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Long-term variability of Norway lobster (*Nephrops norvegicus*) landings in relation to a changing climate in the Northwestern Mediterranean Sea.

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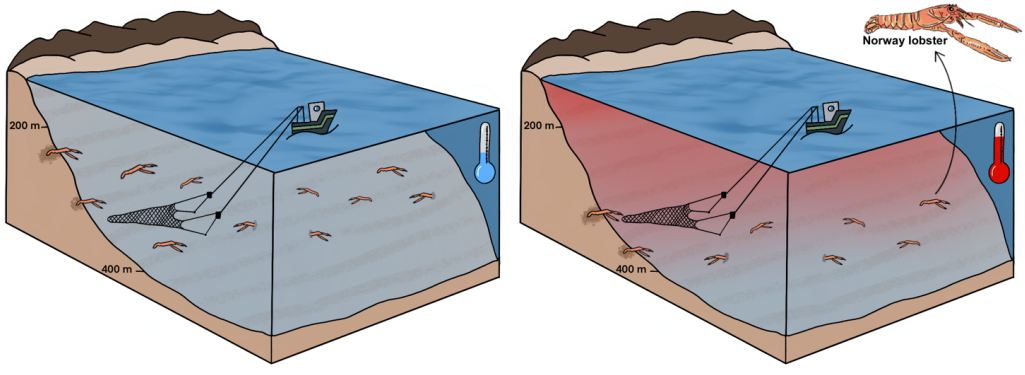
Abstract

Understanding how environmental variability shapes the dynamics of demersal resources is essential for sustainable fisheries management in climate-sensitive regions such as the Northwestern Mediterranean Sea. This study analyses more than five decades (1970–2024) of Norway lobster (*Nephrops norvegicus*) landings in FAO GSA 6 to identify the drivers underlying its decadal variability and the sharp decline observed since the mid-2010s. Fishery-dependent data (landings, Landings Per Unit of Effort (LPUE), depth distribution, and fishing effort) was combined with oceanographic descriptors. Empirical Orthogonal Functions (EOFs) were applied to temperature, salinity, along-shore and across-shore currents at surface, 200 m, 400 m, and 600 m to extract dominant modes of oceanographic variability and assess their correlation with fisheries indicators. The most relevant physical signal was a widespread warming and salinization of intermediate waters, captured within its EOF first modes, that showed the strongest negative correlation with landings and LPUE. Positive phases of these modes corresponded to positive thermal and salinity anomalies and coincided with declining LPUE, a slight deepening of its centroid (depth of maximum LPUE), and reduced landings. These results indicate that intermediate-water warming and salinization might be a key mechanism constraining the Norway lobster catchability. Circulation changes also seemed to influence LPUEs. The second EOF mode of along-shore velocity at 200 m captured variability in the Liguro-Provençal-Catalan current and the North Balearic Front. Its positive phases, reflecting a strengthened boundary current and enhanced recirculation north of the Balearic Islands, were positively correlated with landings, suggesting that frontal dynamics may modulate habitat suitability, for example. Overall, the recent decline of the Norway lobster landings cannot be attributed to fishing effort alone but is also linked to climate-driven changes in intermediate-water physical characteristics. These findings highlight the need to integrate oceanographic indicators into stock assessments to anticipate further climate-induced shifts in demersal resources.



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Keywords

Climate fluctuations

Demersal fisheries

EOFs (Empirical Orthogonal Functions)

Fishery-dependent data

Fisheries environment

Nephrops norvegicus

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1. Introduction

The ocean climate naturally fluctuates on different temporal scales (Munn, 2002). Climate variability derived from anthropogenic activity is causing an additional stress to the marine environment as a consequence of ocean warming, acidification, changes in primary production, oxygen concentration and circulation, among others (Chust et al., 2024; Rhein et al., 2013). Marine species are sensitive to climate change at both organism and population level, meaning that they are directly influenced by the changing environment around them, which they compensate by colonizing new territories (Pinsky et al., 2020). This is causing a rapid redistribution of marine species (Pecl et al., 2017; Pinsky et al., 2020), causing them to move towards the poles, deeper waters, or other directions searching for environmental conditions more suitable for their biological needs (Chen et al., 2011; Parmesan & Yohe, 2003; Perry et al., 2005). Climate change is not only altering the distribution of the species but also their abundance causing, for example, tropicalization or deborealization, that is an increasing abundance of warm-affinity species or decreasing abundance of cold-affinity species (McLean et al., 2021; Zarzyczny et al., 2024). These effects are occurring globally, but not uniformly, and they become especially relevant in some regions considered “hotspots” for climate change (Bilbao et al., 2019), such as the Mediterranean Sea (Giorgi, 2006).

The Mediterranean Sea is a semi-enclosed basin with an overall cyclonic density-driven circulation where deep convection occurs (Millot & Taupier-Letage, 2005). The residence time of its waters is 10 times shorter than those of the global ocean (Durrieu de Madron et al., 2011) and the response to weather-related stress is amplified (Cacho et al., 2002). The Mediterranean Sea is thus a key region to observe the effects of climate change. Warming and salinization of the Mediterranean Sea has been reported in many studies (Adloff et al., 2015; Margirier et al., 2020; Schroeder et al., 2017). For example, temperature has increased at rates of 0.35°C–0.37°C per decade over the last 40 years (Pastor et al., 2020; Pisano et al., 2020). These environmental trends alter the marine-community composition, and can lead to changes in fisheries’ catch composition (i.e. tropicalization of the catch, Vergés et al., 2014), affecting the fishing resources and the socioeconomics of the sector (Perry et al., 2005; Pinsky et al., 2021). In the Northwestern (NW) Mediterranean Sea, the deep-water rose shrimp, *Parapenaeus longirostris* (Lucas, 1846), expanded northwards and increased its abundance becoming one of the most caught species by the bottom-trawling fleet in the recent years (ICATMAR, 2025; Mingote et al., 2024). High climate variability in Mediterranean waters has favored this species distribution, but these environmental changes may affect other target species differently. This may

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be the case of the Norway lobster, *Nephrops norvegicus* (Linnaeus, 1758), that has experienced a decline in catches in the last decade in the NW Mediterranean (ICATMAR, 2025; Vigo et al., 2024).

The Norway lobster is a benthic decapod crustacean found in the northeastern Atlantic Ocean and in the central-western Mediterranean Sea, inhabiting muddy bottoms at depths from 20 to 800 meters across a wide range of environmental conditions (FAO, 2025). In the Mediterranean Sea, populations are mainly found on the upper slope, between depths of 300 and 600 m (Abelló et al., 2002; Maynou & Sardà, 1997). The species is described to tolerate temperatures between 6.4 and 17.3 °C, oxygen concentrations ranging from 5.9 to 9.4 mg O_2 mg L^{-1}, and salinity levels between 31.8 and 38.8 g Kg^{-1} (Johnson et al., 2013), being also influenced by the seasonal and diel (day/night) cycles (Aguzzi et al., 2003). These effects may vary with depth, where light intensity is reduced (Aguzzi et al., 2009), affecting populations and their behavior. Environmental conditions may play a key role in influencing hatching and larval settlement, and consequently their catch. Global catches of the Norway lobster have been reported since 1980 with a total worldwide of 50,869 t in 2023, making it one of the most valuable fisheries in all European waters (FAO, 2025). In the NW Mediterranean Sea, this fishery resource, mainly fished by bottom trawlers together with other species (Sardà, 1998), has lost importance both in landings and revenues between 2008 and 2024, with a reduction of 57% and 50%, respectively (ICATMAR, 2025). Moreover, total annual catches have been surpassed by other species that 10 years ago were not present in catches, such as the blue crab, *Callinectes sapidus*, or by other species whose landings have increased exponentially, such as the deep-water rose shrimp.

In 2018, the European Union (EU) implemented the Western Mediterranean Multi-Annual Plan (WMMAP) through regulation COM/2018/0115 final - 2018/050 (COD), aiming to promote sustainable fishing and secure associated economic, employment, and social benefits. In the NW Mediterranean, the WMMAP covers the most commercially important demersal species (i.e., the red mullet, the European hake, the deep-water rose shrimp, the Norway lobster, and the blue and red shrimp), providing a framework for their sustainable management. Considering its importance as a fishery resource and the observed reduction in catches in recent years, the aim of this work was to determine the factors driving the fluctuations in Norway lobster catches over more than 50 years (i.e., 1970-2024) and the declining trend observed in the last 10-15 years in the Food and Agriculture Organization (FAO) Geographical Subarea 6 (GSA 6). This work evaluates the time series of landings and Landings Per Unit of Effort (LPUE) of the Norway lobster, including its distribution in depth. Then, fishing effort and environmental variables are examined and correlated to landings and LPUE trends.

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2. Materials and methods

2.1. Study area

The study area considers the NW Mediterranean Sea, focusing on fishery-dependent data from the GSA 6 Fig. 1), which extends from Cape Creus to Cartagena, as defined by the General Fisheries Commission of the Mediterranean (GFCM; EU 1343/2011; Resolution GFCM/33/2009/2).

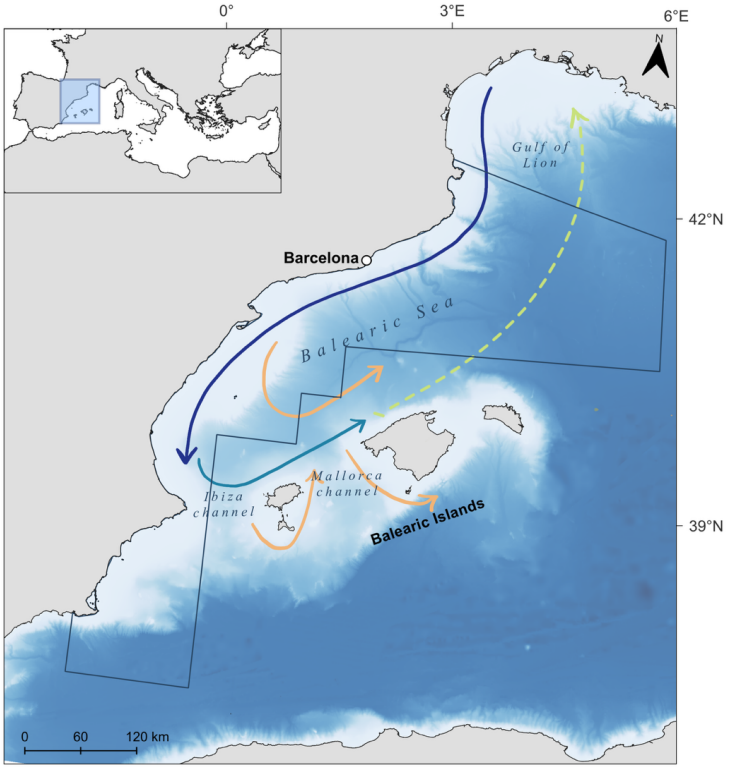

Figure 1. Study area indicating the geographical limits of the GSA 6. Surface currents are indicated in different colors: Liguro-Provençal-Catalan current, in solid blue; recirculation in solid light blue; North Balearic front in dashed light green; permanent path in solid orange. Information adapted from Millot & Taupier-Letage (2005).

An important oceanographic feature of the NW Mediterranean Sea is the Liguro-Provençal-Catalan current also known as “Northern Current” (Castellón et al., 1990). This current originates in the Ligurian Sea and flows southwestward along the northern edge of the NW Mediterranean Sea while receiving input from major rivers. As the Liguro-Provençal-Catalan current reaches the end of the Balearic Sea and the shallower ridge created by the Balearic Islands, a fraction of the current retroflects northwestward along the northern sides of the

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islands, while other fractions continue south through Ibiza and Mallorca channels (Fig. 1; see also Balbín et al., 2014). This general circulation creates two main density fronts. While the Catalan front is associated with strong salinity gradients created by the Liguro-Provençal-Catalan current, the Balearic front is formed by temperature gradients between the cooler retroflection and the warm waters surrounding the Balearic Islands. In the central area of the Balearic Sea between those two frontal systems, instabilities generated by cyclonic eddies keep the stratification weak (Font et al., 1988).

2.2. Dataset

2.2.1. Landings and Landings Per Unit of Effort time series

Data on the Norway lobster landings from 1970 to 1986 were obtained from the official Spanish Fishing Statistics (*Estadística de Pesca*) and Yearbook of Maritime Fishing (*Anuario de Pesca Marítima*) from the *Subsecretaría de la marina mercante* later called *Subsecretaría de pesca y marina mercante* of the Spanish Government. The Spanish annual demersal landings statistics were collected from 1933 to obtain national information on landings and effort for statistical purposes, but the compilation stopped in 1986 after the entry of Spain into the European Union (Punzón et al., 2020). In these books, data are aggregated in eight regions (*Balear*, *Canaria*, *Cantabrica*, *Levantina*, *Noroeste*, *Surmediterranea*, *Suratlántica* and *Tramontana*), with values provided for the provinces included in each of them. Only data from provinces within the GSA 6 area were considered for this study, i.e. Girona, Barcelona, Tarragona, Castelló, Valencia, Alacant and Murcia.

