Author Response to Referee 2 (RC2)

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A Comparative Analysis of Clustering Algorithms for Characterizing Sea Surface Temperature and Kinetic Energy Variability in the Western Mediterranean

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We acknowledge Referee 2 for the careful reading and useful comments. We have tried to answer all of the referee's concerns. In the following we reproduce each of the referee's comments, followed by our response, and a summary of the changes to be introduced in the revised manuscript.

As a summary, the major changes introduced in this revision are:

- We have updated our title to *"A Comparative Analysis of Clustering Algorithms for Characterizing Sea Surface Temperature and Kinetic Energy Variability in the Western Mediterranean"* to better specify the scope of our work.
- We have performed a non-parametric bootstrap analysis to confirm that 4 clusters is optimal.
- We have included new Infomap calculations for SST. In this new version we thus provide calculations for both fields SST and KE with the three methods: K-means, SOM and Infomap.

We expect that with this revision the manuscript would be found suitable for publication in Ocean Science.

Emilio Hernández-García,
on behalf of all the Authors.

Major comment 1:

> *"Line 61-62: possibly the state of the art describing the patterns in the area could be briefly introduced."*

Author Response:
We added to Section 1 a summary of the circulation in our study area to describe regional hydrodynamics before discussing clustering results.
Manuscript Revision:
in section 1:

> *"The Ibiza Channel controls water mass exchange between the Liguro-Provençal and Algerian basins (Pinot et al, 2002). Its circulation is governed by the competition between the southward flow of the Northern Current and Western Intermediate Water (WIW), and northward intrusions of Modified Atlantic Water (MAW). Additionally, anticyclonic Algerian eddies periodically disrupt channel flow and induce localized, high-velocity jet filaments. Unsupervised clustering provides an objective framework to identify whether these circulation features organize into discrete, recurrent dynamical regimes."*

Major comment 2:

> *"Introduction: Please briefly introduce what metrics will be used for the comparison of the three methods, state of art and whether they were developed or adapted for the purpose"*

Author Response:
Section 1 now introduces the evaluation metrics: the Silhouette Score with bootstrap resampling to determine cluster count, and the Jaccard similarity index to measure temporal partition agreement across algorithms.
Manuscript Revision:
Section 1, closing paragraph:

> *"We evaluate and compare the clustering algorithms using two quantitative metrics. First, the Silhouette Score (Rousseeuw, 1987) measures internal cluster cohesion relative to cluster separation across snapshot state vectors; we pair it with bootstrap resampling to obtain confidence intervals and objectively determine the optimal cluster count. Second, the Jaccard similarity index quantifies partition agreement across independent algorithms. This index resolves arbitrary label permutations and generates an automated pairwise confusion matrix to measure inter-method consistency without manual matching."*

Major comment 3:

> *"Line 190: please explain why InfoMap has not been applied to SST as well"*

Author Response:
This revised version now applies InfoMap both to SST and to KE. We recognize that inclusion of the InfoMap analysis of SST was needed to keep consistence with the rest of the manuscript. The InfoMap clustering results for SST give a partition completely consistent with the one found by K-means and SST. This contrasts with the striking and useful differences found when analyzing KE, which reveal the power of InfoMap to identify low-frequency but relevant KE spatial configurations.

A list of the additions to the revised manuscript related to InfoMap, the methodological adaptations needed for treating SST consistently, and the new text and figures to be incorporated in the revised manuescript can be found in our response to comment 3 by reviewer 1.

Major comment 4:

> *"Line 190: is the metric comparing the clustering methods only applied to SOM and K-means? Why it is not applicable to InfoMap? Is there any other metric that could be used to quantify the differences of InfoMap compared to the other methodologies?"*

Author Response:
In this revised version we apply InfoMap also to the SST dataset. Thus, we can now compare its clustering results with the ones obtained by the other methods (which were very similar, so that comparison with just one of them is enough). For example, Figure 1, to be included in the revised manuscript, compares the four SST clusters obtained from InfoMap and from K-means.

