Derivation of a standardized index to explore spatial, seasonal and between-year variation of squid (*Loligo* spp.) abundance in the English Channel

Anna Marcout[a], Eric Foucher[b], Graham Pierce[c], Jean-Paul Robin[a]

[a] Normandie Université, UNICAEN, Alliance Sorbonne Université, MNHN, UA, CNRS, IRD, Biologie des Organismes et Ecosystèmes Aquatiques (BOREA), Esplanade de la Paix, 14032 Caen

[b] Ifremer, Laboratoire Ressources Halieutiques, Port-en-Bessin, France, France

[c]Instituto de Investigaciones Marinas (CSIC), Eduardo Cabello 6, 36208 Vigo, Spain

Corresponding author: +33 (0)6 84 68 68 16; anna.marcout@unicaen.fr ;

Abstract

Long-finned squids are among the valuable resources exploited by English Channel demersal fisheries. This resource consists of two short-lived species (not distinguished by fishers): *Loligo forbesii* and *Loligo vulgaris*, which differ in the timing of their life cycle.

In the present study, we investigated spatial, seasonal and long-term biomass variation of *Loligo* spp. in the English Channel using 22 years (2000-2021) of commercial fishing data to compute biomass indices. Results indicated that LPUE indices (computed per month for each statistical rectangle of the English Channel), standardized by vector autoregressive spatio-temporal (VAST) method, provided the best squid biomass estimator.

Two distinct geographical patterns were observed in the English Channel, with low and stable biomass indices in the West and most of the fluctuations and seasonal variations in East. Seasonal patterns seem likely to be related to the presence of the two species, with the beginning of increase in June in the western part of the English Channel probably corresponding to the recruitment of *L. forbesii* and a second increase further east in October probably corresponding to *L. vulgaris* recruitment. Over the 22-year series there was an eastward shift in squid biomass since 2014, suggesting that *L. forbesii* distribution has declined in the English Channel.

KEYWORDS: biomass trends, VAST LPUE Standardization, bottom trawl fishery data, time series clustering, centre of gravity, seasonal distribution

Introduction

Marine ecosystems are exposed to increasing climate change and other anthropogenic pressures (e.g., overfishing, pollution) which are expected to further intensify in the future (Moullec et al., 2021). Changes in biomass and distribution of marine species are taking place, influencing the entire food web (Albouy et al., 2014). Such changes take place against a background of natural climate variation (including cyclic variation). Understanding spatio-temporal patterns of abundance in marine species is a crucial issue in ecology and conservation biology (Fletcher et al., 2019) and for defining appropriate fisheries management units (Cadrin, 2020). Such information is used to adapt resource management strategies and anticipate ecological consequences of environmental changes (Morrison and Termini, 2016). In short-lived species such as squid the phenology of the life cycle, growth rate, body size and population abundance are known to be highly sensitive to climatic variation (Caddy et al., 1983; Dawe et al., 2007; Fogarty 1989; Pierce et al., 2008, 2010), presenting particular challenges (Arkhipkin et al., 2015).

Fisheries scientists have long acknowledged the importance of population spatial structure (Berkeley et al., 2004). However, in conventional stock assessments, the fisheries resource is assumed to be a single homogeneous population within a spatial domain, in part because of data and computational limitations (Cadrin et al., 2020, Cao et al., 2020). By ignoring fine-scale spatial heterogeneity, some conservation management has failed in marine ecosystems (Kerr et al., 2010). In the present study, we illustrate the use of classical methods to describe spatio-temporal changes in stock structure that may have consequences for population assessments with the English Channel long-finned squid stock.

Temporal changes in spatial distribution of demersal species are generally best described with scientific trawl survey data because they use consistent sampling gear, sampling scheme and protocol (Grosselin and Laurec, 1982; National Research Council, 2000). However, because they cover many boats over a wide area and during the whole year, commercial fishery data can be useful for stocks that are more widely distributed than the area covered by the surveys and for species that require finer temporal resolution than that of the annual snapshot of an annual survey.

Cephalopods in general and squids in particular differ from many other fished species due to biological and ecological characteristics like a short lifespan (approximately 1 year), semelparous reproduction, rapid growth, high natural mortality and sensitivity to environmental conditions that can affect their migration cycle. In English Channel Loliginid squids such biological traits are documented since a long time (Tinbergen and Verwey, 1945; Holme, 1974; Sims et al., 2001; Moreno et al., 2002) and are not different from what is described in other squid fisheries (Boyle and Rodhouse., 2005; Hastie et al., 2009; Arkhipkin et al., 2015; Rodhouse et al., 2014). The attempt to describe spatio-temporal variations using Channel Ground Fish Surveys (CGFS) survey data was limited to the situation in October in the Eastern part of the Channel (ICES subdivision 7D) (Carpentier et al., 2009). Therefore, landings and effort from the French commercial trawler fishery were used in the present study for their greater coverage in space (ICES subdivisions 7D and 7E) and their better temporal resolution (allowing us to track monthly changes).

Acknowledging the potential for fishery-dependent data sources to produce misleading biomass indices, such indices are frequently "standardized" to mitigate factors that could alter catchability. Cheng et al. (2023) have recommended that an initial step should involve comparing catch rates derived from logbooks with those obtain from survey data. As in the present study, such comparisons can enhance our understanding of potential biases caused by varying observation techniques, paving the way for the development of more accurate and integrated indices of biomass.