Landing data from 1987 to 2003 were extrapolated to the whole GSA 6 area based on existing landings data from Catalonia (Martín, 1991) and daily commercial fishing landings provided by the Catalan government (Department of Climate Action, Food and Rural Agenda). The extrapolation consisted in defining a relation factor between landings in Catalonia and GSA 6 the years when data were available in both cases (1970-1986, 2004-2024). For data between 1987 and 1999, the relation factor defined was 1.58 and was calculated averaging data from 1980 to 1986. For years 2000 to 2003, the relation factor used was 1.29 and was calculated averaging data from 2004 to 2007. The use of two different relation factors was determined after evaluating the available trends for Catalonia landings data.

Data from 2004 to 2024 were obtained from landings of the Spanish Fisheries Secretariat (*Secretaría General de Pesca,* SGP, Spanish Government). As described in Mingote et al. (2024), in the Spanish Mediterranean, landings are sold fresh daily at the fishing auctions, providing information on the economic value and the total

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kg by each landed species. These data are gathered by the SGP and later processed by the Catalan Institute of Research for the Governance of the Sea, ICATMAR (ICATMAR, 2025; Ribera-Altimir et al., 2023) for the GSA 6 region. Finally, the landing time series for the three periods (1970-1986, 1987-2003, and 2004-2024) were merged into a single dataset.

For obtaining LPUE time series from 2008 to 2024, we followed the procedure described in Mingote et al. (2024) and briefly summarized here. Vessel Monitoring System (VMS) data for the trawling fleet were analyzed following the methodology described in Sala-Coromina et al. (2021) for obtaining information on georeferenced vessel hauls and fishing time in hours. Then, VMS and landing data were joined resulting in a dataset with information on the Norway lobsters' landings and total fishing time for each vessel fishing haul. Then, the variables were aggregated yearly for the whole fleet in a 1 km^2 grid (EPSG 4326) on the GSA 6 area, enabling the calculation of LPUE (kg h^{-1} km^{-2}) averaged per year.

2.2.2. Fishing effort trend

Fishing efforts from 2004 to 2024 were estimated using data on the number of fishing trips and vessels operating in the bottom-trawl fleet. In the study area, vessels operate in the vicinity of each port and land their catch daily (Carreton et al., 2025). Accordingly, a fishing trip, also referred to as a fishing day, is defined as the period between a vessel's departure from port and its return, occurring within the same day. Fishing trips are identified using a unique vessel identifier and the date of the activity. Information on both the number of vessels from the bottom-trawl fleet in the GSA 6 area, and the fishing trips conducted was obtained from the SGP landings database.

2.2.3. LPUE depth distribution and centroid depth

LPUE data were associated with bathymetric data obtained from the General Bathymetric Chart of the Oceans (GEBCO) portal, with a spatial resolution of 15 arcsec (GEBCO Compilation Group, 2024). Depth values were extracted from the bathymetry shapefile and joined with georeferenced LPUE (1 km^2 grid described above) to obtain the depth of each grid point. Data were aggregated by year and depth for representing the distribution of averaged LPUE values in depth. Then, the centroid depth, or average depth where most of the LPUE occurs, was calculated yearly following this formula:

$$\text{Centroid depth} = \frac{\sum_i (LPUE_i \cdot z_i)}{\sum_i LPUE}$$

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where Σ_i refers to a sum on all 1 km^2 pixels with LPUE values for a certain year ($LPUE_i$), and z_i refers to the depth of the sea floor at that location (i.e., where the fishing occurs).

2.2.4. Environmental data

Monthly fields of the Mediterranean Sea Physics Reanalysis (Escudier et al., 2020, 2021; Nigam et al., 2021) were extracted from the Mediterranean Forecasting System (MFS) openly available on the Marine Data Store of the E.U. Copernicus Marine Environment Monitoring Service (CMEMS). The model has a horizontal grid resolution of 1/24˚ (ca. 4-5 km) and 141 unevenly spaced vertical levels. Temperature and salinity vertical profiles as well as and along track satellite Sea Level Anomaly observations are assimilated in the model. The core reanalysis product covers the period 1987-01-01 to 2025-12-01. Then, data for the NW Mediterranean Sea were extracted, here defined as the region between [36.06, 43.87] °N and [-1.84, 7.27] °E, for the complete time series between 1987 and 2024.

2.3. Analyses

Empirical Orthogonal functions (EOFs) is a type of Principal Component Analysis (PCA) commonly used in Earth Sciences to decompose complex spatio-temporal signals into a finite set of dominant spatial patterns (Hannachi et al., 2007). EOFs are by essence a statistical exploratory method and in consequence the resulting components and scores may not always be meaningful from a mechanistic point of view. They are however a powerful tool often used in atmospheric and ocean sciences to extract patterns of variability that may be otherwise hidden under multiple complex interactions.

In this study, EOFs were performed using the Python package *xeofs* (Rieger & Levang, 2024). EOFs were applied on Temperature, Salinity and Currents from discrete depth levels. All fields were linearly de-trended before applying the EOFs to remove any long-term trends attributable, for example, to anthropogenic climate change. We selected the closest depth level from the model data to surface, 200 m, 400 m and 600 m. These depths were chosen to cover the optimal depth for the Norway lobster, or the depth range where the species is caught, and to help us understand any relevant oceanographic process. Ocean currents (East and North) were also rotated by -210°, which is equivalent to a 210° anticlockwise rotation of the axis system, so the x-axis matches the flow direction of the Catalan Current (U positive southwestward along shore, and V positive southeastward across shore).

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The EOF analysis decomposes a spatiotemporal signal into a series of orthogonal (i.e. independent) modes, each explaining a decreasing fraction of the variance of the original signal. Each mode comprises a component (spatial maps of variance) and a time-varying score (how the component varies in time). Ultimately, the original signal could be re-constructed by adding each mode together.

To better explain the interpretation of the EOFs, temperature at 400 m is used as an example (Fig. 2). Mode 1, the dominant pattern, explains approximately 78% of the variance. It is characterized by a near-homogeneous spatial pattern, with all the region colored in red (positive values, Fig. 2), associated with a temporal variability representing decadal cycles over the period studied. This can be interpreted as a widespread increase or decrease in temperature on annual time scales. Mode 2 and 3 represent faster fluctuating temporal signals, with more than 7% and 3% of the variance explained, respectively (Fig. 2). These modes represent inter-annual oscillations in temperature at smaller regional scales compared to the widespread mode 1. For example, mode 2 spatial pattern presents two well-distinguished areas: northern area (Balearic Sea) positive, and southern (Central NW Mediterranean south of the Balearic Islands) negative. This means that when the temporal pattern scores are positive, the expression of this mode is characterized by warmer temperatures north of the Balearic Islands, and colder temperatures in the south. This mode possibly relates to a local process of temperature changes with an inshore/offshore component. Mode 3 is similar to mode 2, with three well-distinguished areas, representing an even more local process. Overall, mode 2 and 3 remain marginal compared to mode 1 that explains more than 10 times more variance.

The decomposition procedure was repeated for all variables and depths considered in this study and the three leading modes for each of the 16 combinations (i.e., 4 variables at 4 depths) are provided in the Appendices. Then the resulting scores were all cross correlated (16 x 3 modes = 48) with the landings and LPUE time series. The environmental time series best correlated with the fisheries data were selected for further analysis in Sect. 3.

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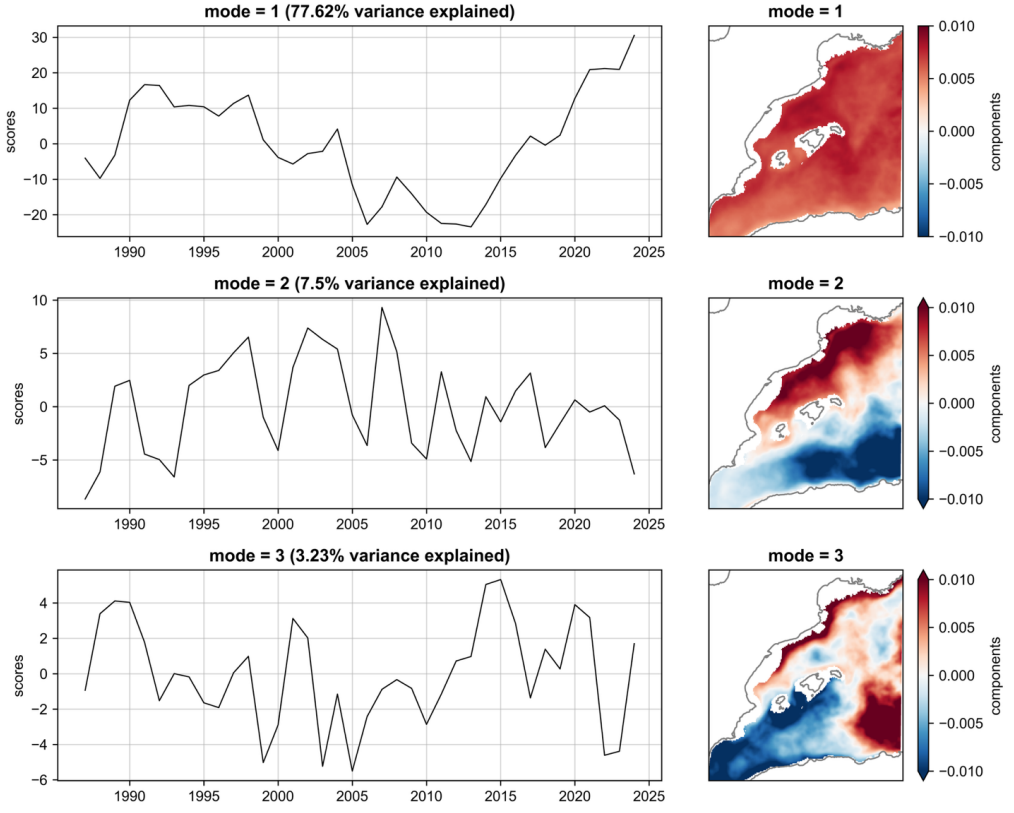

256 Figure 2. EOFs of the three first modes of variability for the de-trended annual temperature at 400 m between 1987 and
257 2024. The EOF components (spatial correlation maps) are shown on the right panels, with the scores (temporal variability
258 of the components) on left panels. The percentage of the variance explained by each mode is also shown on top of the left
259 panels. Here, positive score values indicate increasing temperature in areas where the spatial correlation is positive (red
260 on the maps).

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3. Results

3.1. Variability of the Norway lobster time series

Total yearly landings (t) of the Norway lobster were plotted together with LPUE (kg h^{-1} km^{-2}) and centroid depth (m) from 1970 to 2024 (Fig. 3). During this period, total landings presented large decadal fluctuations. Landings between 1970 and 1998 remained relatively low, oscillating between 217 and 366 t, only with a peak value of 435 t in 1977. Between 1999 and 2014, landings presented an increasing trend, reaching the maximum value of all the time series of 568 t in 2012. From 2015 onwards, the landings decreased and reached their lowest level of the time series of 185 t in 2023. The difference between the highest and lowest peak represents a reduction of 67% in Norway lobster landings in 11 years. Total landings and LPUE from 2008 to 2021 presented similar trends (Fig. 3). That is, between 2008 and 2012, LPUE followed an increasing pattern, reaching its highest peak of 0.9 kg h^{-1} km^{-2} also in 2012. From 2013 to 2023, LPUE was reduced by almost 58%, reaching the lowest value of 0.4 kg h^{-1} km^{-2} in 2021.

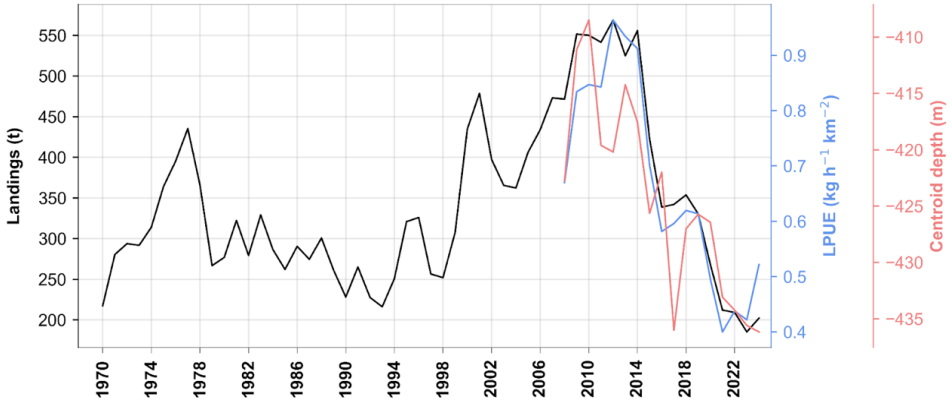

Figure 3. Historical series of total yearly landings of the Norway lobster from 1970 to 2024 (solid black line, t); yearly average LPUE from 2008 to 2024 (solid blue line, kg h^{-1} km^{-2}); and yearly centroid depth from 2008 to 2024 (solid red line, m). All landing data correspond to the GSA 6 area.