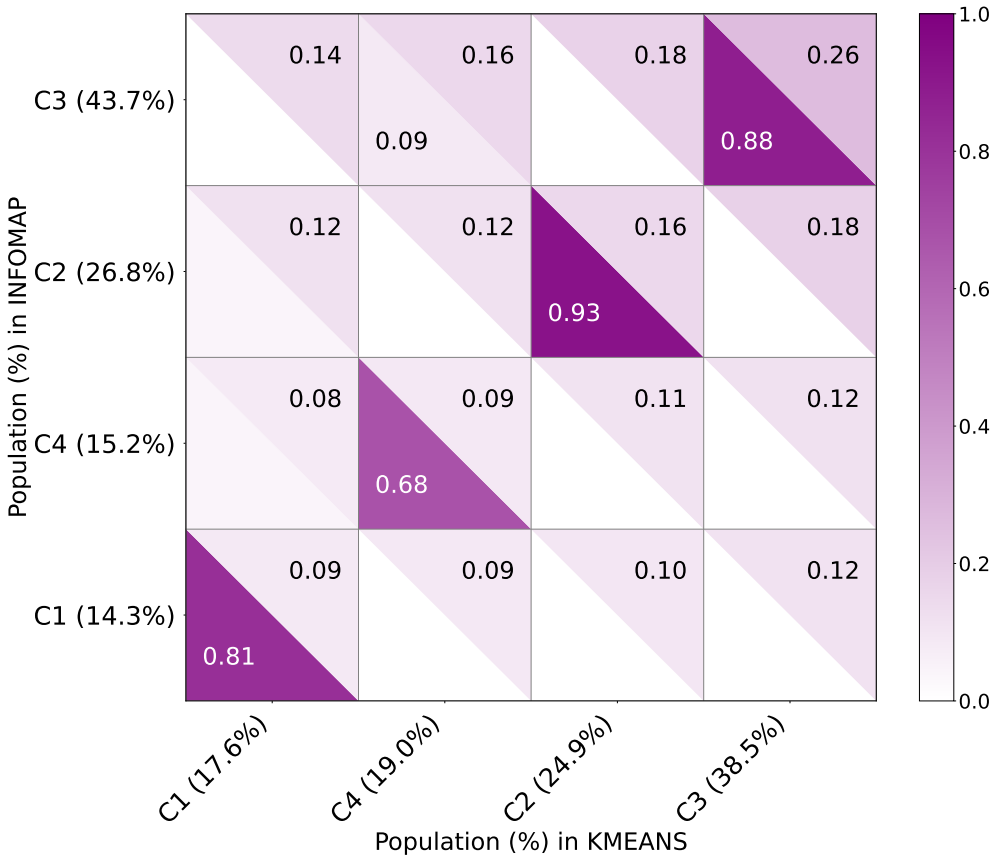


Figure 1: Jaccard similarity matrix comparing InfoMap and K-means clustering for SST. Matrix values range from 0.0 to 1.0, where darker purple indicates higher similarity (overlap). In each cell, the lower-left triangle represents the actual Jaccard index between the two methods, while the upper-right triangle represents a baseline Jaccard index calculated using randomized samples that preserve the original cluster sizes of both the K-means and InfoMap populations. The axes indicate the population percentage for each cluster.

The comparison between InfoMap and the other methods for KE can also be done via Jaccard similarity, but the result is obvious: the clusters do not agree between the two types of methods. InfoMap partitions the kinetic energy configurations into a dominant background module (99.54%) and rare anomaly states ($< 0.5\%$). SOM and K-means are able to detect only clusters with a balanced composition, being thus very different from InfoMap's, and a Jaccard matrix would yield near-zero diagonal values. This highlights the distinct potential of InfoMap with respect to SOM and K-means: the later methods find clusters of most common configurations, whereas the former finds consistently distinct clusters even if some of them represent just a minority of the states in the dataset.

We take the opportunity of this revision and this question by the referee to add to the manuscript (Section 3.3.3) a comparison that was just mentioned in the original submission. Figure 2 compares the centroid of the C4 cluster obtained from InfoMap, displaying a KE jet in the southern part of the domain, and the C4 codebook vector obtaind by SOM when trained only with the first 500 snapshots (i.e. first 500 days) of the dataset. The agreement between both images (Pearson correlation of $r = 0.9692$, $p < 10^{-15}$, and a cosine similarity of $S_c = 0.9027$) confirms that InfoMap can find recurrent configurations that occur only during a short part of

the whole dataset. Other methods reveal only the most common configurations.