In the English Channel, long-finned squids support a large-scale fishery, with the highest squid landings of any areas in the Northeast Atlantic (ICES, 2020). Between 2000 and 2021, annual common squid landings from the English Channel averaging 3520 t were mainly caught by bottom trawlers (ICES, 2023) of the French and UK fleets (80% and 15% respectively) with some recent increase in catches by the Netherlands (Figure 1, redrawn from ICES, 2023). In 2019-2021, loliginid landings were below both the historical mean (2000-2021) and recent past values (2016-2018) suggesting that the status of loliginid populations in this area may be of concern (ICES, 2023).

The Channel squid stock includes two species (not distinguished by fishers or in fisheries statistics), *Loligo forbesii* (Steenstrup, 1856) and *Loligo vulgaris* (Lamarck, 1798), both of which have an approximately one-year lifespan (Holme, 1974; Guerra and Rocha, 1994) but which differ in the timing of their life cycle (Royer, 2002; Laptikhovsky et al., 2022). The recruitment to the fishery of *L. forbesii* begins in June whereas *L. vulgaris* starts appearing in fishery catches in September and the fishing season ends in May (Robin and Boucaud-Camou, 1995; Royer, 2002). English Channel long-finned squid have been considered as a mixed resource in previous ecological and stock assessment studies (Robin and Denis, 1999; Denis et al., 2002; Royer et al., 2002; ICES 2020). Although various authors, including ICES WGCEPH have called for progress in species identification and recording in fisheries statistics (ICES, 2020; ICES, 2023), at present the analysis of time series for temporal trends can only consider the two species together.

In the present study, 22 years (2000-2021) of commercial fishery data were used to compute biomass indices to improve our understanding of spatio-temporal dynamics of *L. vulgaris* and *L. forbesii* in the English Channel. The main objectives of this study were to (1) compute the best estimator of squid biomass by testing several different standardization methods, (2) provide a description of seasonal and interannual variation in squid biomass in the English Channel, identifying the areas with the highest squid abundance and quantifying seasonal and interannual shifts in squid distribution.

Materials and methods

1. English Channel dataset sources

Commercial squid landings (kg) and effort (hours of trawling) for all French bottom otter trawls (OTB) were collected from national databases managed by Ifremer (Système d'Information Halieutique-SIH) by fishing sequence, year, month and ICES rectangles from 2000 to 2021 in the English Channel. A fishing sequence is defined as a succession of hauls carried out during the same fishing trip, taking place in the same ICES statistical rectangle and using the same fishing gear (Mahevas et al., 2011). Using the European Vessel Registry, vessel engine power (kW) has been associated with each fishing sequence. To characterize squid distribution, we have linked each ICES rectangle to the geographical coordinate of its barycentre using QGIS software and the shapefile: "ICES_Statistical_Rectangles_Eco.shp" downloaded from the ICES website (Figure 2). In total, 927 281 fishing sequences from 1011 different vessels were analyzed.

The different computations applied to commercial data will be compared to Channel Ground Fish Surveys (CGFS) conducted in October, which operates only in the Eastern part of the Channel (ICES division 7D). The data also available in the Database of Trawl Surveys (DATRAS) were extracted on national databases maintained by Ifremer (Système d'Information Halieutique-SIH).

2. Computation of squid biomass indices

Commercial datasets were used to compute Landings Per Unit Effort (LPUE) by ICES rectangle and by month for catches in the English Channel (30 rectangles) during the period 2000-2021 (264 months), using hours of trawling as effort. According to onboard observations provided by the Ifremer program "OBSMER", as well as declarations by France and the UK, there is a low squid discard level in the English Channel, which is always below 6% (ICES, 2011; 2017). Discards were considered as negligible (Royer et al. 2002; ICES, 2020). To obtain the best estimator of squid biomass, three different LPUE indices were computed: basic LPUE, LPUE standardized with vessel power, and LPUE standardized using a spatio-temporal model.

2.1 Basic LPUE

The basic LPUE for each month *m* and rectangle *i* is the sum of landings (*L*) divided by the sum of effort (*E*):

$$\text{LPUE}_{\text{basic}\ m,i} = \frac{\sum L_{m,i}}{\sum E_{m,i}}$$

Where *L* is landing in kg, *E* is effort in hours of fishing.

2.2 LPUE standardization with vessel power

Vessel power has an effect on LPUE: vessels with higher engine power can use larger gear and trawl more fish at higher speeds resulting in higher landings. To make the LPUE comparable between vessels, LPUE values were standardized to the LPUE of a 400 kW vessel (the most common vessel power in our fishing data) by month *m* for each ICES rectangle *i* following this equation (Hammen et al., 2011; Rijnsdorp et al., 2006):

$$\text{LPUE}_{\text{vessel}\ m,i} = \sum \frac{L_{m,i}}{\frac{\text{E}_{m,i} * \text{kW}_{m,i}}{400}}$$

Where *L* is landing in kg, *E* is effort in hours of fishing, kW is vessel power in kW. This formula is valid under the assumption that LPUE is linearly related to the vessel power in kW.