3.2. Variability of fishing effort

The total number of fishing trips and vessels in the bottom-trawl fleet showed a consistent declining trend between 2004 and 2024 (Fig. 4). Over this period, the bottom-trawl fleet operating in the GSA 6 area was reduced by 47%, decreasing from 758 vessels in 2004 to 404 in 2024. A similar pattern was observed with the number of fishing trips, which declined by 55%. This reduction in fishing trips is directly linked to the diminution of the fleet, as fewer vessels conducted fewer fishing operations.

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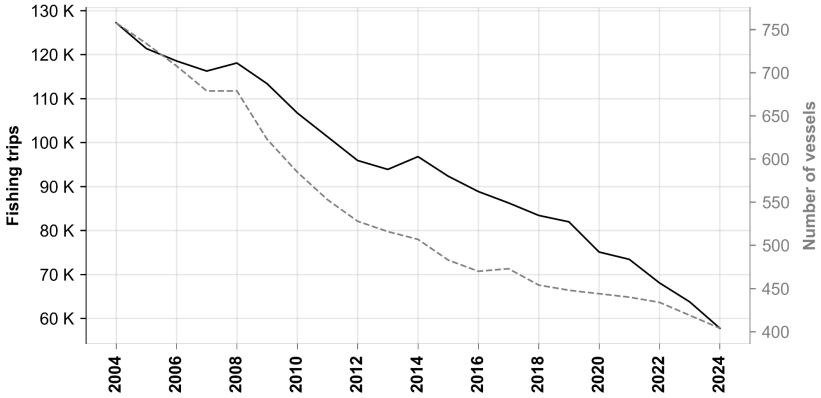

Figure 4. Time series of fishing trips (solid black line) and number of bottom-trawlers (dashed grey line) from 2004 to 2024 within the GSA 6 area.

3.3. Distribution of the Norway lobster LPUE and temperature anomaly in depth

The centroid depth between 2008 and 2024 followed a fluctuating but with an increasing trend (i.e., deeper depths; Fig. 3). Depths for the maximum LPUE during this period oscillated between a minimum of 410 m and a maximum of 435 m reached in 2010 and 2024, respectively. The trend observed here outlines a general pattern of higher values of LPUE are obtained when fishing occurs in shallower areas while lower LPUE are associated with fishing in deeper areas. This suggests that as the average LPUE declines, the maximum LPUE are found at deeper depths, and vice-versa.

The annual vertical distribution of LPUE averaged over GSA 6 between 2008 and 2024 and its relation to the temperature anomalies (ºC) is shown in Fig. 5. The yearly centroid depth (from Fig. 3) is also added to this figure (horizontal dashed lines), together with its average over the time series (horizontal solid lines). In the period examined, LPUE follow a pattern of higher values around 400 m depth that decrease at shallower and deeper depths. This trend indicates the depths where the LPUE mainly concentrates. The maximum LPUE was achieved in 2013, with 6.6 kg h^{-1} km^{-2} at 401 m depth. Then, values decreased but were concentrated around similar depths. In detail, centroid depths changed a few meters in the time series, as shown in Fig. 5, with a general pattern of higher depths coinciding with lower LPUE values. This also matches with a tendency of positive anomalies of temperature in the water column that started in 2016 and accentuated between 2020 and 2024. This suggests that the recent reduction of LPUE and its shift to greater depths also correspond to increase in temperature.

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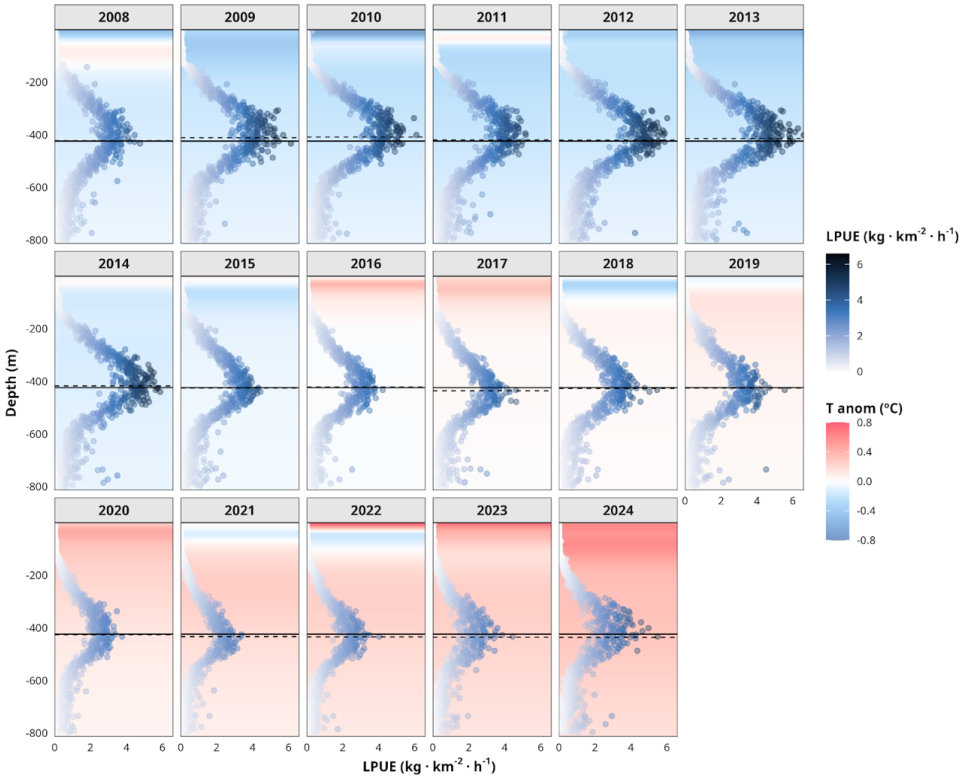

315 Figure 5. Depth distribution of LPUE (kg h^{-1} km^{-2}) of the Norway lobster and temperature anomaly (ºC) from 2008 to 2024.
316 Temperature reanalysis data were extracted from the Marine Data Store of the E.U. Copernicus Marine Environment
317 Monitoring Service (CMEMS). Solid black line represents mean centroid depth of LPUE, at 424 m; dashed black line
318 represents yearly centroid depth of LPUE. All data correspond to the GSA 6 area.
319
320 **3.4. Cross-correlations between environmental descriptors and the Norway lobster landing**
321 **time series**
322 The EOF scores of the environmental variables across different depth strata were correlated with the time
323 series for landings and LPUE of the Norway lobster. The resulting cross-correlation matrix (Fig. 6) shows that
324 landings of the Norway lobster are anti-correlated with the respective scores for temperature at 200, 400 and
325 600 m depth (T_{200} [1], T_{400} [1], T_{600} [1]; the number in bracket indicates the mode), salinity at 400 and 600 m
326 depth (S_{400} [1], S_{600} [1]), and correlated with the scores of along-shore velocity at surface and 200 m depth
327 (U_{surf} [2], U_{200} [2]). The highest correlation value is with T_{400} [1], with a Pearson coefficient value of -0.89. On
328 the other hand, the LPUE presents correlation and anti-correlation values similar to those with landings, but
329 reaching stronger Pearson coefficient values, such as -0.93 also with T_{200} [1] and T_{400} [1].

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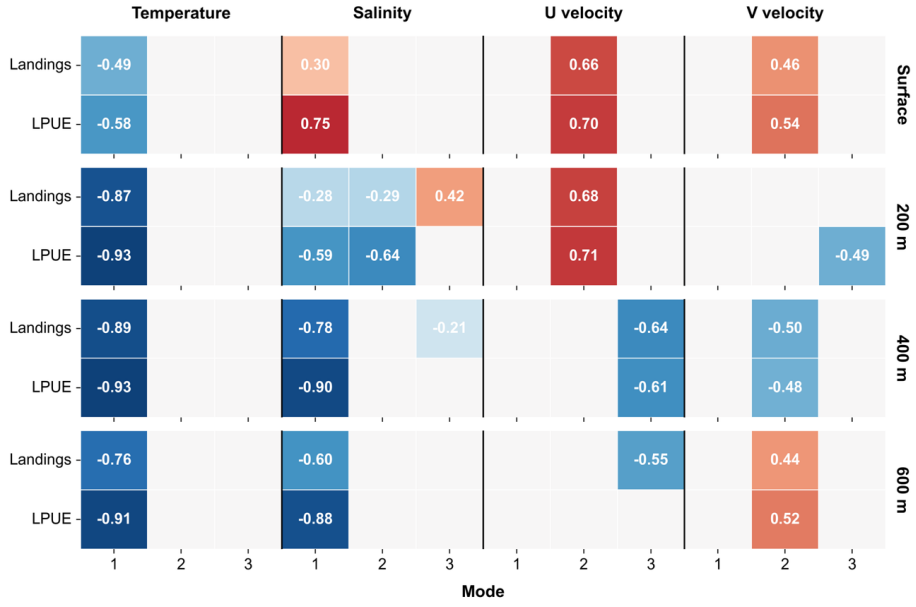

330 Figure 6. Cross-correlation matrix between landings (t) of Norway lobster from 1970 to 2024, LPUE (kg h^{-1} km^{-2}) from 2008
331 to 2024, and output for the annual, de-trended, spatial modes 1 to 3 of EOFs on reanalysis and forecast temperature,
332 salinity, along-shore velocity (U), and cross-shore velocity (V) data from 1987 to 2024 at surface, 200 m, 400 m and 600
333 m depth. Landings and LPUE data correspond to the GSA 6. Only significant (p-value < 0.05) Pearson correlation
334 coefficients are shown in the matrix, with positive correlations in red and negative correlations values in blue. Darker colors
335 indicate stronger correlations.

336 Following the cross-correlation analysis (Fig. 6), a subset of meaningful time series was selected for further
337 analysis. These were chosen based on scientific interpretation of the results (Table 1). For example, because
338 maximum LPUE of the Norway lobster were mostly between 200 and 400 m (Fig. 5), EOFs at 400 m were
339 prioritized for further analysis when the correlation was strong with different depth ranges (e.g. landings are
340 anti-correlated with temperature at 200 m, 400 m and 600 m). Following this reasoning, temperature and
341 salinity at 400 m and along-shore velocity at 200 m were selected because they all have high correlation with
342 landings and represent a meaningful depth range for the Norway lobster´s LPUE. Along-shore velocities at
343 surface were also selected because they are highly correlated with the landings, while being potentially
344 indicative of changes in the path of the Liguro-Provençal-Catalan current in the area. The selected modes for
345 each environmental variable are shown in Fig. 7 to understand better the meaning of their spatiotemporal
346 pattern.
347

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Table 1. Summary of the selected EOF outputs for the analyses and their Pearson correlation coefficient (r) with landings and LPUE. T400 corresponds to temperature at 400 m depth; S400 corresponds to salinity at 400 m depth; Usurf corresponds to along-shore velocity at surface; U200 corresponds to along-shore velocity at 200 m depth. A short interpretation is provided along with each correlation. Variables are ordered from highest to lowest percentage of variance explained and correlation value. All Pearson correlation coefficients shown are significant (p-value ≤ 0.001).

EOF	Mode (%var)	Corr w/ landings	Corr w/ LPUE	Interpretation
T_{400}	1 (78%)	-0.89	-0.93	Landings/LPUE decrease when widespread temperature at 400 m increases
S_{400}	1 (68%)	-0.78	-0.90	Landings/LPUE decrease when widespread salinity at 400 m increases
U_{surf}	2 (10%)	0.66	0.70	Landings/LPUE decrease when velocity at surface in the Liguro-Provençal-Catalan current decreases
U_{200}	2 (8%)	0.68	0.71	Landings/LPUE decrease when velocity at 200 m in the Liguro-Provençal-Catalan current decreases

3.5. Description of the selected EOF modes

The first EOF mode of temperature at 400m, T_{400} [1], explains nearly 78% of the variance (Fig. 7a). In periods when the score values are positive (e.g., the 1990s and after 2020), the annual temperature throughout the region is above average (higher temperatures). Conversely, the periods with negative scores (e.g. mid-2000s to mid-2010s) have a temperature at 400 m below average (lower temperatures). As mentioned in Sect. 2.3, this mode corresponds to a widespread increase or decrease of temperature affecting the entire NW Mediterranean Sea on near-decadal time scales and is likely reflective of changes in the mean climate over the region.

