Response to Reviewer #1

We are grateful for all the comments received from this reviewer. We think they have substantially improved the quality of the manuscript, and we hope to have addressed the suggestions and recommendations properly. We have also performed an English language review to facilitate the comprehension of the text. Please note that line references are given following the manuscript version published as a preprint.

Introduction

Line 69. You could also refer to Vargas-Yáñez et al, 2017, Progress in Oceanography, doi: 10.1016/j.pocean.2017.09.004

We have added Vargas-Yáñez et al. (2017) at Line 69 alongside the existing references.

Lines 90–95. It would be interesting to include a graph showing trends in the main fish species caught over the same period (1970–2024) as the Norway lobster, since this information is referenced in the discussion. This would also allow for an update to the current Figure 3, focusing on the same period as the physical reanalyses with which it is compared (1987–2024).

We agree that a multi-species comparison would be highly informative. However, the long-term landings series compiled here (1970-2024) was specifically reconstructed for the Norway lobster, combining heterogeneous sources defined in Section 2.2.1. Equivalent multi-source reconstructions for the other commercially relevant species mentioned in the introduction and discussion, such as the deep-water rose shrimp, the blue crab or the European hake, are a project we are actively pursuing but they fall outside the scope of the present study.

Regarding the temporal coverage of Figure 3, we note that the landings series is already restricted to the 1987-2024 period wherever it is directly compared to the temporal pattern of environmental variables EOF analyses (see Fig. 8). We chose to keep the full 1970-2024 series in Figure 3 because this is the first fisheries figure of the manuscript, and it seemed important to give the reader an overview of the long-term historical variability of the Norway lobster catches in GSA 6.

Lines 134–144. Could you provide more information about the characteristics of the Northern Current (such as its depth and seasonal variations)? This information will be useful for analyzing its impact later in this article.

We agree this background is helpful for the subsequent interpretation. We have extended the description of the Liguro-Provençal-Catalan current in Section 2.1 (Lines 121-146). The revised text now specifies the vertical and horizontal dimensions of the jet (approximately 35-40 km wide, centered over the 400 m isobath, with surface velocities of 30-50 cm s^{-1}), its marked seasonal cycle in transport (from ~1 Sv in summer to ~2 Sv in winter) and in mesoscale activity (more active in spring and autumn, decreasing in winter), and its interaction with freshwater inputs from the Rhône and Ebro rivers and with dense water formation and cascading processes in the Gulf of Lion. We also describe how the current is shaped by the irregular shelf morphology of the Catalan margin, incised by several submarine canyons, and how it eventually splits into two branches at the southern end of the Balearic Sea, giving rise to the Catalan and Balearic density fronts discussed later in the manuscript.

Materials and methods

Figure 2. This figure is very clear and important. However, I have some doubts about the position of the Northern Balearic Front. To my knowledge, it should extend eastward rather than northward (toward the Gulf of Lion shelf) (See the paper by Barral et al., 2021, Progress in Oceanography, doi: 10.1016/j.pocean.2021.102636).

We thank the reviewer for this observation but understand the comment refers to Figure 1 of the manuscript. After consulting Barral et al. (2021) and García-Ladona (2016), we agree that the North Balearic Front extends predominantly eastward (north of the Balearic archipelago, towards the Algerian basin) rather than northward toward the Gulf of Lion shelf. We have revised the Figure 1 accordingly, repositioning the arrows to better reflect the patterns of Liguro-Provençal-Catalan current and North Balearic Front, and we now cite both studies in the figure caption.

Section 2.3. You applied an empirical orthogonal function (EOF) decomposition to oceanographic variables over a domain that extends well beyond the boundaries of the GS6 region. I wonder whether the modes obtained would be significantly different if you had applied this decomposition only to the GS6 region.

The choice of the broader NW Mediterranean domain was deliberate and was made for two reasons: (i) the dominant modes of oceanographic variability affecting GSA 6 are basin-scale processes (e.g., the warming and salinization of intermediate waters, the path and recirculation of the Liguro-Provença-Catalan current, the position of the North Balearic Front) that are best characterized when the domain encompasses the regions where these processes originate or terminate; and (ii) restricting the spatial domain to GSA 6 alone would amount to imposing administrative boundaries on a continuum of ocean dynamics, which we considered physically less defensible.

