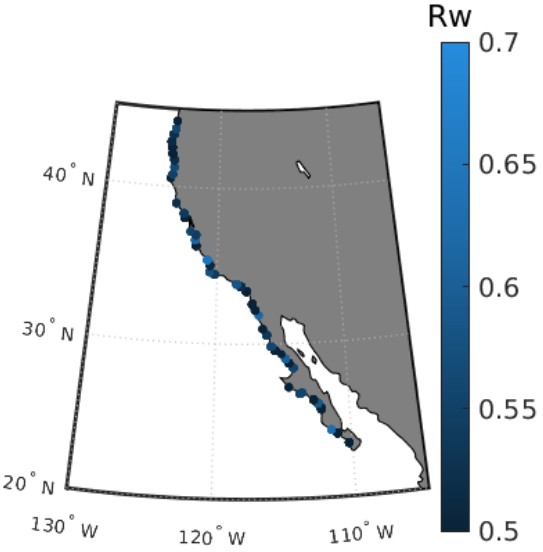

Figure 5. Phase-based coherence methodology applied to the tide-corrected satellite-derived shoreline dataset (HRTC) from Graffin et al., 2025 over the common transect shared with the GlobC dataset (no micro-tidal filter).

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