The first EOF mode of salinity at 400m, S_{400} [1], explains around 68% of the variance (Fig. 7b). It follows a similar spatiotemporal pattern to temperature, also characterized by annual widespread increase or decrease on its values. This indicates that positive phases of the score are associated with periods of increased salinity at 400 m.

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Cross-shore velocity at surface and 200m, U_{surf} [2] and U_{200} [2], explain approximately 10% and 8% of the variance, respectively (Fig. 7c, 7d). We note that mode 1 for these two signals only explains a slightly greater portion of the variance (both approximately 17%), but the component signal in this case is stronger in the Alboran Sea and south of the Balearic islands, while mode 2 shows a stronger signal in the Balearic Sea and in the region of interest (GSA 6) in the vicinity of the Liguro-Provençal-Catalan current. This is especially true for U_{200} (Fig. 7d) for which a strong spatial signal extending from the Gulf of Lion to the coast of Catalonia is found along the path of the Liguro-Provençal-Catalan current (red in the figure). For the same component, a band of negative correlation (blue), is found immediately north of the Balearic Islands, which may be interpreted as a recirculation current eastward as part of the Balearic front (we recall that the U current is positive southwestward in the main direction of the current). Overall, the spatial pattern for U_{200} [2] may be interpreted as a stronger Liguro-Provençal-Catalan, recirculation and Balearic front when the score is high (late 2000s and early 2010s) and a weaker current, recirculation and front when the score is low (in the 2020s).

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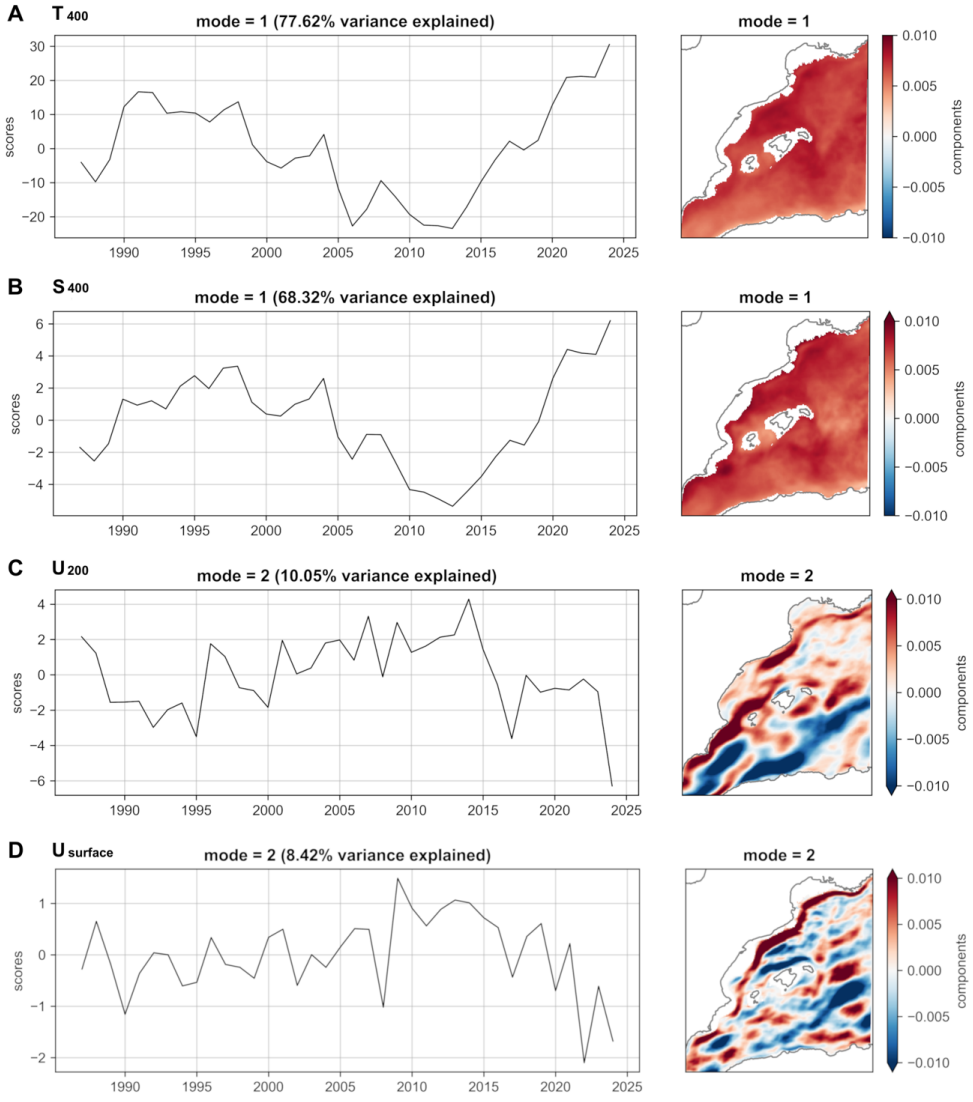

390 Figure 7. Meaningful EOF modes selected for the analysis. (a) Mode 1 for temperature at 400 m depth; (b) Mode 1 for
391 salinity at 400 m depth; (c) Mode 2 for along-shore velocity at surface; (d) Mode 2 for along-shore velocity at 200 m depth.
392 The EOF components (spatial correlation maps) are shown on the right panels, with the scores (temporal variability of the
393 components) on left panels. The percentage of the variance explained by each mode is also shown on top of the left
394 panels.

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3.6. Relation between the selected EOF modes and the Norway lobster time series

Temporal patterns of T_{400} [1] and U_{200} [2] were selected to compare with landings of the Norway lobster (Fig. 8a, 8b, respectively). The selected modes for salinity and along-shore velocity at surface were not considered for the comparison because they presented either similar or less distinguished patterns with the other variables. The temporal patterns of both environmental variables were also compared (Fig. 8c). The selection of landings instead of LPUE for the comparison is due to the availability of larger data time series, and because both parameters have similar high correlation values with the environmental variables evaluated.

During the period evaluated, landings followed an inverse pattern than T_{400} [1], with the highest values of landings correspond to the lowest score values of temperature and salinity at 400 m depth, and vice-versa (Fig. 8a). Because an increase in T_{400} [1] scores translates into a widespread increase in temperature (and salinity for S_{400} [1]) across the region (Fig. 7a, 7b), a negative correlation with the landings means a decrease in landings of the Norway lobster when temperature and salinity increase (Table 1, Fig. 8).

Landings and U_{200} [2] followed similar trends, with increasing landings when the score values for U_{200} [2] increase too (Fig. 8b). Along-shore velocity at 200 m depth does not follow a homogenous spatial pattern within all the region, but U_{200} [2] component shows a strong correlation in the Liguro-Provençal-Catalan current region (Fig. 7d). This means that a decrease in the Norway lobster landings could be related with an increase in the velocity of the Liguro-Provençal-Catalan current, and a potential displacement of the North Balearic front at 200 m depth (Table1, Fig. 8).

T_{400} [1] is anti-correlated with U_{200} [2] (Fig. 8c). These inverse patterns suggest that years with a widespread increase in temperature at 400 m depth are most likely to be associated to a decrease in the velocity of the Liguro-Provençal-Catalan current velocity and a decrease in the velocity of the recirculation north of the Balearic Islands at 200 m depth (Fig. 8). This dynamic is explored further in the Discussion.

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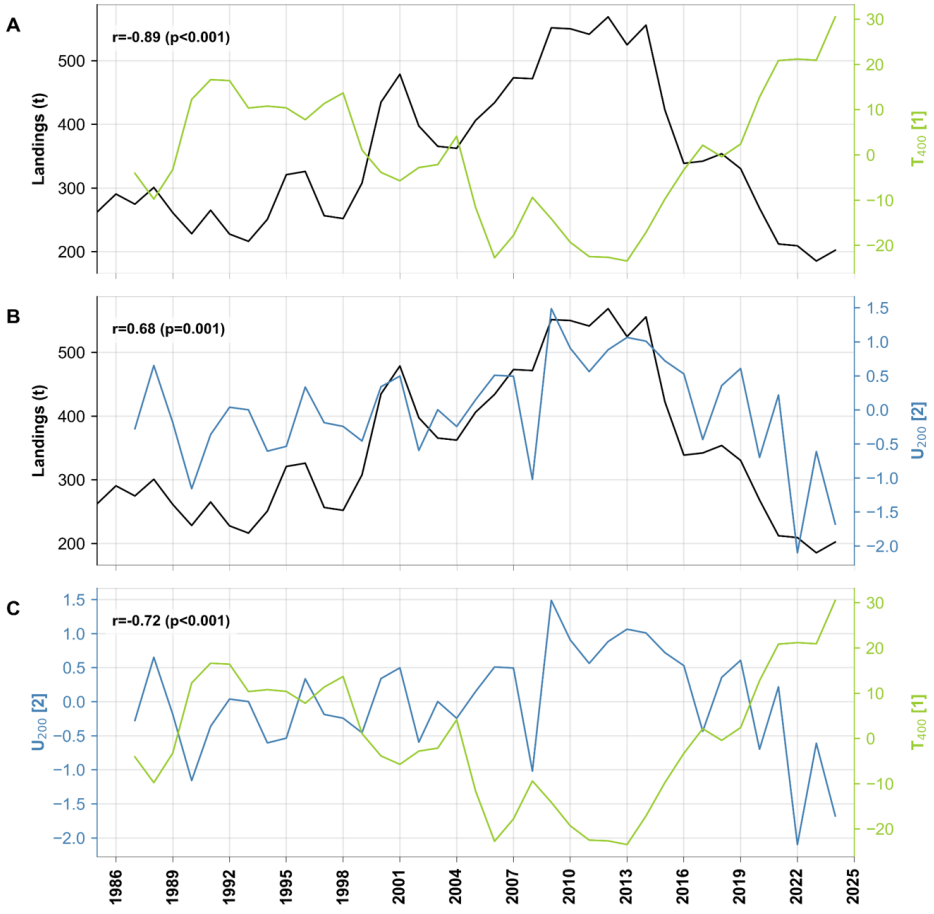

Figure 8. Time series of total yearly landings (t) of the Norway lobster (solid black line, t) from 1986 to 2024, and the temporal pattern of the selected modes of environmental variables from 1987 to 2024. (a) Comparison between landings and T_{400} [1], corresponding to the mode 1 score values for temperature at 400 m depth (solid green line); (b) Comparison between landings and U_{200} [2] corresponding to the mode 2 score values for along-shore velocity at 200 m depth (solid blue line); (c) Comparison between U_{200} [2] and T_{400} [1]. Values presented in the y-axis for the environmental variables correspond to the score value obtained from the EOFs calculations. The Pearson correlation coefficients (r) and p-values between the curves in each plot are shown.

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4. Discussion

Landings of the Norway lobster in the GSA 6 region (NW Mediterranean Sea) show important fluctuations over the past 54 years, in addition to a sharp decline in landings and LPUE over the last 15 years. This recent decline has also been reported in other areas, such as the North and NW Iberian Peninsula or SW Ireland, where landings of the species decreased by 80-90% in 25 years (Fariña & González Herraiz, 2003; González Herraiz et al., 2009, 2015). The Norway lobster is a valuable fishing resource and the variability of its landings and catchability rely partially on the efficiency of the fishing gear, the accessibility of the fishing grounds and its vulnerability to the gears (Maynou & Sardà, 2001). Several studies have found depth, atmospheric pressure, cloud cover, current speed, turbidity and nature of the sediments, among others, to have an effect on the Norway lobster catch rates (Aguzzi et al., 2003; Chapman & Howard, 1988; Maynou & Sardà, 2001; Newland et al., 1988; Sardá, 1995; Tuck et al., 1997; Tully & Hillis, 1995). Therefore, the reasons behind those fluctuations in catches can be diverse and may include environmental and fishing traits. Here, we review observed fluctuations in Norway lobster catches and LPUE and propose hypotheses to interpret these patterns in the context of changing environmental conditions and fishing effort.

4.1. Reduction of fishing effort

In the Spanish Mediterranean, bottom trawling is restricted to a maximum of 12 fishing hours per day and five days per week (EC 1626/1994; EC 1967/2006), a regulation aimed at controlling total effort and reducing pressure on demersal resources. In recent years, under the EU WMMAP framework, fishing effort for the bottom-trawl fleet has been reduced through limits on days at sea, within a broader context in which the number of operating bottom-trawl vessels has also declined (MAPA, 2025). This coincides with the most recent period of a declining trend in Norway lobster catches (Fig. 3, 4). However, the simultaneous decrease observed in both landings and LPUE suggests that the reduction in landings cannot be explained simply by the reduction in fishing effort. Even under conditions of fewer vessels and fewer fishing trips, LPUE continue to decline, indicating a decrease in stock availability or abundance. This pattern may reflect broader ecological or environmental drivers, such as changes in habitat conditions, recruitment success, or ecosystem dynamics, which are acting independently of effort reduction and may be limiting the recovery of the Norway lobster stock.