This was, however, a question we had ourselves raised during the elaboration of the study. To verify that the choice of domain did not bias our interpretation, we repeated the EOF decomposition of the environmental variables over the GSA 6 sub-domain only. As an illustrative example, we present here the output for temperature at 400 m depth (Fig. R1): the leading modes are very similar to those obtained over the full NW Mediterranean domain, with a spatially homogeneous pattern dominated by the same decadal signal.

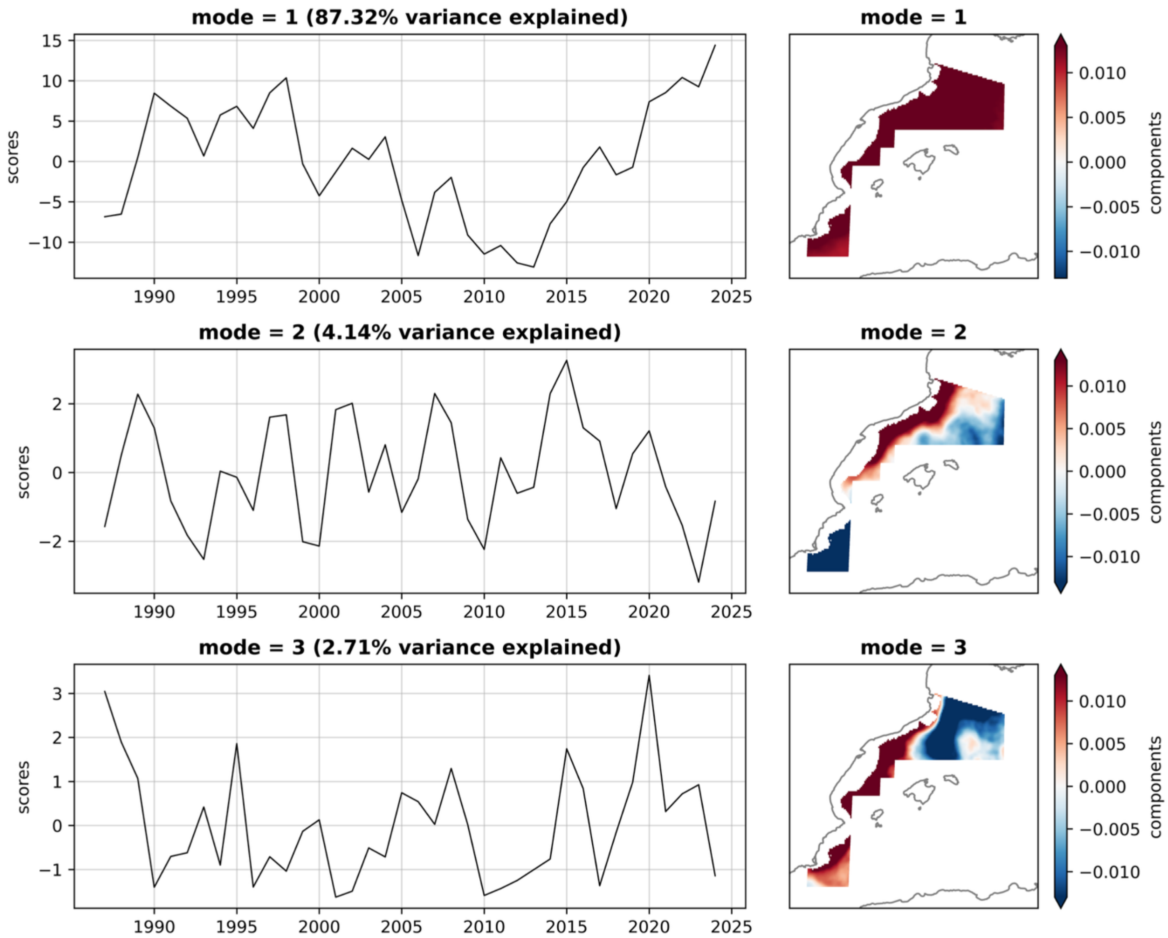

Figure R1. EOFs of T400 over the GSA 6 sub-domain only.