2.3 LPUE standardization with spatio-temporal model

We applied a vector autoregressive spatio-temporal (VAST) model implemented using the R package "VAST" (https://github.com/James-Thorson-NOAA/VAST) (Thorson, 2019) to standardize squid LPUE by month from 2000 to 2021 (264 months in total) and by rectangle. This delta generalized linear mixed model method includes two components, the probability of encounter and the positive catch rate:

$$(1)\ \ \Pr[c] = \Pr[C>0] \times \Pr[C = c \mid C>0]$$

Where c is the catch rate (catch per fishing hours) for each fishing sequence, Pr [C>0] is the probability of a positive catch and Pr [$C = c| C>0$] is the probability of catch c given that the catch is positive. Pr[C>0] is modeled as a Bernoulli random variable, and Pr [$C = c| C>0$] as a Gamma distributed random variable:

$$(2)\ \Pr[C>0] = p_{m,i}$$

$$(3)\ \Pr[C = c| C>0] = \text{Gamma}\,(c, \sigma^{-2}, r_{m,i}\sigma^{2})$$

Where p_i is the encounter probability and $r_{m,i}$ the positive catch rate. σ^{-2} and $r_{m,i}\,\sigma^{2}$ are the shape and scale terms of the Gamma distribution.

We implemented the spatio-temporal model by incorporating vessel power as a covariate which affects catchability (Thorson et al., 2019). The encounter probability (p) for month m and rectangle i was modeled using a logit linked linear predictor, and the positive catch rate (r) for month m and rectangle i was modeled using a log-linked linear predictor as suggested by Thorson et al. (2021):

$$(4)\ \text{logit}\ p_{m,i} = \beta_m^{(p)} + L_\omega^{(p)}\omega_i + L_\varepsilon^{(p)}\varepsilon_{m,i} + L_\eta^{(p)}\eta_{m,i}$$

$$(5)\ \log r_{m,i} = \beta_m^{(r)} + L_\omega^{(r)}\omega_i + L_\varepsilon^{(r)}\varepsilon_{m,i} + L_\eta^{(r)}\eta_{m,i}$$

where βm are the month-specific intercepts, L_η are vessel effects included to capture differences in fishing power among vessels. $L\omega$ and $L\varepsilon$ are spatial and spatio-temporal random effects approximated using Gaussian random fields, which imply correlations in spatial variation decay as a function of distance. More detailed information about this model was provided by Thorson (2019). The biomass indices ($B_{m,i}$) in month m for rectangle y were obtained as:

$$(6)\ \text{LPUE}_{\text{VAST}\ m,i} = \text{logit}^{-1}\left(\beta_m^{(p)} + L_\omega^{(p)}\omega_i + L_\varepsilon^{(p)}\varepsilon_{m,i} + L_\eta^{(p)}\eta_{m,i}\right) \text{ x } \exp\left(\beta_m^{(r)} + L_\omega^{(r)}\omega_i + L_\varepsilon^{(r)}\varepsilon_{m,i} + L_\eta^{(r)}\eta_{m,i}\right)$$

The number of knots determining the spatial resolution of the VAST model was set to 30 corresponding to the number of ICES rectangle in the English Channel analyzed.

2.4 CGFS index

In order to look at differences between commercial LPUE and fishery-independent data, scientific CGFS survey data were used to compute a CGFS index from 2000 to 2021.

The CGFS occurs each year during October (Coppin et al., 2002). For each rectangle *i* and month *m*:

$$\text{CGFS}_{m,i} = \frac{C_{m,i}}{A_{m,i}}$$

Where *C* is catch in kg and *A* is the trawl area swept for each ICES rectangle in km^2.

3. Statistical analysis

All statistical analysis were performed in R (R Development Core Team, 2023).

3.1 Assessing the accuracy of standardization by comparing with indices from scientific surveys

To test the accuracy of LPUE indices standardized as an estimator of biomass, we examined correlations between the CGFS index (per rectangle in October) and the three different indices obtained from commercial data (per rectangle in October): $\text{LPUE}_{\text{basic}}$, $\text{LPUE}_{\text{vessel}}$, $\text{LPUE}_{\text{VAST}}$ between 2000 and 2021. Normality was checked with Shapiro-Wilk normality test. If the data followed a normal distribution and were homoscedastic, Pearson's correlation test were conducted otherwise Spearman's correlation test were conducted.

Of these three different LPUE, the one most correlated with CGFS was used for further analysis as the most accurate index for biomass.

3.2 Seasonal decomposition of time series

We investigated interannual and long-term variability of the squid biomass index using a Seasonal and Trends Loess (STL) (Cleveland et al., 1990) decomposition analysis of the average time series 2000 – 2021 (264 months) (i.e. averaged over all ICES rectangles of the English Channel). STL use LOESS (locally estimated scatterplot smoothing) to extract smooth estimates of three components from the original series (Y_t): the global trend component (T_t), which represents the long-term evolution, the seasonal component (S_t), which is periodic, and the remainder (R_t) component, representing irregular fluctuations:

$$Y_t = T_t + S_t + R_t \qquad 1 \leq t \leq n$$

Where n is the total number of months in the time series.