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4.2. Warming temperature, species displacement and changing fishing strategy

Warming of the ocean has been recorded globally since 1880 (NOAA, 2024). In the NW Mediterranean Sea, higher temperatures have been observed since 2014 (Bahamon et al., 2020; Margirier et al., 2020), matching the trend observed here at depth for the same period (Fig. 7a, A2a, A3a). This recent warming trend also corresponds to a decline in LPUE and an increase in the depth at which the maximum LPUE is found (i.e. LPUE centroid depth; Fig. 3). Overall, this supports the idea that as water temperature warms, the Norway lobster population is moving deeper. Vertical displacement to reach cooler waters has been reported as a strategy followed by some species to adapt to ocean warming (Jorda et al., 2020), moving a few meters per year to keep pace with climate change (Poloczanska et al., 2013). We could hypothesize a shift in the species vertical distribution to escape environmental conditions that are less suitable for them and, consequently, fishers changing their fishing strategy or target. In a multispecific fishery, such as the bottom-trawl in the NW Mediterranean Sea, the diversity of the catch and the mobility of the species can protect the communities from environmental change effects (Young et al., 2019). For example, the deep-water rose shrimp is another target species of bottom trawlers at this depth showing an exponential increase of its abundance during the same period as the decline of the Norway lobster (Mingote et al., 2024). This species became the second most important fishing resource economically, and the first in weight in the GSA 6 in 2024, potentially offsetting the loss of revenue caused by the reduction of catches of the Norway lobster (ICATMAR, 2025).

4.3. Large-scale oceanographic changes in the Mediterranean Sea

In this study, we detected a widespread increase in temperature and salinity in the region from surface to 600 m depth (Fig. 5a, 5b, A1-A7a) starting from 2014 up to now. This trend matches with previously reported warming and salinization of the intermediate and deep layers of the Western Mediterranean (Bahamon et al., 2020; Margirier et al., 2020). The NW Mediterranean Sea is known for its deep or intermediate convection and deep-water formation that take place due to winter heat loss and evaporation resulting from cold and strong northerly winds (Fig. 9a; Puig et al., 2013). Margirier et al. (2020) reported the accumulation of warmer and more saline Levantine Intermediate Water (LIW) in the northwestern basin until 2018 related to a weak winter convection in 2014 (Fig. 9b). This phenomenon caused an increase in stratification below the LIW that, together with the air-sea heat fluxes intensity, constrained the depth of convection. Vertical sinking of organic material from the euphotic zone is known to be the main source of nutrients to the deep-sea floor, controlling the dynamics of biological processes (Billett et al., 1983; Gage, 2002). The transport of organic matter to the

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deep basin thus likely determine the nutritive condition of populations and the reproductive output (Company et al., 2008). So, the increase in stratification because of warmer and saltier water weaken the convection and less nutrients arrive to deeper depths, potentially affecting the income of organic matter of benthic populations.

We also found a pattern of change in the intensity of the Liguro-Provençal-Catalan current and the North Balearic front at 200 m depth. Oceanographic conditions in the NW Mediterranean Sea are mostly controlled by this current, which is associated with a permanent shelf/slope density front (Font et al., 1988; Salat, 1995) that plays a key role in the distribution of planktonic organisms (Sabatés et al., 2004). Our observations suggest that the strength of the Liguro-Provençal-Catalan current, associated here to the second mode of variability of the along-shore current (Fig. 7d), has increased from the mid-1990s to the early 2010s and reduced since (Fig. 9a, 9b). The weakened intensity of the current may be also associated to less export to the sea floor (Fig. 9b). Lévy et al. (2018) suggested that submesoscale ecological processes might play a significant role on productivity, affecting ocean biodiversity.

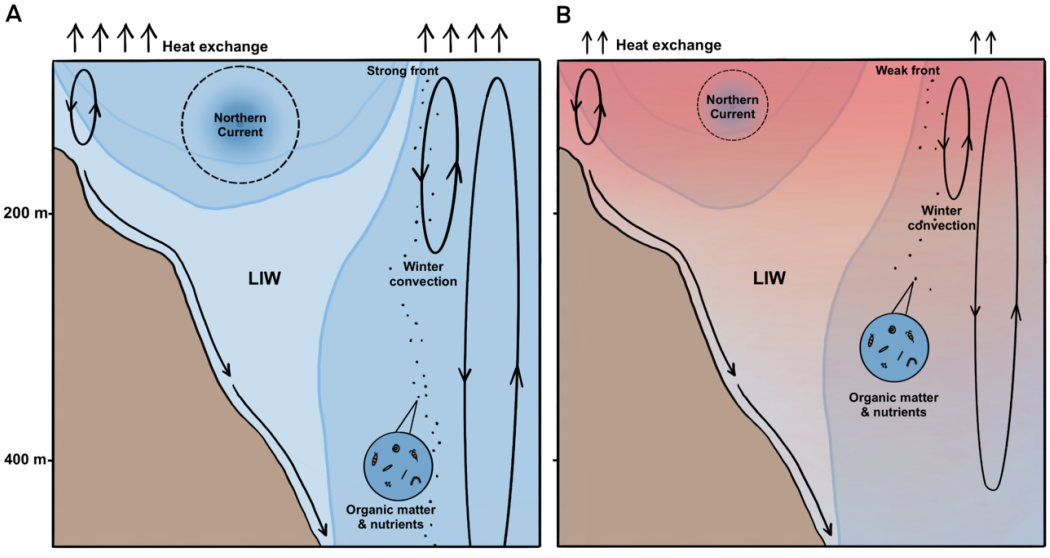

Figure 9. Oceanographic processes from the surface to 400 m depth are represented under two contrasting scenarios. (a) Low temperature, strong front, and enhanced heat exchange associated with intense winter convection. High transport of organic matter and nutrients to the seafloor. High intensity of the Liguro-Provençal-Catalan current (Northern Current). (b) Increased temperature, weak front, and reduced heat exchange associated with weak winter convection. Limited transport of organic matter and nutrients to the seafloor. Reduced intensity of the Liguro-Provençal-Catalan current. The Levantine Intermediate Water (LIW) is also shown in both scenarios.

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4.4. Norway lobster catches track ocean dynamics changes over four decades

Norway lobster LPUE and landings are well correlated between 2008 and 2024 (Fig. 3). While LPUE data are not available prior to 2008, Norway lobsters' landings have been used as a proxy for the status of the population since 1970. In order to explain the near-decadal fluctuations in Norway lobster landings we relate those observations to environmental variability patterns extracted with EOFs since 1986 (beginning of the environmental data availability period).

Norway lobster landings are marked by a slight decrease between the 1970s and early 1990s, followed by a rapid increase between the mid-1990s and the early-2010s and by another more pronounced decline since. Long-term analysis of landings of the Norway lobster shows a strong temporal correlation with temperature and salinity at 400 m depth. The widespread increase in temperature and salinity across the region is highly correlated to a decrease in landings of the Norway lobster. As stated before, the increase in temperature and salinity at 400 m depth, can be related with the reported warming and salinization trend of the LIW reported by (Margirier et al., 2020), which caused an increase of stratification and weakening of intermediate convection (Fig. 9b). This suggest that the reduction of deep convection may negatively affect Norway lobster's populations.

Our results support the fact that environmental conditions might be indirectly affecting the landings of the Norway lobster in the GSA 6 region. For example, González Herraiz et al. (2009) reported negative correlations between the North Atlantic Oscillation (NAO) and the LPUE of this species in the Porcupine bank (SW Ireland), linking stormy, warm and wet conditions with a loss of density of the Norway lobster and consequently LPUE low values. Furthermore, some studies have reported the impact of temperature and hydrographic factors in the larval phase of this species (Bailey et al., 1995; Dickey-Collas et al., 2000). It is known that abiotic factors such as temperature, salinity and circulation patterns have a direct effect on marine organisms' movement, migration and recruitment, or indirect by affecting the distribution and abundance of lower trophic levels (Nye et al., 2009). Then, could the reduction in Norway lobster landings and the observed deepening of its LPUE be attributed to a behavioral strategy to avoid higher temperatures? Might this downward shift result in reduced nutrient availability due to weaker vertical convection associated with increasing temperature and salinity at intermediate depths? Is the increase of stratification in intermediate waters retaining larvae and limiting their arrival to the sea floor? Additionally, are rising temperatures affecting lower trophic levels in ways that limit

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food availability and, consequently, hinder the growth of Norway lobster populations? Our study suggests that the answers to those questions may be affirmative, but more studies need to be conducted.

4.5. Limitations of the study

In this study, EOFs were performed on environmental data from reanalysis, not direct observations, assuming the variability inherent to these data are representative of the natural variability of the NW Mediterranean Sea. These reanalysis simulations, however, include data assimilation and have been validated and assessed through comparison to in-situ and satellite observations (Escudier et al., 2021). The low frequency variability, critical for this study, is also well resolved (Pinardi et al., 2015). However, the EOF separation into statistical modes may also be imperfect.

Another limitation of this study is the use of landings pre-2008 as a proxy of biomass density. LPUE can be used as a proxy for the species abundance assuming that its trend follows the changes in the stock abundances (Hoyle et al., 2024; Leitão et al., 2022; Maunder & Punt, 2004; Mingote et al., 2024). Then, as landings and LPUE trends followed similar trends between 2008 and 2024 (Fig. 3), we assume this similarity extends to the whole time series and use landings because there is more available data and we want to evaluate the general trend and not a specific value.

4.6. Outlook and implications for fisheries management

Climate projections indicate a global temperature increase of approximately 1.5 °C between 2030 and 2052 (IPCC, 2018), which is expected to alter marine environmental conditions and affect species productivity. However, population dynamics are also influenced by natural environmental variability operating at multiple temporal scales. As a result, shifts in species composition may occur, with certain species potentially benefiting from changing conditions while others decline. Norway lobsters' trend in landings coincides with decadal-scale temperature variability, suggesting that environmental forcing plays an important role in shaping its population dynamics.

Disentangling fishing mortality from environmentally driven variability remains a major challenge, as both processes are intrinsically linked (Hilborn & Litzinger, 2009; Rothschild, 2007). Favorable environmental conditions may temporarily sustain fishing levels that would otherwise be unsustainable, whereas fishing

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mortality can amplify the effects of adverse environmental conditions and accelerate stock declines (Cyr et al., 2025). Consequently, Norway lobster's stock that has historically been exploited sustainably may become overfished if its productivity decreases in response to unfavorable temperature regimes. This highlights the importance of incorporating environmental parameters, such as temperature variability, into stock assessment frameworks. Stock assessments are often primarily based on biological variables, and the inclusion of environmental variable may improve management advice and better reflect ecosystem dynamics. Understanding these natural fluctuations is therefore essential when evaluating fishing pressure. If a decline in abundance is driven by environmentally induced reductions in productivity, even reduced fishing effort may exert a disproportionate impact on an already weakened stock (Essington et al., 2015).

5. Conclusions

This study demonstrates that long-term fluctuations in Norway lobsters' landings in GSA 6 are driven by a combination of fishing pressure and, more importantly, environmental variability. Although fishing effort has steadily declined since 2004, this reduction alone cannot explain the sharp decline in landings and LPUE observed over the past 10–15 years. The results show that large-scale oceanographic changes in intermediate waters play a central role. The first EOF mode of temperature and salinity at 400 m, which explains nearly 78% of the variance, is strongly and negatively correlated with landings and LPUE, indicating that widespread warming and salinization at depth are associated with reduced catches. LPUE also shifted slightly deeper during years with positive temperature anomalies, suggesting behavioral responses to changing environmental conditions. Circulation patterns further contribute to the observed trends, with the strength of the Liguro-Provençal-Catalan Current and the North Balearic Front showing positive correlations with landings. Overall, the decline of the Norway lobster in recent years appears to be tied to intermediate-water warming, salinization, and changes in current intensity rather than to fishing effort alone. These findings highlight the need to incorporate environmental indicators into stock assessments and management strategies, particularly in the Mediterranean Sea, a recognized climate-change hotspot.

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Appendices

All figures from A1 to A15 show the EOF outputs for the environmental variables selected at discrete depths, as explained in Sect. 2.2. For all of them, the EOF components (spatial correlation maps) are shown on the right panels, with the scores (temporal variability of the components) on left panels. The percentage of the variance explained by each mode is also shown on top of the left panels.