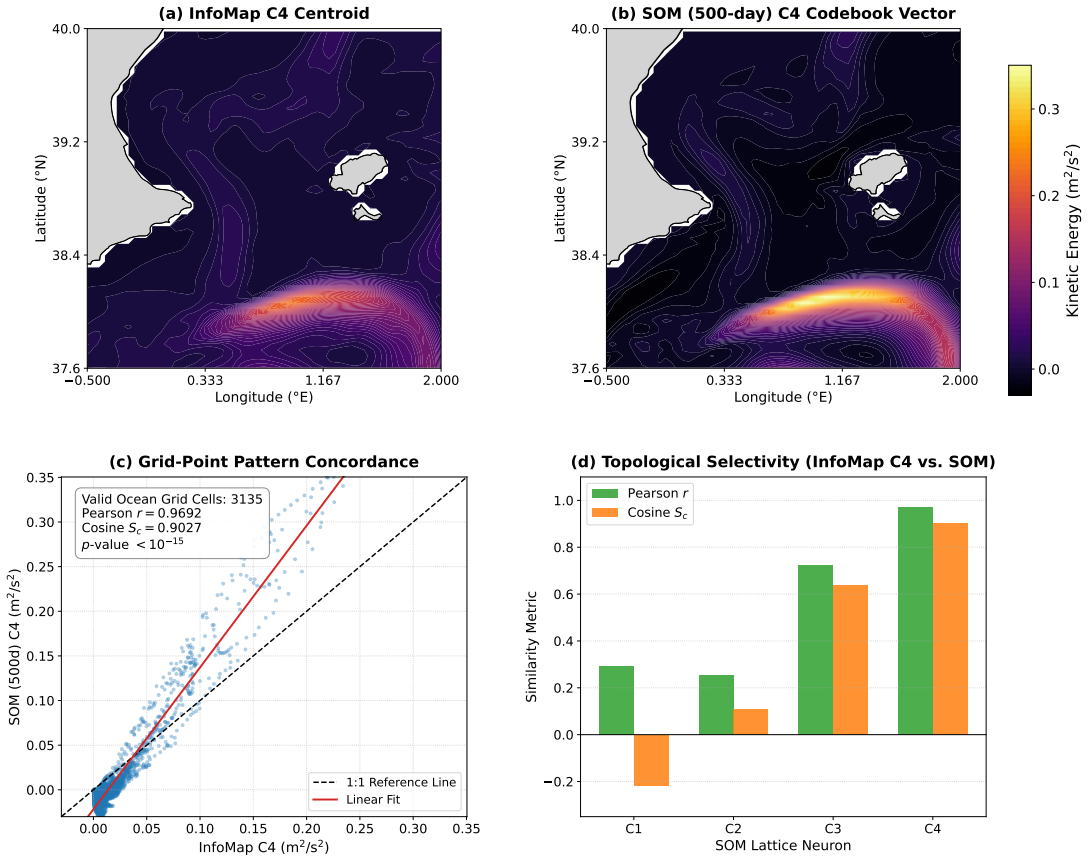


Figure 2: Spatial comparison between InfoMap C4 from the whole dataset and the SOM C4 mode obtained from just the first 500 snapshots of the dataset. (a) InfoMap C4 centroid; (b) SOM (500-day) C4 codebook vector; (c) scatter plot of the 3,135 ocean cells contained in each of the panels a) and b), with a linear fit in red demonstrating the strong correlation between the two cluster representatives; (d) Pearson correlation (r) and cosine similarity (S_c) between InfoMap C4 (full dataset) and each SOM neuron (C1–C4 of the first 500 days).