3.3 Time series Clustering

To investigate spatial variability, time series clustering was applied on the squid biomass index time series of each ICES rectangle of the English Channel to identify groups of rectangles with similar temporal dynamics.

Euclidian distance is the most commonly used distance measure for cluster analysis however it may not be the most appropriate tool for time series due to its high sensitivity to small distortions in the time axis. In other words, two time series that are very similar but are slightly shifted in time relative to each other can be classified as very different time series. We addressed this issue by using Dynamic Time Warping (DTW) methodology (Berndt and Clifford, 1994; Aghabozorgi et al., 2015), an elastic, shape-based similarity measure that deals with temporal drift.

First, a dissimilarity matrix was calculated between time series, considering all rectangle pairs, minimizing the distance and allowing comparison at different time steps using the dynamic time warping (DTW) method. The resulting distance matrix was analyzed using hierarchical clustering agglomerated with the “ward.D2” method, which minimizes within-cluster variance. Time series are first considered as distinct clusters, then gradually merged together in a bottom-up way (Aghabozorgi et al., 2015), resulting in a dendrogram.

DTW analysis were implemented using the dtw R package (Giorgino et al., 2009).

*3.4 Spatial parameter*s

To quantify shifts in squid biomass indices distribution, we computed the centre of gravity for longitude and latitude, the inertia, and the average distance from the coast, by month from 2000 to 2021. These parameters are similar to those described by Cotter et al. (2009) in the case of trawl survey data.

- Centre of gravity of the biomass indices

For each month *m*, we computed a “weight” corresponding to the proportion of the biomass indices that were located in each rectangle *i*:

$$W_{m,i} = \frac{\mathrm{LPUE}_{m,i}}{\sum_{i=1}^{n} (\mathrm{LPUE}_{m,i})} \text{ and } \boldsymbol{\Sigma}\ W_{m,i} = 1$$

Using ICES rectangle centroids with coordinates X_i and Y_i for longitude and latitude respectively, centres of gravity [X_{gm}, Y_{gm}] were obtained as:

$$X_{gm} = \sum_{i=1}^{n} (X_i * W_{m,i}) \text{ and } \mathrm{Y}_{\mathrm{gm}} = \sum_{i=1}^{n} (Y_i * W_{m,i})$$

- Inertia

In month *m*, a measure of biomass index concentration is the Inertia (C_m), which is computed as follows:

In each rectangle *i*, the distance between the rectangle centroid and the centre of gravity in month *m* is:

$$D_{m,i} = \sqrt{(X_i - X_{gm})^2 + (Y_i - Y_{gm})^2}$$

and the inertia of all biomass indices in month m is: $C_m = \frac{\Sigma\ (\mathrm{LPUE}_{m,i}\ *\ D_{m,i}{}^2)}{\Sigma\ \mathrm{LPUE}_{m,i}}$

- Average distance from the coast of the biomass indices

In each rectangle *i*, the shortest distance between the centroid and the nearest coast (based on the countries shapefile taking into account England, the Isle of Wight, and the Continent Mainland) is computed with ArcGIS, and stored in variable L_i.

In month *m* the average distance from the coast of the biomass indices is given by:

$$L_m = \Sigma \, (L_i * W_{m,i})$$

Results

1. Comparison of squid biomass indices

To quantify variations in squid abundance using fishery-dependent data, various standardized methods for calculating Landings-Per-Unit-Effort (LPUE) were analyzed and contrasted with CGFS survey-derived estimates (Figure 3). The CGFS index (kg/area swept) obtained in October showed non-significant positive correlations with $LPUE_{basic}$ ($r = 0.33$, $p = 0.13$) and $LPUE_{vessel}$ ($r = 0.32$, $p = 0.14$) between 2000 and 2021. However, $LPUE_{VAST}$ was significantly correlated ($r = 0.63$, $p = 0.002$) with the CGFS indices between 2000 and 2021, suggesting that $LPUE_{VAST}$ is the most realistic index for biomass. For the rest of the analysis, biomass indices refer to $LPUE_{VAST}$.

Monthly biomass indices from 2000 to 2021 for each ICES rectangle of the English Channel were represented in 264 maps, which can be found in an animation gif in the supplementary material (Appendix 1). Four “example” maps were selected to provide an overview the spatio-temporal variations across season and year (Figure 4). The data from 2012 and 2017 indicate that biomass indices were notably higher in December than in July, with a greater concentration of squid in the eastern part of the English Channel. Moreover, the biomass indices in December 2017 surpassed those of December 2012, highlighting seasonal, spatial, and interannual variations in squid biomass indices. To quantify the variations between all 264 maps, different quantitative methods were employed, detailed in the subsequent sections.

2. ***Seasonal decomposition of time series***

First, interannual and long-term variability of the squid biomass index were investigated by using a Seasonal and Trends Loess (STL) decomposition analysis over all ICES rectangles in the English Channel between 2000 and 2021 (Figure 5).

The general trend (Figure 5.b) shows a very high peak at the start and after that illustrates irregular interannual variability with highs in 2004, 2010, 2015 and 2017 and lows in 2005, 2009, 2013, 2016, and 2020. Rather stable periods are observed in 2006-2008 and 2017-2019. Apart from the initial (2000) peak, interannual variations suggest that the biomass index can be multiplied/divided by 2-3 from one year to the next. The general trend does not reveal any cyclic pattern in interannual variations.