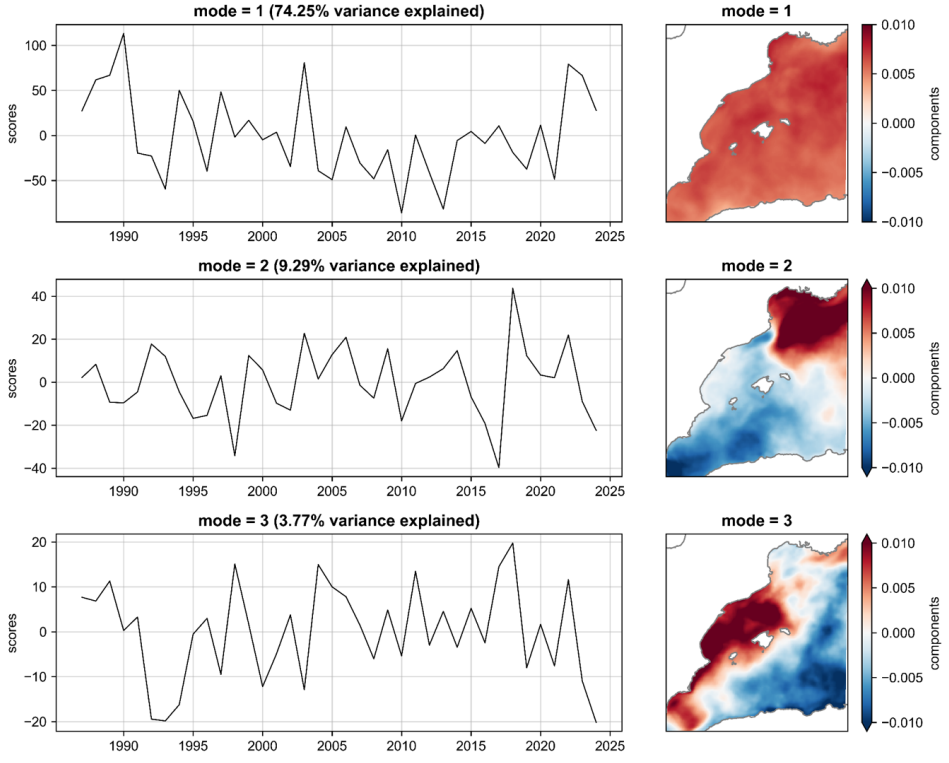

Figure A1. EOFs of the three first modes of variability for the de-trended annual temperature at surface between 1987 and 2024. Here, positive score values indicate increasing temperature in areas where the spatial correlation is positive (red on the maps).

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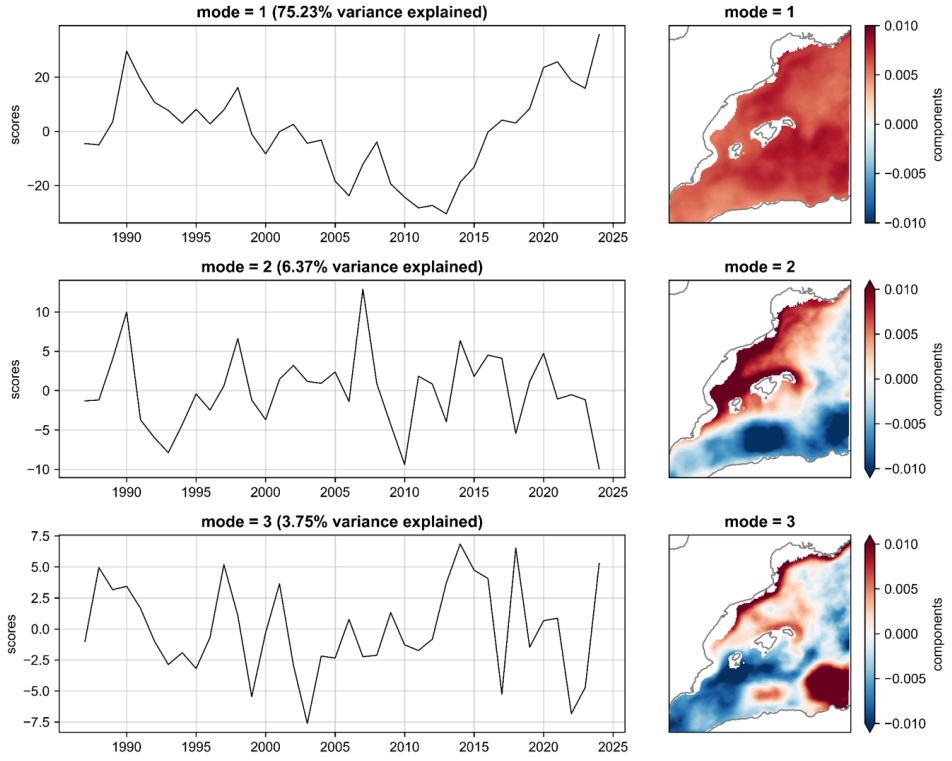

602 Figure A2. EOFs of the three first modes of variability for the de-trended annual temperature at 200 m between 1987 and
603 2024. Here, positive score values indicate increasing temperature in areas where the spatial correlation is positive (red on
604 the maps).

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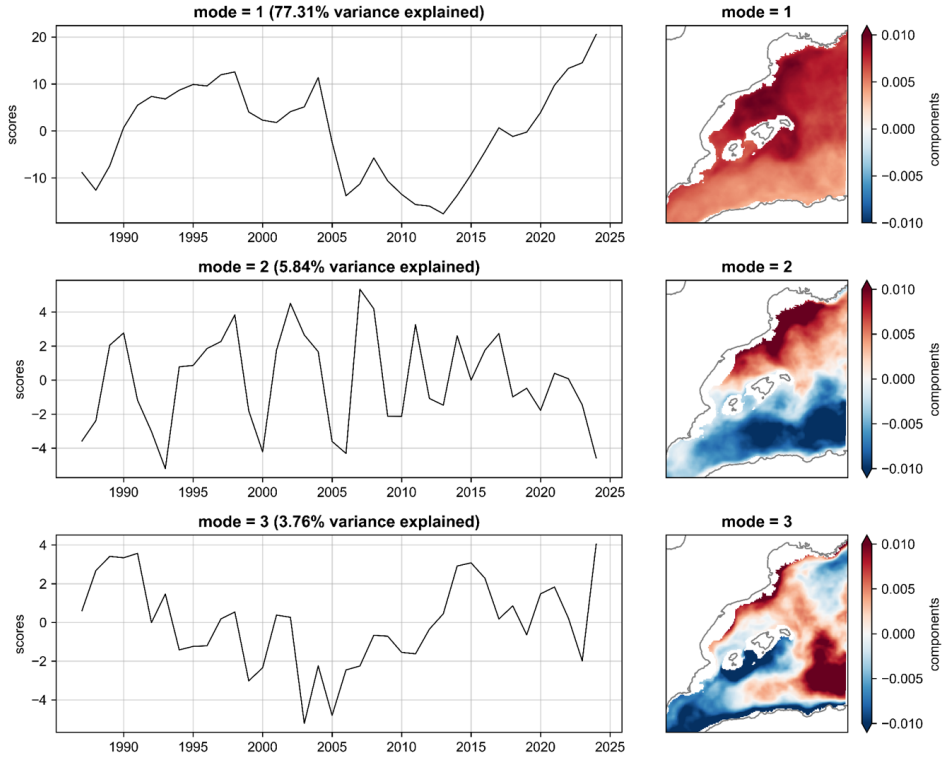

Figure A3. EOFs of the three first modes of variability for the de-trended annual temperature at 600 m between 1987 and 2024. Here, positive score values indicate increasing temperature in areas where the spatial correlation is positive (red on the maps).

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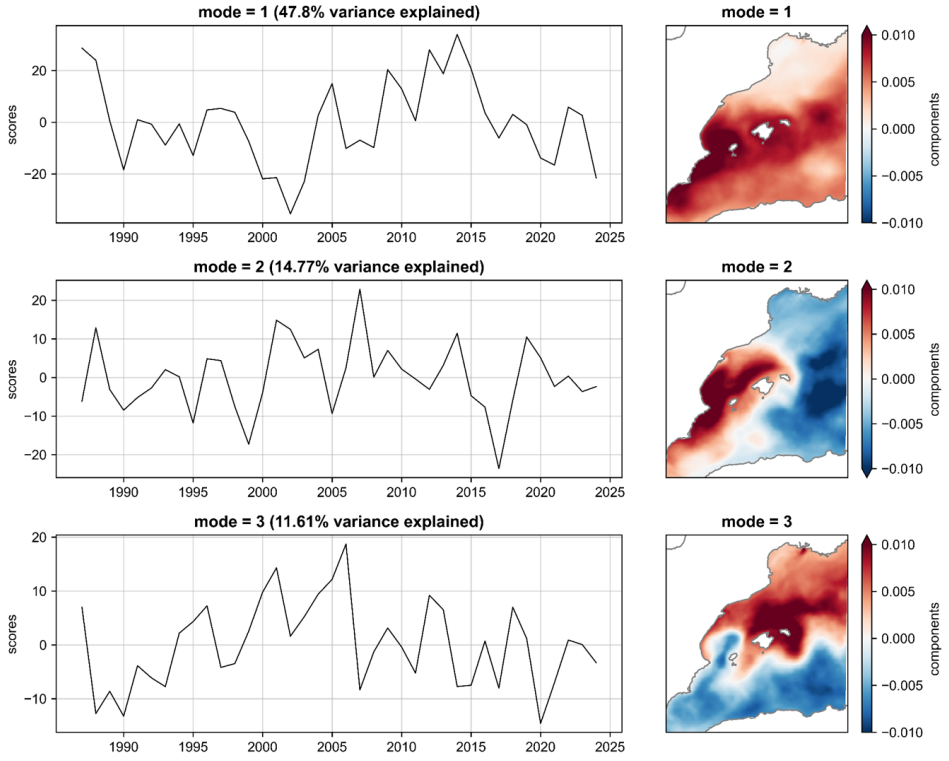

608 Figure A4. EOFs of the three first modes of variability for the de-trended annual salinity at surface between 1987 and 2024.

609 Here, positive score values indicate increasing salinity in areas where the spatial correlation is positive (red on the maps).

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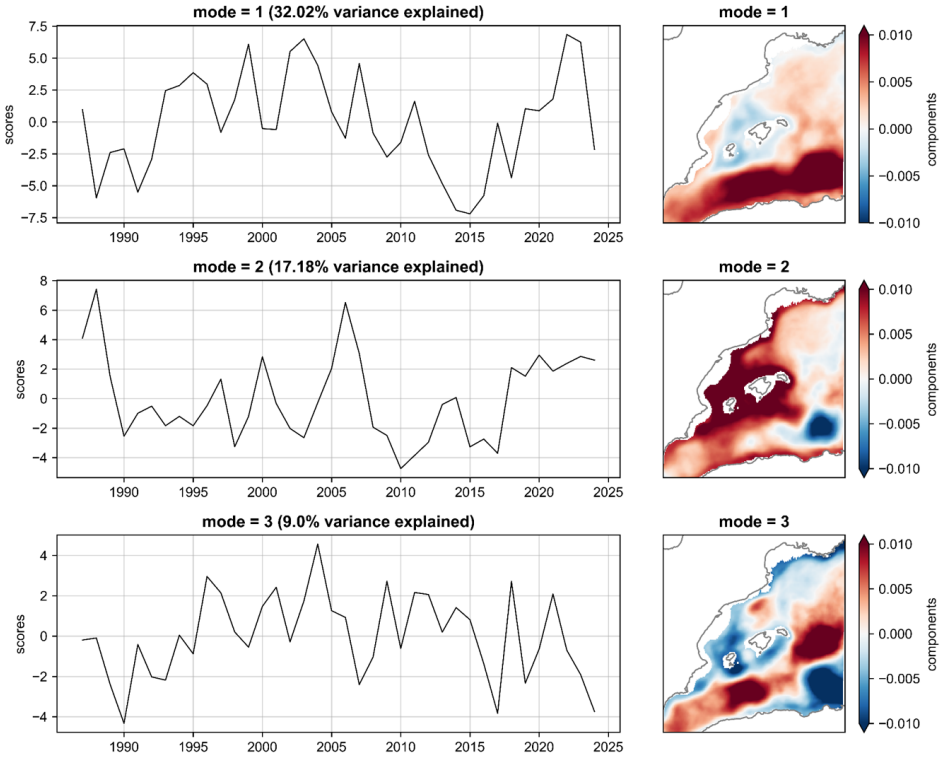

610 Figure A5. EOFs of the three first modes of variability for the de-trended annual salinity at 200 m between 1987 and 2024.

611 Here, positive score values indicate increasing salinity in areas where the spatial correlation is positive (red on the maps).