Major comment 5:

> *"Line 250: Do the authors have considered whether the mean SST signal or the anomalies show some trend in such a long time series? Does the shape or recurrence of any specific pattern change across the climatic time series?"*

This was not one of our objectives in this work, but we can use our results to evaluate decadal changes, as the referee suggests. Figure 3 displays the results, that can be summarized as follows:

- Mean SST increased by $+0.201 \pm 0.054\,°\mathrm{C}$/decade ($p = 6.84 \times 10^{-4}$).
- This warming shifts regime duration: the summer regime (C2) expands by $+5.6$ days/decade ($p < 0.05$), while the winter regime (C3) contracts by -7.2 days/decade ($p < 0.01$).
- Despite these decadal trends, the spatial-structure clusters remain stable. To show this we divided the 1987–2022 study period into two eras of equal duration (Era I: 1987–2004 and Era II: 2005–2022), and recomputed the K-means clusters for each of them. The high spatial Pearson correlation ($r \geq 0.81$) and spatial cosine similarity ($S_c \geq 0.999$) between the clusters in the two eras show that decadal warming alters regime duration, but their spatial patterns remain stable, probably anchored by the underlying topography.

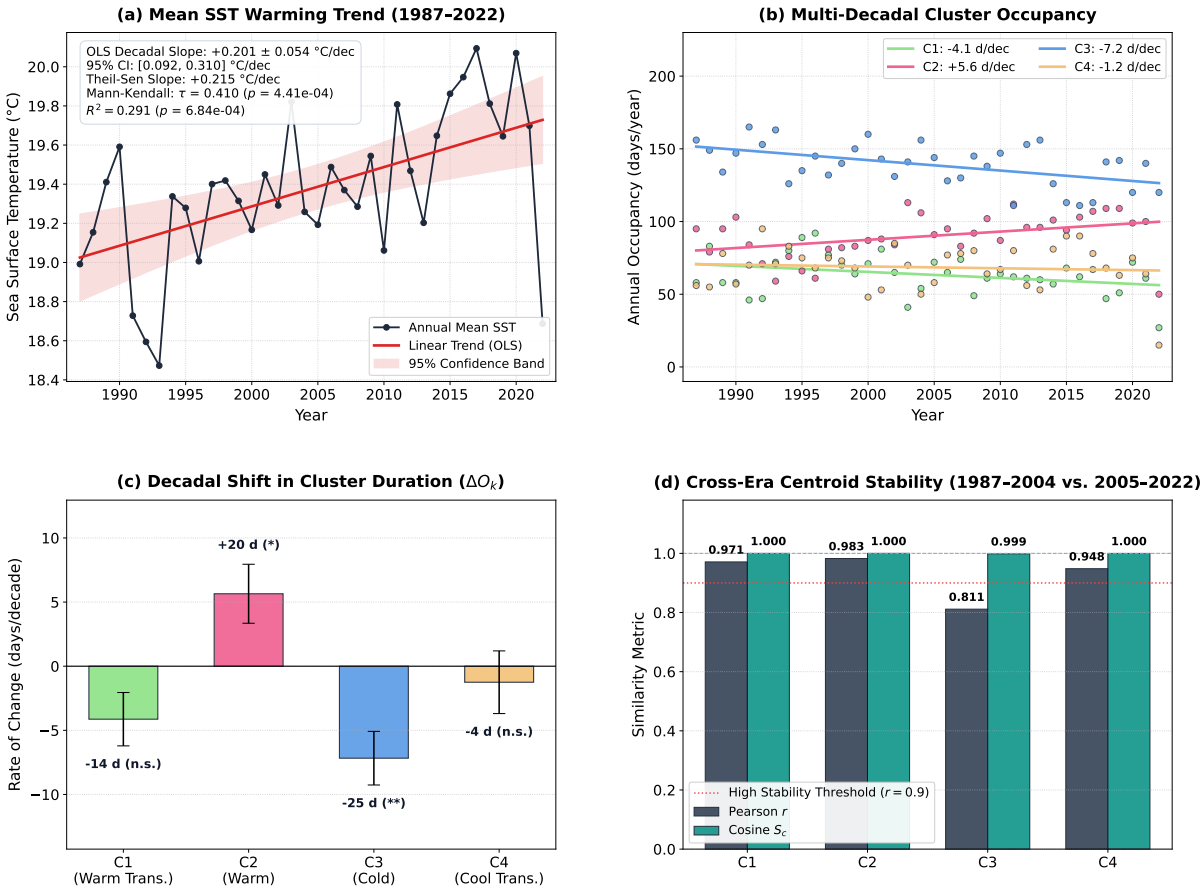


Figure 3: Multi-decadal warming, cluster occupancy dynamics, and centroid morphological stability in the study area (1987–2022). (a) Latitude-weighted annual mean SST with ordinary least-squares fit ($+0.201 \pm 0.054\,^{\circ}$C/decade, $p = 6.84 \times 10^{-4}$) and 95% confidence band. (b) Annual occupancy time series for the SST K-means clusters C1–C4. (c) Decadal rate of change in cluster duration (ΔO_k, days/decade) with standard error bars. (d) Cluster centroids similarity between Era 1 (1987–2004) and Era 2 (2005–2022) for the four clusters, via 2D spatial Pearson correlation (r) and cosine similarity (S_c) across the 3,135 ocean grid points.