Lines 210-211. Change 'complete time series between 1987 and 2024' by 'complete monthly time series for the period from 1987 to 2024'.

We have modified the sentence as suggested. The text now reads: "[…] for the complete monthly time series for the period from 1987 to 2024."

Lines 226,229. You use a local coordinate rotation to define along-slope and cross-slope velocity components from the horizontal currents (u, v). While this is a reasonable first-order approximation in areas with relatively straight bathymetry, it may not adequately capture the dynamics of the northern current and the Balearic current in the topographically complex NW Mediterranean. A bathymetry-based decomposition would provide a more physically consistent representation of the flow, because the along-slope direction is expected to follow the local contour lines of the continental slope rather than a fixed geographic axis. […] The main along-slope current will remain a continuous, coherent feature in the u_along variable, even as it curves around the Gulf of Lion and recirculates in the Balearic Sea.

We thank the reviewer for this methodological suggestion, which prompted a robust analysis that has strengthened the manuscript. We agree that a bathymetry-based decomposition is, in principle, a more physically consistent representation of along- and cross-slope flow in topographically complex regions. We therefore implemented the decomposition following the formula suggested by the reviewer: the GEBCO 2024 bathymetry was smoothed with a 2D Gaussian filter, the gradient ∇H was computed with xarray.differentiate, and the horizontal velocity field was projected onto the local along- and cross-slope unit vectors at each grid cell. The EOF decomposition was repeated on the resulting u_along fields at surface, 200 m, 400 m and 600 m using the same procedure and package (xeofs) as in the main text. The full results are now reported in the new Appendix B.

The bathymetry-based decomposition yields spatially cleaner along-slope patterns at 200 m and 600 m, as anticipated by the reviewer. Importantly, the two selected EOF modes retained in Table 1 of the main text, the second mode of along-shore velocity at the surface (U_{surf} [2]) and at 200 m (U_{200} [2]), remain significantly correlated with landings (p=0.002 and p=0.006, respectively) and with LPUE (p=0.004 and p=0.004) in the bathymetry-based framework, with comparable magnitudes to those obtained with the fixed-axis rotation (Fig. 6 of the main text). This confirms that the association between a weakening of the Liguro-Provençal-Catalan current and the decline of Norway lobster landings and LPUE is robust to the choice of reference frame.

Interestingly, the negative correlations that the fixed-axis rotation produced at 400 m and 600 m (U_{400} [2], U_{600} [2]; Fig. 6 of the main text) become marginally significant or non-significant in the bathymetry-based decomposition (Table B1 in Appendix B). These modes had not been selected for interpretation in Table 1, but this comparison suggests that at least part of the sign reversal at deeper levels was likely associated with the choice of a single fixed rotation angle applied over the whole basin and provides an a posteriori justification for having restricted the interpretive discussion to the surface and 200 m modes. We have chosen to retain the fixed-axis rotation in the main text for two reasons: first, because it produces a coherent joint pattern of the Liguro-Provençal-Catalan current and the recirculation north of the Balearic Islands within a single mode (Fig. 7d of the main text), which makes the physical interpretation of the Catalan-Balearic circulation system more direct; and second, because the interpretive conclusions of the study are unchanged by the alternative decomposition. To address the reviewer's comment on the physical justification of the rotation, we have also strengthened Section 2.3: it now makes explicit that the -210° angle was chosen so that the positive x-axis aligns with the dominant southwestward transport of the Liguro-Provençal-Catalan current along the Catalan continental slope, which is the region most relevant to the Norway lobster fishery in GSA 6.

Lines 416–419. Do you have any references to support this finding linking the increase of temperature (and salinity) at 400 m with the decrease of the Northern Current at 200 m? Besides, the opposite behavior of the Balearic Current compared to the Northern Current is likely related to the choice of axis rotation. This will probably change using the new along- and cross-slope reference frame.