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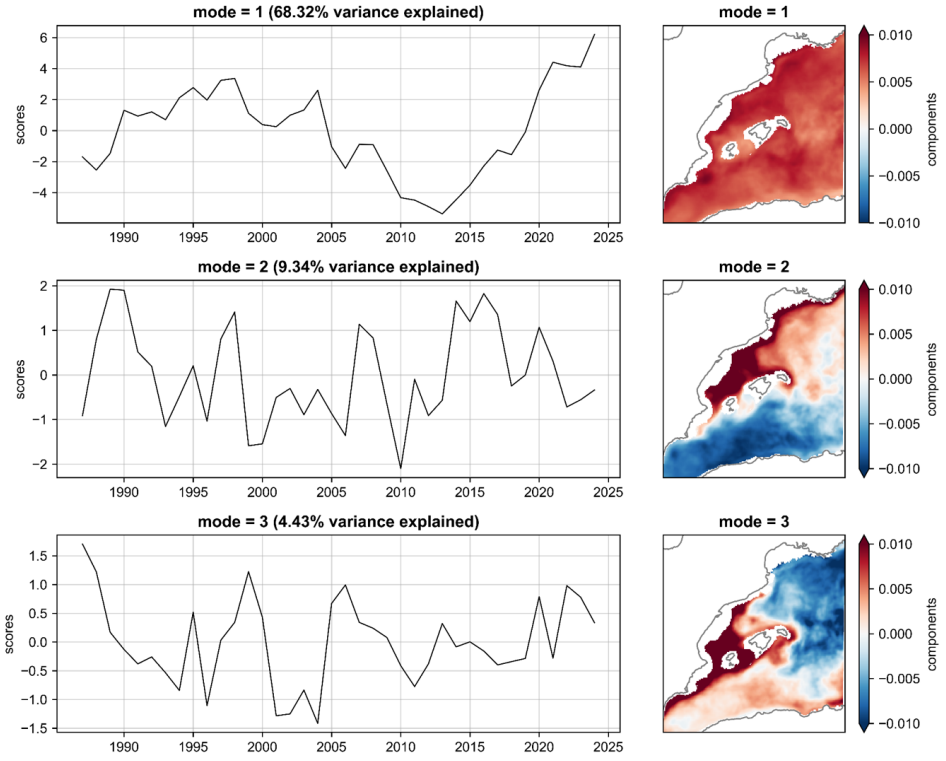

612 Figure A6. EOFs of the three first modes of variability for the de-trended annual salinity at 400 m between 1987 and 2024.

613 Here, positive score values indicate increasing salinity in areas where the spatial correlation is positive (red on the maps).

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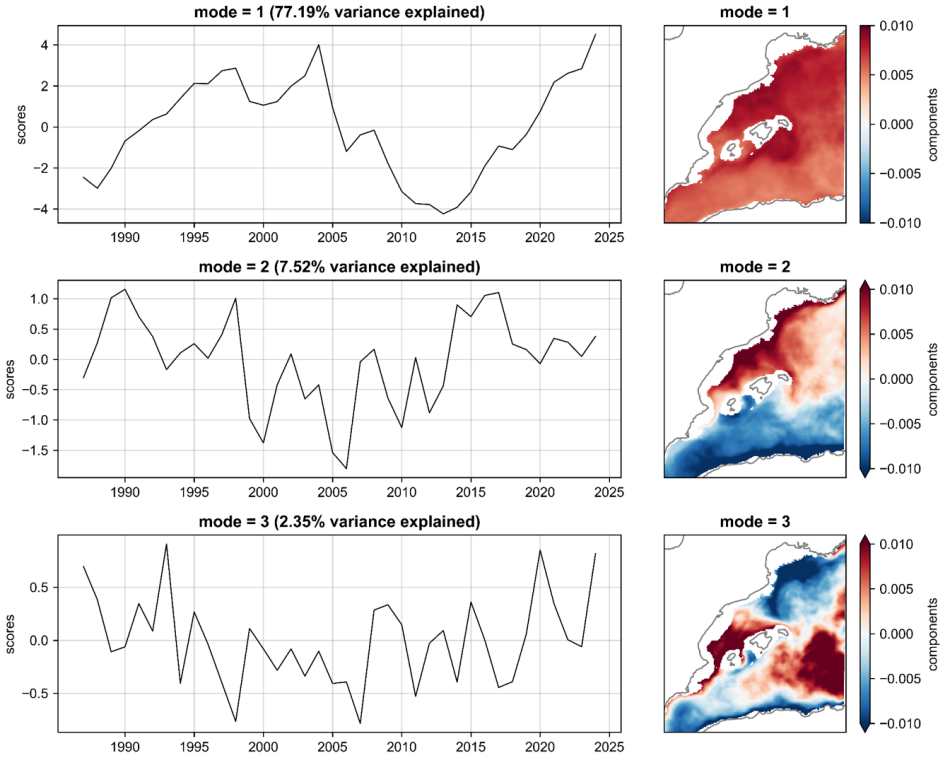

614 Figure A7. EOFs of the three first modes of variability for the de-trended annual salinity at 600 m between 1987 and 2024.

615 Here, positive score values indicate increasing salinity in areas where the spatial correlation is positive (red on the maps).

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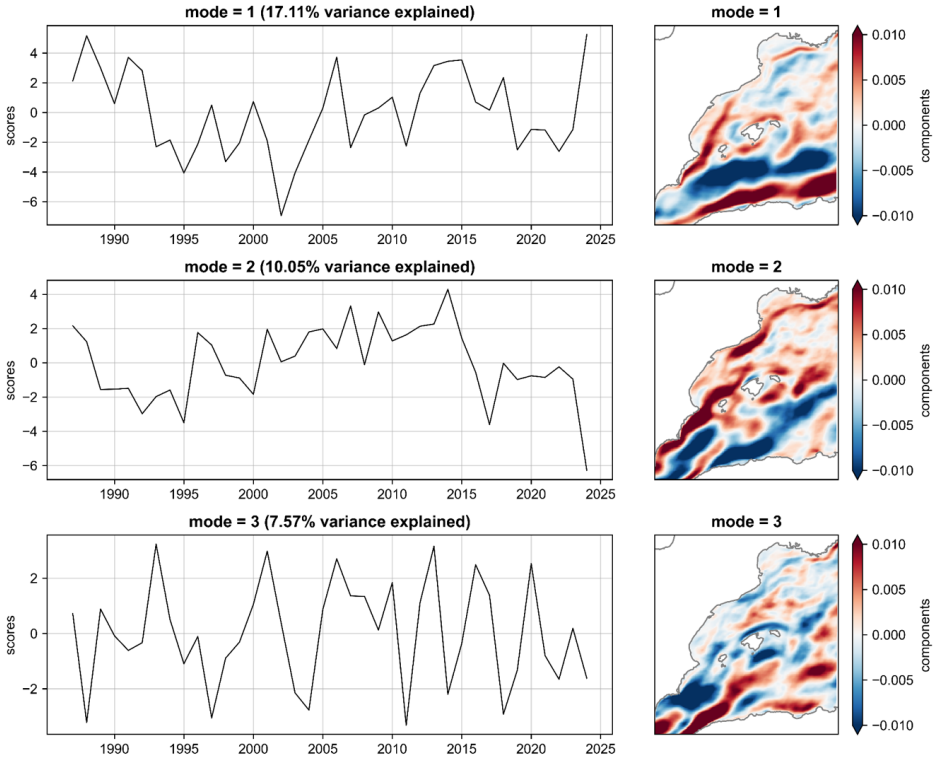

616 Figure A8. EOFs of the three first modes of variability for the de-trended annual current southwestward along shore (U) at
617 surface between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where the
618 spatial correlation is positive (red on the maps).

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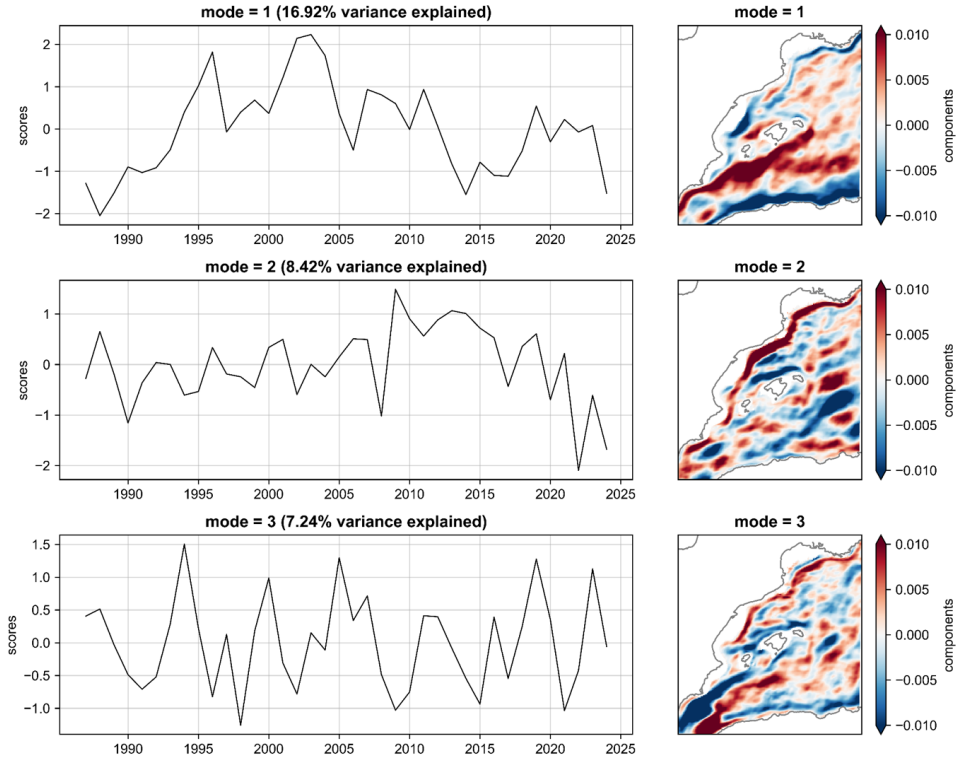

619 Figure A9. EOFs of the three first modes of variability for the de-trended annual current southwestward along shore (U) at
620 200 m between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where the
621 spatial correlation is positive (red on the maps).

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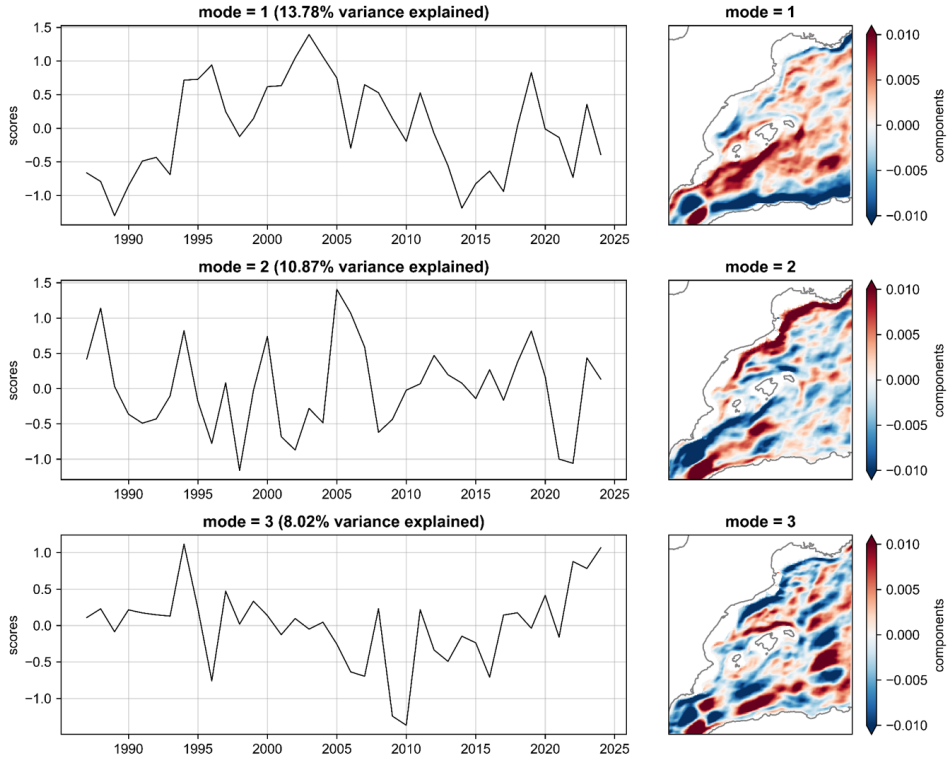

622 Figure A10. EOFs of the three first modes of variability for the de-trended annual current southwestward along shore (U)
623 at 400 m between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where
624 the spatial correlation is positive (red on the maps).