Time series decomposition indicated the existence of regular seasonal patterns (Figure 5.c) in biomass indices. From 2000 to 2013, the amplitude of seasonal variations seems to have been stable [-5 ; +5]. There was a gradual increase in the amplitude of seasonal variation from 2014 to 2021, reaching values between -5 and 13 after 2017.

Biomass indices showed seasonal variations (Figure 6) following a very regular pattern with an increase from June to December and gradually decreased from January to May (Figure 6.a). In summer months, biomass indices gradually increased from an average around 3 in June to an average around 6 in September. There are more marked increases later in the year, with biomass indices reaching averages of 9 in October, 13 in November and 15 (the maximum) in December. From January to May, biomass indices decreased from an average around 11 to a minimum average of 1.

Analysis over the years of monthly indices (Figure 6.b) show that the peak in biomass indices in 2000, as observed in Figure 6, is due to very high values in January and February. Apart from the initial (2000) peak, biomass indices seem to have been stable for each month between 2000 and 2014. Since 2014, two different dynamics were observed, a decrease of the monthly average biomass indices in summer months and an increase in Autumn-Winter, which together are responsible for the increase of seasonal variations found in Figure 5.c.

3. ***Common temporal patterns between rectangle biomass indices using clustering***

To identify homogeneous groups of ICES rectangle biomass indices for the English Channel, time series clustering was used. The cluster analysis (Figure 7) shows that the groups of rectangles having similar temporal trends in biomass are clearly geographically distinct with a Western cluster and an Eastern cluster. Time series decomposition of each cluster shows different dynamics, with low and stable biomass indices for the Western cluster (Figure 7.c) and important fluctuations in the Eastern cluster (Figure 7.d). Seasonal fluctuations are observed in both clusters with similar rhythmicity but with a slightly delayed timing in the Eastern cluster and with a much higher amplitude in this Eastern group of rectangles. Most of the variations observed at the scale of the whole of the Channel (Figure 5) are thus found in the East of the English Channel.

4. ***Analysis of spatial parameters***

Centre of gravity, inertia, and average distance to the coast were calculated by month from 2000 to 2021 to quantify shifts in distribution of squid biomass indices.

4.1 Seasonal variations of squid centre of biomass

Analysis of monthly centre of gravity reveals that seasonal variations are more important than interannual variability. Figure 8.a shows that barycentres are grouped by months. Monthly averages plotted in Figure 8.b underline that changes in average biomass location occur in a cyclic sequence. Between June and September, gravity centres are found in the West of the English Channel (49.5, 49.7°N ; -3.1, -2.5°E), with a slight west to east movement associated with a gradual increase in mean biomass indices. From September to December gravity centres move eastwards (49.7, 50°N ; -1.8, -0.8°E) and mean biomass indices increases to reach maximum values in December. From January to March, mean biomass indices decreases progressively while gravity centres are still located in the eastern part of the English Channel (50.1, 50.2°N ; -0.6, -0.3°E). From April, gravity centres move westwards (49.7, 50.0°N ; -1.7, -0.49°E) and mean biomass index reaches its lowest value in May.

Longitude (X_g) and latitude (Y_g) of the monthly gravity centres are highly correlated ($r = 0.88$, $p < 0.0001$) suggesting homogeneous shift north-east and south-west. Squid biomass indices are positively correlated to the gravity centres coordinates (longitude: $r = 0.31$, $p < 0.0001$; latitude: r = 0.39, $p < 0.0001$) reflecting highest squid concentration in the north-east of the English Channel. Over the course of an average fishing season (between June and March, Figure 8.b) the squid resource moves more than 110 nautical miles.

Monthly analysis of the mean distance to the coast and the Inertia (measure of dispersion) confirmed the centre of gravity observations. From June to August, when the centre of gravity is further west in the English Channel (the widest part of the English Channel; Figure 8), the mean distances to the coast were the highest (Appendix 2.a). The gradual decrease in the mean distances to the coast observed since October (Appendix 2.a) corresponds to the eastward shift of squid biomass indices (the narrowest part of the English Channel; Figure 8).

For the dispersion parameter, maximum values were found in May and October (Appendix 2.b) corresponding to the shift periods between east and west (Figure 8).

4.2 Interannual variations of squid concentration

Yearly centres of gravity are much closer together than monthly averages (Figure 9). The maximum distance between annual mean points is less than 32 nautical miles (2005 vs 2018). The temporal trend shows a decadal shift in the English Channel with mean centres of gravity located between -1.85 and -1.48°E during the period 2000 – 2013 and between -1.54 and -1.05°E for the period 2014-2021, this eastward shift in squid concentration since 2014 is consistent with the temporal trend observed in the eastern cluster of rectangles.

This shift is also observed in long-term trends in inertia (a measure of dispersion) and average distances to the coast, which decrease sharply from 2014 (Appendix 3.a and b). Inertia is negatively correlated to squid biomass indices (r = -0.13, p = 0.03) suggesting a smaller scattering of the distribution around the centre of gravity when squid biomass is high.