Regarding the correlation between the warming and salinization at 400 m and the weakening of the Liguro-Provençal-Catalan current at 200 m, we are not aware of a published study that directly links these two signals in the NW Mediterranean; to our knowledge, this is an association identified in the present study rather than a previously documented relationship. We note, however, that a plausible physical link exists between the two: a weaker Liguro-Provençal-Catalan current is symptomatic of a slower basin-scale circulation, which is also associated with reduced winter convection and with the accumulation of warmer, saltier Levantine Intermediate Water (LIW) at intermediate depths (Margirier et al., 2020; Somot et al., 2018). We consider the physical coupling between basin-scale circulation strength and intermediate-water properties a direction for future work.

Regarding the choice of axis rotation, please see our detailed response to the comment on Lines 226 and 229. As shown there (Appendix B), the along-slope mode capturing the Liguro-Provençal-Catalan current and its recirculation north of the Balearic Islands remains significantly correlated with landings and LPUE under the bathymetry-based decomposition, confirming that this behavior is a robust physical feature rather than an artefact of the fixed-axis rotation.

Results

Figure 3. It would be preferable for these time series to cover the same period as the environmental data (i.e., 1987–2024), in order to improve comparability and avoid any confusion arising from different time scales. The complete time series (1970–2024) should be presented in a separate figure in the introduction, alongside the landing data for the other relevant species mentioned in the state-of-the-art review.

We understand the rationale of harmonizing the periods between the fisheries and environmental data. However, we would like to keep Figure 3 covering the full 1970-2024 period because this is the first fisheries figure of the manuscript and it gives the reader an initial overview of the long-term historical variability of Norway lobster catches in GSA 6, the context in which the recent post-2014 decline should be interpreted. Wherever the fisheries series is compared to the temporal pattern of the environmental EOFs, the temporal coverage is already restricted to the 1987-2024 period (see Fig. 8 of the main text). Regarding the suggestion to present the 1970-2024 series alongside landings of other relevant species, please see our response to the comment on Lines 90-95.

Figure 5. Can you explain how the temperature anomaly is calculated? It would be interesting to add a plot of the average temperature to these graphs.

In the revised version of the manuscript, we have added an explicit definition of the temperature anomaly in Section 2.2.4. The anomaly at depth z and year y is computed as the deviation of the annual mean temperature at that depth (averaged over the horizontal extent of GSA 6) from the climatological mean at the same depth over the full 1987-2024 period,

$$\mathrm{T}'(\mathrm{z},\mathrm{y}) = \langle \mathrm{T}(\mathrm{z},\mathrm{y}) \rangle - \langle \mathrm{T}(\mathrm{z}) \rangle_{1987\text{--}2024}$$

where $\langle\cdot\rangle$ denotes the spatial average over GSA 6. Positive (red) values in Figure 5 therefore indicate that the annual mean temperature at that depth was warmer than the long-term average, while negative (blue) values indicate cooler conditions.

Following the reviewer's suggestion, we have also added a side panel to Figure 5 showing the mean vertical temperature profile $\langle \mathrm{T}(\mathrm{z}) \rangle_{1987\text{--}2024}$, so that the anomalies can be interpreted against their absolute reference, together with a shaded band indicating the ±1 standard deviation across years. The caption of Figure 5 has been updated accordingly.

Line 323. Replace 'The resulting cross-correlation matrix (Fig. 6)' with 'The resulting cross-correlation matrix for landings (Fig. 6)' for clarity, since you describe the cross-correlation for LPUE later on.

We have made the suggested edit. The text now reads: "The resulting cross-correlation matrix for landings (Fig. 6) […]".

Table 1. You sometimes use 'Liguro-Provençal-Catalan Current' and other times 'Northern Current' in the table and elsewhere in the text. You should standardize the terminology and, once the two terms have been introduced in section 2.1, use only one of them.

We have standardized the terminology throughout the manuscript. Both names are introduced together in Section 2.1, and the term "Liguro-Provençal-Catalan current" is used consistently in the rest of the text, in Table 1 and in all figures and corresponding captions.