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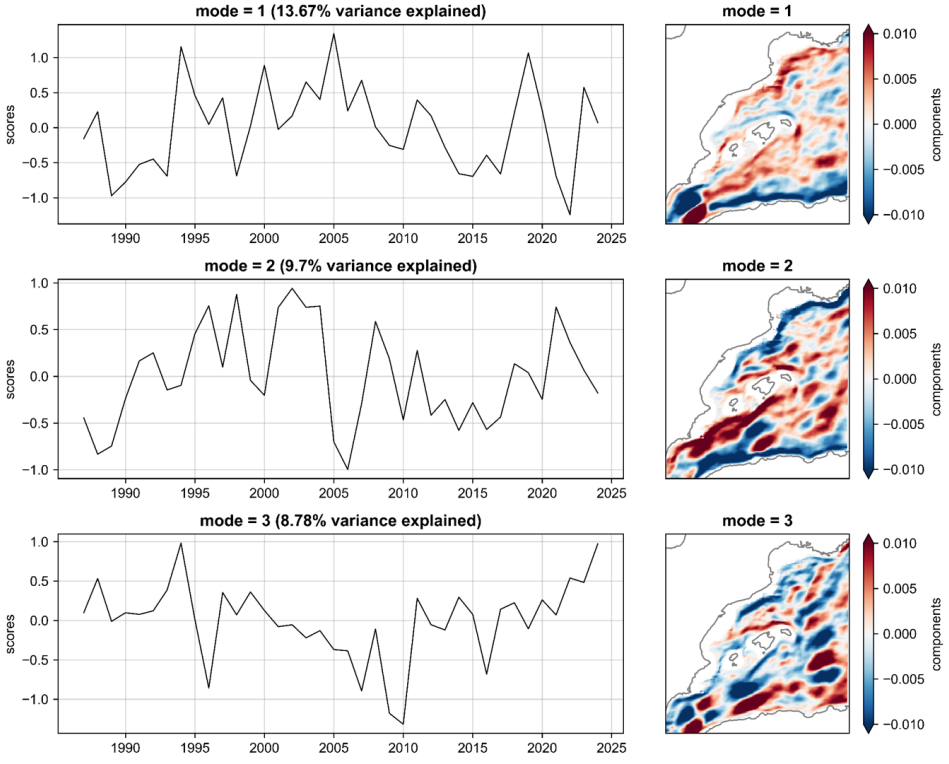

625 Figure A11. EOFs of the three first modes of variability for the de-trended annual current southwestward along shore (U)
626 at 600 m between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where
627 the spatial correlation is positive (red on the maps).

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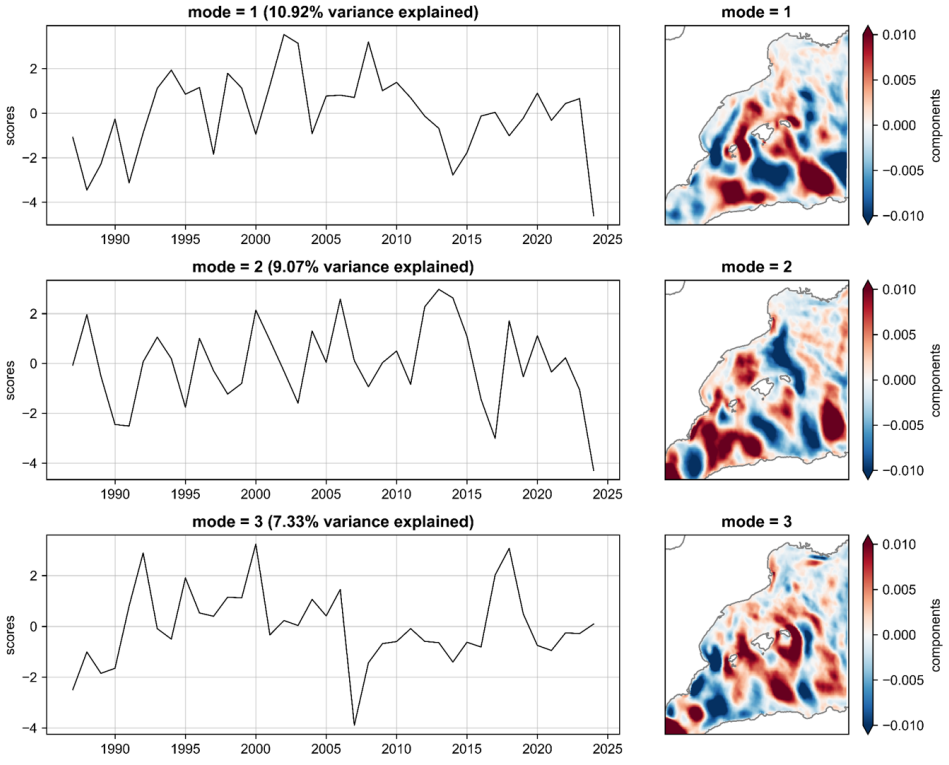

628 Figure A12. EOFs of the three first modes of variability for the de-trended annual current southeastward across shore (V)
629 at surface between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where
630 the spatial correlation is positive (red on the maps).

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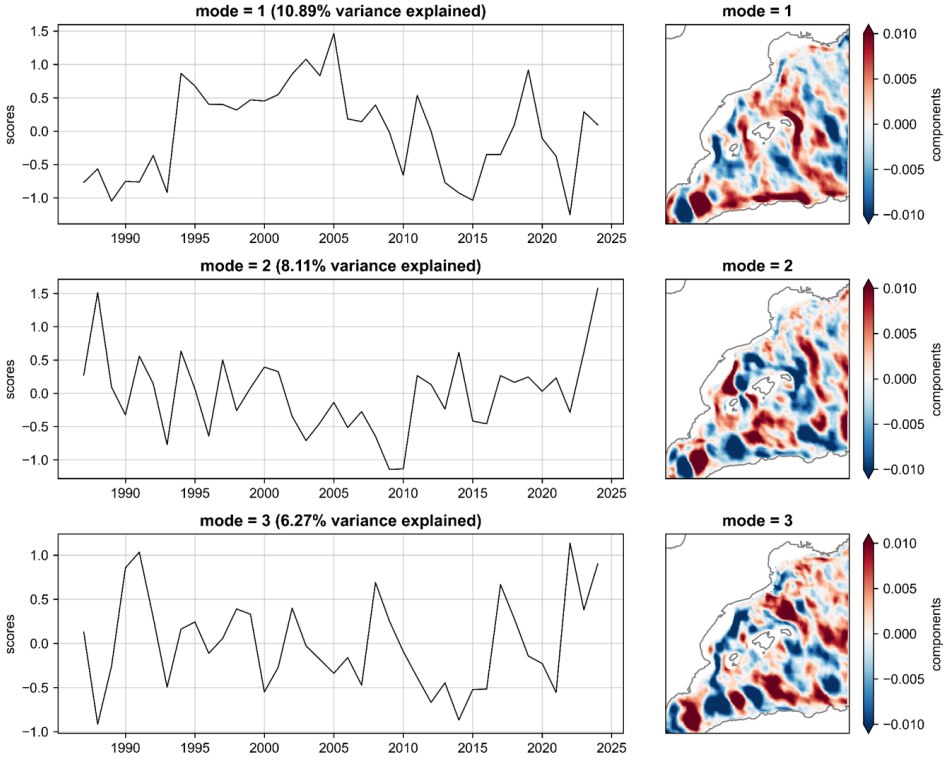

631 Figure A13. EOFs of the three first modes of variability for the de-trended annual current southeastward across shore (V)
632 at 200 m between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where
633 the spatial correlation is positive (red on the maps).

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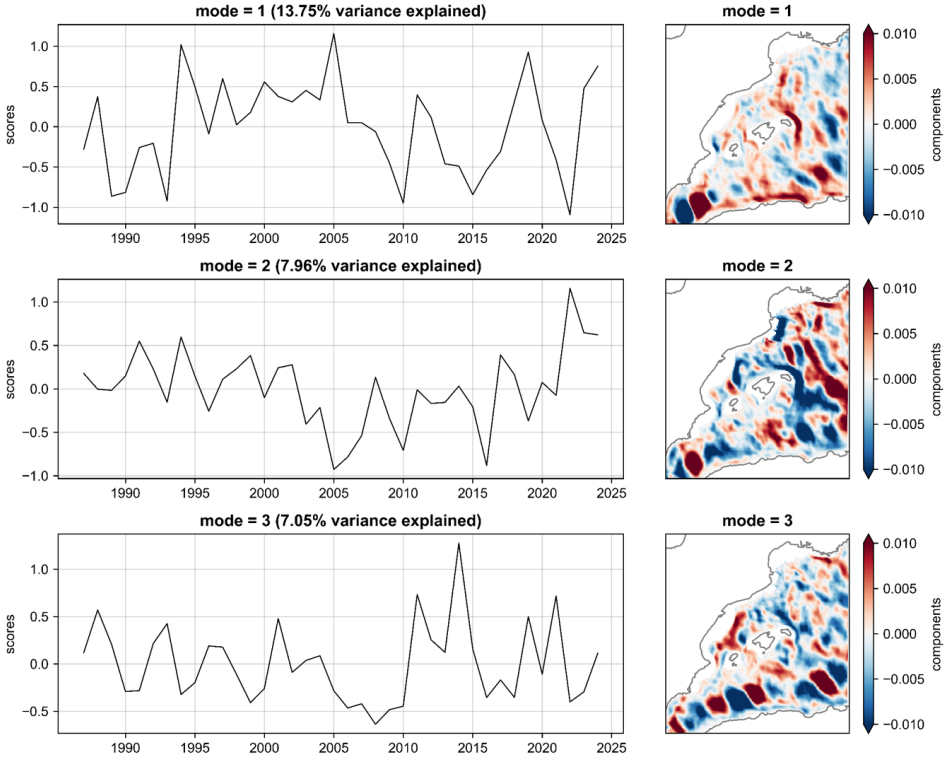

634 Figure A14. EOFs of the three first modes of variability for the de-trended annual current southeastward across shore (V)
635 at 400 m between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where
636 the spatial correlation is positive (red on the maps).

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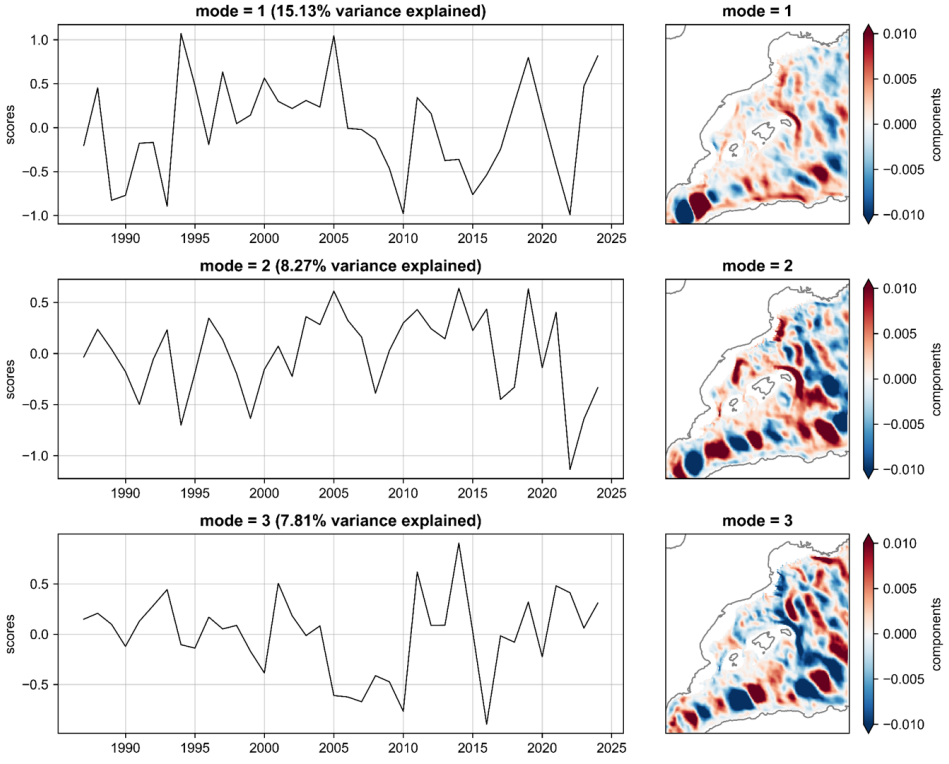

637 Figure A15. EOFs of the three first modes of variability for the de-trended annual current southeastward across shore (V)
638 at 600 m between 1987 and 2024. Here, positive score values indicate increasing intensity of the current in areas where
639 the spatial correlation is positive (red on the maps).

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Data availability statement

Data and code used for this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.18874070. Environmental data were obtained from Marine Data Store of the E.U. Copernicus Marine Environment Monitoring Service (CMEMS; https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1).

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Frédéric Cyr: conceptualization, methodology, formal analysis, writing (original draft), writing (review and editing), supervision.
Eve Galimany: conceptualization, writing (original draft), writing (review and editing), supervision.
Ricardo Santos-Bethencourt: data curation, visualization, writing (original draft), writing (review and editing).
Jordi Isern-Fontanet: conceptualization, writing (review and editing).
Jordi Ribera-Altimir: data curation, writing (review and editing).
Joan Sala-Coromina: data curation, writing (review and editing).
Mariona Panisello-Garriga: data curation, writing (review and editing).
Joan B. Company: conceptualization, writing (review and editing), supervision.

Conflict of interest statement

Authors declare no conflict of interest.

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