Manuscript Revision:
In section 3.2.1, end of section: :

> *"Over the 35-year study period (1987–2022), the domain-averaged SST exhibits a robust warming trend of* $+0.201 \pm 0.054\,^{\circ}C$ *per decade* ($p = 6.84 \times 10^{-4}$, *linear regression; Theil–Sen estimator:* $+0.215\,^{\circ}C$*/decade,* $p = 4.41 \times 10^{-4}$*). This warming signal is accompanied by temporal shifts in cluster occurrence. By tracking annual cluster occupancy, we observe a significant expansion of the warm regime (C2) at* $+5.6$ *days/decade* ($p < 0.05$, *net* $+20$ *days over 35 years) and a concomitant contraction of the cold regime (C3) at* -7.2 *days/decade* ($p < 0.01$, *net* -25 *days). Conversely, the transitional states (C1:* -4.1 *days/decade; C4:* -1.2 *days/decade) exhibit non-significant changes."*

In section 3.2.2:

> *"To assess whether this climatic warming has distorted the spatial morphology of the cluster patterns, we divided the time series into two independent sub-periods (1987–2004 and 2005–2022) and recomputed the detrended SST anomaly centroids. The spatial cross-correlations between the sub-period centroids remain exceptionally high (*$r = 0.971$ *for C1,* $r = 0.983$ *for C2,* $r = 0.811$ *for C3, and* $r = 0.948$ *for C4; all* $p < 10^{-15}$*, with cosine similarity reaching or exceeding* 0.999 *across all regimes. This decoupling demonstrates that the detected long-term trend in the Western Mediterranean operates primarily as a temporal duration shift—prolonging summer stratification while abbreviating winter cooling—while the spatial configuration of internal fronts remains essentially invariant, possibly because of topographic anchoring. "*

Major comment 6:

> *"Conclusions: please further discuss the SST and KE patterns based on the physical properties and circulation reported in literature: analogies, anomalies and climatic trends."*

Author Response:
Section 4 has been rewritten to interpret the statistical clusters within regional dynamics: linking detrended SST modes to the Catalan shelf-slope front, kinetic energy regimes to Northern and Balearic Current circulation, the InfoMap C4 jet to anticyclonic Algerian eddy impingement, and cluster duration shifts to regional warming.
Manuscript Revision:
Section 4 (Conclusions):

> *"By synthesizing unsupervised clustering with established regional oceanography, our findings provide new insight into the hydrodynamics of the Ibiza Channel. The SST clustering captures the seasonal cycle, but when spatially detrended, isolates internal frontal structures that align with the shelf-slope density boundary between the cold Northern Current and warmer offshore waters. For KE, K-means and SOM delineate the classical circulation baseline: the southwestward Northern Current and its northeastward diversion along the Balearic Current, driven by winter baroclinic instabilities. Crucially, the network-based InfoMap algorithm identifies fine-scale circulation anomalies that are smoothed away by variance-minimizing methods. In particular, the rare southern jet anomaly (cluster C4) reflects the signature of open-sea anticyclonic Algerian eddies impinging onto the channel's southern sill, compressing transport into a narrow, high-velocity jet. Finally, our multi-decadal analysis reveals that regional warming manifests*

> *as a significant expansion of the summer regime (+5.6 days/decade) and an equivalent contraction of the winter state (−7.2 days/decade), while the spatial morphology of the internal anomaly patterns remains stable. These findings illustrate the complementary utility of geometric partition and network flow algorithms for operational monitoring, hazard detection, and ecological modeling in mesoscale marine environments."*

Minor comment:

We have straightforwardly corrected the uncompiled reference