Line 369. Rather than writing 'changes in the mean climate' which suggests that you are also taking the long-term trend into account, I suggest writing 'fluctuations of the mean climate' to make it clear that these are deviations from that long-term trend.

We have replaced "changes in the mean climate" with "fluctuations of the mean climate" as suggested, to emphasize that these are deviations from the long-term trend that we have subtracted prior to the EOF decomposition.

Lines 397–399. Regarding the modes associated with currents, please refer to my previous comment on the use of bathymetry-based decomposition.

We refer the reviewer to our detailed response to the comment on Lines 226-229. In brief, the bathymetry-based decomposition has been implemented, and its EOF results are reported in the new Appendix B. The two along-shore modes retained for interpretation in the main text (U_{surf} [2] and U_{200} [2]) remain significantly correlated with landings and LPUE under the bathymetry-based framework ($p \leq 0.006$ in all cases; Table B1), confirming that these findings are robust to the choice of reference frame. The justification of the fixed-axis rotation has also been strengthened in Section 2.3, making explicit that the -210° angle is selected to align the x-axis with the dominant southwestward transport of the Liguro-Provençal-Catalan current along the Catalan continental slope.

Discussion

Section 4.2. Although there is a strong correlation between global warming and a decrease in LPUE, as well as an increase in the depth at which LPUE is at its maximum, I believe the authors should also highlight the rise in salinity and the decline in oxygen concentration (not documented here but a real phenomenon), whose current levels are approaching the tolerance thresholds of the Norway lobster. […] These two factors, whether considered separately or together, may be just as important – or even more so – than temperature, whose current values fall in the middle of the tolerance range.

Regarding salinity, we agree it deserves more emphasis. Sections 4.2 and 4.4 have been expanded to discuss temperature and salinity jointly as tracers of the changing thermohaline properties of the intermediate layer, specifically the accumulation of warmer and saltier LIW documented by Margirier et al., 2020. Within this water-mass framing, both variables are interpreted as a combined signature of a shifting physical envelope experienced by the Norway lobster, rather than as independent drivers.

Regarding oxygen, we agree that dissolved oxygen is a plausible additional stressor for the Norway lobster and should not be overlooked. However, oxygen was not among the environmental variables analyzed here, and any statement on its recent trend in GSA 6 would require a dedicated biogeochemical reanalysis or in-situ time series beyond the scope of this work. A sentence has been added in Section 4.5 acknowledging oxygen, together with other biogeochemical variables not analyzed here, as factors worth incorporating in future studies of Norway lobster in the region.

Section 4.3. The time series you are analysing represents deviations from the long-term thermohaline trends that you have subtracted from your data. However, these trends are truly significant and have *resulted in increases over three decades of approximately 1 °C in temperature and 0.15 g/kg in salinity. […] I am trying to understand why the dynamics of this species, as observed through catches and landings, would be more sensitive to decadal fluctuations in environmental conditions, particularly temperature and salinity as noted in your work, than to long-term increases, which are even more pronounced.*

This is an important point, and we agree that the long-term trend itself deserves more explicit attention in the manuscript. The reason we de-trended the series before applying the EOFs was methodological: we were specifically searching for modes of inter-annual to decadal variability that could be put into correspondence with the equally low-frequency fluctuations of Norway lobster landings, which show a near-decadal increase from the mid-1990s to the early 2010s and a pronounced decline since, superimposed on a comparatively modest long-term trend.

Section 4.3 has been expanded in two directions. First, the magnitude of the recent warming and salinification of intermediate waters in the NW Mediterranean is now discussed explicitly, drawing on the values reported for the LIW by Margirier et al. (2020), and it is highlighted that the leading EOF modes of temperature and salinity reveal a positive phase becoming particularly pronounced after 2014, consistent with the regime shift documented by Margirier et al. (2020). Second, we discuss why the species response may currently be more visible in the decadal fluctuations than in the underlying long-term trend. The Norway lobster is a long-lived, slow-growing species (Sardà, 1998; Vigo et al., 2024), whose population dynamics integrate environmental conditions over several recruitment cycles. A smooth, monotonic trend is therefore expected to elicit a gradual response, partly buffered by the demographic inertia of long-lived populations (Perry et al., 2010). In contrast, the more abrupt regime change captured by the mode-1 scores after 2014 acts on top of this underlying trend and pushes thermohaline conditions beyond the range historically experienced by the species, plausibly triggering the marked decline observed in landings.