Discussion

The starting point for this study was the lack of data to describe changes in the spatial distribution of English Channel squid on an appropriate timescale. In such short-lived migrating populations (Holme, 1974, Tinbergen and Verwey, 1945, Sims et al., 2001, Royer, 2002), it is necessary to take into account distribution changes during the course of a fishing season and at all stages of cohort exploitation, as well as between years (i.e. between annual cohorts). In the absence of scientific surveys designed at a relevant temporal scale it is rather common to derive indices from commercial fishery data (Rosenberg et al., 1990; Roa-Ureta, 2012). Indices derived from landings per unit of effort (LPUE) of commercial trawlers are biomass estimates rather than abundance estimates since there is no biological sampling programme that would enable conversion of weights into numbers and, indeed, the high variability in growth rate means that length-weight relationships are also variable, thus requiring more frequent and intense sampling than would otherwise be the case.

(a) LPUE standardization

Standardized LPUE indices (computed per month and rectangle) were compared to the only (survey-based) series of observations available: biomass indices derived from the CGFS surveys carried out in October. Results of correlation analyses suggested that LPUE standardized by the vector autoregressive spatio-temporal method (VAST, Thorson 2019) shows the best match with squid biomass estimated from survey data, in comparison with non-standardized LPUE or LPUE that was standardized based on engine power. The value of this delta-glm model is that it takes into account both the probability of encounter and the positive catch rate and allows the integration of co-variables that influence biomass or catches (such as vessel power). Data from trawl surveys have also drawbacks (Knijn et al., 1993; Baudrier et al., 2018), mainly related to selectivity issues and to the fact that fishing operations were not designed specifically for catching squid. The VAST standardization method has been compared to other standardization procedures like GLMs or GAMs and, although this was not the objective of our study, it is worth mentioning that in these other comparisons VAST provided the best fits (Grüss et al., 2019). This procedure has enabled us to obtain for the first time in the analysis of these resources, biomass indices per month (from 2000 to 2021) and per statistical rectangle in the English Channel which is the first step in studying spatio-temporal variations in squid stocks. It is applicable in other short-lived species provided that the stock's range is regularly explored by a commercial fleet.

Variations in the timing of the appearance of *L. forbesii* in the local area off Plymouth had already been studied (Sims et al., 2001). However, this study is the first decomposition of temporal trends in 30 ICES rectangles of the English Channel.

(b) General interannual trend

Temporal analyses of biomass indices suggest a relatively stable trend during the first decade, with ups and downs. In the last decade, there was an increasing trend from 2014 and 2018 followed by a decreasing trend in 2019 and 2020. This decline in the 2019-2020 observations coincided with a drop in total landings from the same area, and suggests that the status of loliginid populations in the English Channel may be of concern (Figure 1, ICES, 2023). Environmental drivers of this variability may be sought and relationship with temperature have already been shown (e.g. Waluda and Pierce, 1998; Robin and Denis, 1999; Challier et al., 2005). However, observations in the period 2000-2021 do not suggest that English Channel squid undergo long-term cycles of abundance. The hypothesis of the influence of the 10-12 years solar cycle on English Channel communities (Southward et al., 1975) do not seems to apply to squid populations. The hypothesis that its effect would be masked by other factors, e.g. the global warming context (Southward et al., 1995) is not supported by time series decomposition.

(c) Seasonality

The present findings also indicated the existence of a seasonal fluctuations. Seasonal peaks and trough are consistent with the annual life-cycle of Loliginid squids (Holme, 1974; Guerra and Rocha, 1994; Moreno et al., 2007). The slight shift in the timing of seasonal cycles in the Western and Eastern parts of the Channel seems likely related to the presence of the two species *Loligo forbesii* and *Loligo vulgaris* in the resource with different timings of their life-cycles (Holme, 1974; Robin and Boucaud-Camou, 1995; Royer, 2002, Laptikhovsky et al., 2022) and with differing importance in the Western and Eastern parts of the Channel. Within each year, the beginning of an increase in abundance in June is likely to correspond to the recruitment to the fishery of *L. forbesii* and a second increase in October then corresponds to *L.vulgaris* recruitment. Again, time series decomposition of VAST standardized indices provides for the first-time evidence that the seasonal pattern is consistently repeated. A similar seasonality over more than 20 fishing seasons illustrates that the life-cycle of both species is repeating in a regular way and that sub-cohorts or variable timing of recruitment peaks as observed in *L. forbesii* in Scottish waters (Pierce et al., 1994) are of minor importance in Channel stocks.

(d) Spatial patterns

Cluster analysis identify two distinct geographical patterns (West/East) among ICES rectangle time series. Low and stable biomass indices were found in the Western English Channel and most of the fluctuations and seasonal variations were found in Eastern English Channel. This result is different from the clustering with spatial contiguity constraint applied by Royer (2002). This is likely a difference related to the temporal window analysed since *L. forbesii* was more abundant in 1992-1999 (Chen et al., 2006).