The link between this section and the outlook (Section 4.6) has also been strengthened, so that the projected +1.5 °C warming by 2030-2052 (IPCC, 2018) is read as superimposed on, rather than separate from, the trends documented here.

Lines 543–548. […] I suggest the authors consider, or at least discuss, the potential of Archetypal Analysis – AA – (Cutler & Breiman, 1994, Technometrics). AA could offer several advantages over the current EOF framework: AA identifies archetypes which are extreme and representative states of the system […]; AA does not impose orthogonality, allowing it to better capture the actual co-variability of the environmental 'envelope'; AA is particularly suitable to see how a system migrates between archetypal profiles over time.

We agree that Archetypal Analysis (AA; (Cutler and Breiman, 1994) is a valuable complement to the EOF framework because it identifies extreme, physically interpretable states of the system rather than statistical axes of orthogonal variance, does not impose orthogonality, and is well suited to describe how a system migrates between regime-like configurations over time.

Following this suggestion, we have implemented AA on the annual, de-trended fields of temperature, salinity and along-slope velocity at 400 m depth in the study region, using K = 3 archetypes. The methodology and full results are reported in a new Supplement to the manuscript and briefly discussed in Section 4.5, where it serves as an independent robustness check of the regime shift interpretation drawn from the EOFs.

In brief, the three archetypes identify a warm-saline state (Archetype 1), a cold-fresh state (Archetype 3), and a transitional state with an intensified Liguro-Provençal-Catalan current (Archetype 2); their time-varying weights reveal a clear migration of the system from the cold-fresh state dominant between 2005 and 2015 to the warm-saline state dominant from 2018 onwards, strongly and significantly correlated with the Norway lobster landings ($r = -0.88$ and $r = +0.69$ respectively; $p < 0.001$).

We also acknowledge that AA has its own methodological limitations (user-defined K, archetypes representing hypothetical extreme states, lower fraction of variance explained than the leading EOFs, and dependence introduced by the sum-to-one constraint on the weights). For these reasons, we have chosen to retain the EOF analysis as the backbone of the main text and to present the AA as a complementary regime-shift interpretation. The two approaches converge on the same central finding: the intermediate water column of the NW Mediterranean has migrated from a cold-fresh to a warm-saline regime since the mid-2010s, in parallel with the observed decline of Norway lobster landings and LPUE in GSA 6.

Line 483. You can also refer to Houpert et al., 2016, Journal of Geophysical Research, doi: 10.1002/2016JC011857

We have added (Houpert et al., 2016) at Line 483 in support of the description of deep convection and the warming and salinization of intermediate waters in the NW Mediterranean.

Lines 490–491. You hypothesize that increased stratification and reduced winter convection lead to a decrease in the flux of organic matter to deeper layers. I agree with this idea, but do you have any references to support it?

We agree that this statement requires explicit support. Section 4.3 has been revised to make the mechanism more explicit and to include a supporting reference. The paragraph now clarifies that a weakening of deep convection reduces both the vertical export of particulate organic matter from the euphotic zone to the sea floor and the resuspension of near-bottom material by dense water reaching the sea floor, the latter being documented by (Durrieu de Madron et al., 2017) for the NW Mediterranean. In addition, Margirier et al. (2020), already cited in the same section, reported that the accumulation of warmer and more saline LIW between 2014 and 2017 was accompanied by weakened winter convection and by an impact on the surface phytoplankton dynamics, consistent with a reduced vertical export of organic matter during that period.

Lines 499–500. You are assuming that a slowdown in the slope current would result in less transport toward the seafloor. This argument remains vague. Could you elaborate on it?