Analysis of monthly centres of gravity provide a quantitative view of squid distribution shifts. From June to September squid biomass is centred in the West, the deepest part of the English Channel (Dauvin, 2012), and the area where the recruitment of *L. forbesii* begins in June (Holme, 1974). From October, squid concentrations move eastwards, probably corresponding to the appearance of *L. vulgaris* in fishery catches (Robin and Boucaud-Camou, 1995). These observations are consistent with the fact that *L. forbesii* has a deeper, more offshore, distribution than its congener *L. vulgaris* (Lordan and Casey, 1999; Hastie et al., 2009). The Eastward shift in the location of centre of gravity and the increase of inertia (a measure of dispersion) in October is likely the result of a combination of two phenomena: the autumn recruitment of *L. vulgaris* and the eastward migration of immature *L. forbesii* (Holme, 1974; Royer, 2002; Vaz et al., 2008). *L. forbesii* gradually migrate eastward, while foraging, into the Eastern Channel and then return to the Western approaches in autumn. Females *L. forbesii* reach maturity in November, spawn in December - January, and the juveniles are seen in the catches around May after hatching from the eggs. Royer (2002) made the first trial to quantify migratory fluxes of the two squid species within the English Channel using spatialized cohort analysis. This preliminary trial was done using strong assumptions (equal catchability and the proportions of both species in catches being the same in all locations, varying according to results of monthly sampling in a single fish market). In comparison, changes in the location of the centre of gravity offer a rather direct quantification of spatial patterns that can be used to better understand interannual variation. The advantage of quantitative parameters like centres of gravity can be seen by comparing the difficulties of analyzing 264 maps like those in Figure 4 with the trends clearly visible in Figure 8.

Such a quantitative approach to the distribution of cephalopod resources could be used in other migrating species like *Sepia officinalis* whose wintering grounds vary according to minimal temperatures (Wang et al., 2003).

(e) Shift in squid biomass distribution from 2014

Analysis of yearly centres of gravity suggested an eastward shift in squid concentration since 2014. These observations coincided with an increase of seasonal variations in biomass indices trends since 2014, with a decrease of the monthly average biomass indices in summer and an increase in autumn-winter.

We hypothesize that these observations reflect a decrease in the biomass of *L. forbesii* present from June to September and localized in the west of the English Channel and an increase in the biomass of *L. vulgaris* present from October and localized in the east. This squid biomass shift is consistent with observations of fishery landings at the Port-en-Bessin fish market suggesting that the proportion of *L. forbesii* is decreasing while *L. vulgaris* is increasing over time in the English Channel (Royer 2002; Marcout et al. in prep). Our findings are also consistent with the findings of Oesterwind et al. (2022) who found that the distribution range of *L. forbesii* has declined in the English Channel, but has increased in the North Sea, suggesting a northward shift in population range.

Conclusion

The present study illustrates the benefits of using commercial fishing data to derive abundance indices, with the advantage of its large spatial coverage and fine temporal resolution. It requires adapted standardization tools but the resulting index provides new insights on squid distribution and stock structure suggesting an East/West division of the resource with a decrease in *L. forbesii* population. Our results highlight the importance of taking into account spatio-temporal changes in stock structure, knowledge of which could be helpful for fishery managers to give adaptative responses in local and regional fisheries.

Climate change may be contributing to the recent eastward shift in squid distribution in the English Channel, as is the case for distribution shifts in other cephalopod populations (Oesterwind et al., 2022) and indeed in the distributions of various fish species in this region (Auber et al., 2017; McLean et al., 2018; Lima et al., 2022). Continued monitoring will be needed to confirm this hypothesis.

Acknowledgements

This work was supported by France Filière Pêche (FFP) and by the Conseil Régional de Basse Normandie. We would like to thank the Système d'Information Halieutique (SIH) of the Ifremer for providing us with French commercial landings and the French Direction des Pêches Maritimes et de l'Aquaculture (DPMA) for granting permission for using commercial data.

References

Aghabozorgi, S., Shirkhorshidi, A. S., & Wah, T. Y. (2015). Time-series clustering–a decade review. Information systems, 53, 16-38.

Albouy, C., Velez, L., Coll, M., Colloca, F., Le Loc'h, F., Mouillot, D., & Gravel, D. (2014). From projected species distribution to food-web structure under climate change. Global change biology, 20(3), 730-741.

Arkhipkin, A. I., Rodhouse, P. G., Pierce, G. J., Sauer, W., Sakai, M., Allcock, L.,. . Zeidberg, L. D. (2015). World squid fisheries. Reviews in Fisheries Science & Aquaculture, 23(2), 92-252.

Arkhipkin, A. I., Hendrickson, L. C., Payá, I., Pierce, G. J., Roa-Ureta, R. H., Robin, J. P., & Winter, A. (2021). Stock assessment and management of cephalopods: advances and challenges for short-lived fishery resources*. ICES Journal of Marine Science, 78(2),* 714-730.

Auber, A., Gohin, F., Goascoz, N., & Schlaich, I. (2017). Decline of cold-water fish species in the Bay of Somme (English Channel, France) in response to ocean warming. *Estuarine, Coastal and Shelf Science, 189*, 189-202.

Baudrier, J., Lefebvre, A., Galgani, F., Saraux, C., & Doray, M. (2018). Optimising French fisheries surveys for marine strategy framework directive integrated ecosystem monitoring. Marine Policy, 94, 10-

Berkeley, S. A., Hixon, M. A., Larson, R. J., & Love, M. S. (2004). Fisheries sustainability via protection of age structure and spatial distribution of fish populations. Fisheries, 29(8), 23-32.19.