We agree the argument was too compact in the original version. The relevant passage in Section 4.3 has been rewritten to make the mechanism explicit. A weakening of the Liguro-Provençal-Catalan current at 200 m implies reduced lateral advection of organic matter from the productive Gulf of Lion and the coastal areas along the Catalan slope, together with reduced mesoscale activity at the shelf-slope front, which has been shown to enhance vertical fluxes of organic matter across such fronts (Lévy et al., 2018; Palanques et al., 2006; Severin et al., 2014). Combined with the reduced winter convection discussed in the same section, these mechanisms coherently reduce the supply of organic matter to the benthic habitat where the Norway lobster is fished.

Lines 516–524. This paragraph partly repeats arguments already presented in the previous section (the potential role of warming and the decrease in winter convection) and does not provide any further evidence. To strengthen these hypotheses, it would be interesting to present long-term time series covering the same period as the landings (i.e., between 1970 and 2024) showing the evolution of temperature and salinity in the intermediate waters, as well as the variability of winter convection (see, for example, Somot et al., 2016, Climate Dynamics, doi: 10.1007/s00382-016-3295-0).

We agree with the reviewer that the original paragraph was partly redundant with Section 4.3. Section 4.4 has been revised to remove the duplicated explanation of the physical mechanism, which is now developed in detail in Section 4.3, and to focus in Section 4.4 on the temporal correlation between the environmental variability and the observed fluctuations in Norway lobster landings.

Regarding the reviewer's suggestion of presenting continuous long-term time series of intermediate-water temperature and salinity and of winter convection covering the full 1970-2024 period, to our knowledge no observation-based continuous time series covering this window is currently available for the intermediate waters of the NW Mediterranean, which is one of the reasons we rely on the CMEMS reanalysis from 1987 onwards. A brief reference to Somot et al. (2016) has been added in Section 4.4 to anchor the observed acceleration since 2014 within the multi-decadal variability of NW Mediterranean deep-water formation documented in that modelling study. In future work, we will investigate the availability of additional observational sources that could allow the environmental analysis to be extended further back in time.

Line 534–540. Once again, it may be necessary here as well to consider the effects of salinity and oxygen concentration, which might be more limiting for the ecological niche of the Norway lobster.

The first of the open questions at the end of Section 4.4 has been reformulated to explicitly consider the joint effect of the concurrent warming and salinization of intermediate waters, rather than temperature alone. This is consistent with the revised framing of Section 4.2, which now interprets temperature and salinity jointly as a thermohaline signature of changes in the LIW. Regarding oxygen, please see our response to the comment on Section 4.5, where we acknowledge dissolved oxygen and other biogeochemical variables as factors worth incorporating in future studies of Norway lobster in the region.

Line 546. You may refer to the work by Fos et al., 2025, Ocean Science, doi: 10.5194/os-21-2169-2025, which demonstrates that the reanalysis successfully reproduces observed intense dense shelf water cascading events in the Gulf of Lion. It might be worth applying an archetypal analysis – Cutler & Breiman, 1994, Technometrics, doi: 10.2307/1269949 – to your dataset.

We have added (Fos et al., 2025) at Line 546 to support the statement that the CMEMS reanalysis adequately reproduces observed mesoscale and submesoscale features such as intense dense shelf-water cascading events in the Gulf of Lion. Regarding the application of Archetypal Analysis, please see our detailed response to the related comment on Lines 543-548 above: AA has been implemented and its results are now reported in Supplement and discussed in Section 4.5.

Lines 585–586. Rather than speaking of 'widespread warming and salinization at depth' I would say that this is a 'widespread acceleration of warming and salinization at depth,' as this pattern is in addition to the long-term upward trend.

We have modified the sentence as suggested. The conclusions now read: "[…] widespread acceleration of warming and salinization at depth are associated with reduced catches", to make explicit that this pattern occurs on top of the long-term thermohaline trend already documented for the NW Mediterranean intermediate waters.

Closing remarks

We thank the reviewer once again for the detailed and constructive comments, which have led to a substantially clearer and more robust manuscript, in particular through the bathymetry-based decomposition exercise now reported in the appendices, the addition of an Archetypal Analysis complementing the EOF framework as a Supplement, the strengthened discussion of salinity (and of long-term trends), and the various improvements to the figures, terminology and wording.

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