Berndt DJ, Clifford J (1994). Using dynamic time warping to find patterns in time series. In: KDD workshop, vol 10, pp 359–370

Boyle, P., Rodhouse, P. (2005). Cephalopods: ecology and fisheries. Oxford: Blackwell Science.

Cadrin, S. X. (2020). Defining spatial structure for fishery stock assessment. *Fisheries Research, 221,* 105397.

Cao, J., Thorson, J. T., Punt, A. E., & Szuwalski, C. (2020). A novel spatiotemporal stock assessment framework to better address fine-scale species distributions: development and simulation testing. *Fish and Fisheries, 21(2)*, 350-367.

Carpentier, A., Coppin, F., Curet, L., Dauvin, J.-C., Delavenne, J., Dewarumez, J.-M.,Dupuis, L., Foveau, A., Garcia, C., Gardel, L., Harrop, S., Just, R., Koubbi, P., Lauria,V., Martin, C., Meaden, G., Morin, J., Ota, Y., Rostiaux, E., Smith, B., Spilmont, N.,Vaz, S., Villanueva, C.-M., Verin, Y., Walton, J., Warembourg, C., (2009). Channel Habitat Atlas for Marine Resource Management—CHARM II, URL http://archimer.ifremer.fr/doc/00000/7377/.

Challier, L., Royer, J., Pierce, G. J., Bailey, N., Roel, B., Robin, J. P. (2005). Environmental and stock effects on recruitment variability in the English Channel squid *Loligo forbesi*. Aquatic Living Resources, 18(4), 353-360.

Chen, C. S., Pierce, G. J., Wang, J., Robin, J. P., Poulard, J. C., Pereira, J., ... & Orsi-Relini, L. (2006). The apparent disappearance of *Loligo forbesi* from the south of its range in the 1990s: trends in Loligo spp. abundance in the northeast Atlantic and possible environmental influences. *Fisheries Research*, *78*(1), 44-54.

Cheng, M. L. H., Rodgveller, C. J., Langan, J. A., & Cunningham, C. J. (2023). Standardizing fishery-dependent catch-rate information across gears and data collection programs for Alaska sablefish (Anoplopoma fimbria). *ICES Journal of Marine Science*, *80*(4), 1028-1042.

Chu, S., Keogh, E., Hart, D., & Pazzani, M. (2002). Iterative deepening dynamic time warping for time series. In *Proceedings of the 2002 SIAM International Conference on Data Mining* (pp. 195-212). Society for Industrial and Applied Mathematics.

Cleveland, R. B., Cleveland, W. S., McRae, J. E., & Terpenning, I. J. (1990). STL: A seasonal-trend decomposition procedure based on loess. *Journal of Official Statistics*, *6*(1), 3–33. http://bit.ly/stl1990

Coppin, F., Carpentier, A., Delpech, J.-P., Schlaich, I., (2002). Manuel des protocoles de campagne halieutique. Campagnes CGFS. V3, URL http://archimer.ifremer.fr/doc/00036/14705/12011.pdf

Cotter, J., Petitgas, P., Abella, A., Apostolaki, P., Mesnil, B., Politou, C. Y., ... Woillez, M. (2009). Towards an ecosystem approach to fisheries management (EAFM) when trawl surveys provide the main source of information. Aquatic Living Resources, 22(2), 243-254.

Dauvin, J. C. (2012). Are the eastern and western basins of the English Channel two separate ecosystems?. *Marine Pollution Bulletin*, *64*(3), 463-471

Denis, V., Lejeune, J., & Robin, J. P. (2002). Spatio-temporal analysis of commercial trawler data using General Additive models: patterns of Loliginid squid abundance in the north-east Atlantic. ICES Journal of Marine Science, 59(3), 633-648.

Fletcher, R. J., T. J. Hefley, E. P. Robertson, B. Zuckerberg, R. A. McCleery, and R. M. Dorazio. (2019). A practical guide for combining data to model species distributions. *Ecology* 100: e02710.

Giorgino, T. (2009). Computing and visualizing dynamic time warping alignments in R: the dtw package.

Grosselin, M. D., & Laurec, A. (1982). Bottom trawl surveys design, operation and analysis. FAO, CECAF/ECAF Series, 1014-9228

Grüss, A., Walter III, J. F., Babcock, E. A., Forrestal, F. C., Thorson, J. T., Lauretta, M. V., & Schirripa, M. J. (2019). Evaluation of the impacts of different treatments of spatio-temporal variation in catch-per-unit-effort standardization models. *Fisheries Research*, *213*, 75-93

Guerra, A., Rocha, F. (1994). The life history of *Loligo vulgaris* and *Loligo forbesi* (Cephalopoda: Loliginidae) in Galician waters (NW Spain). Fisheries Research, 21, 43-69.

Hastie, L. C., Pierce, G. J., Wang, J., Bruno, I., Moreno, A., Piatkowski, U., & Robin, J. P. (2009). Cephalopods in the north-eastern Atlantic: species, biogeography, ecology, exploitation and conservation. *Oceanography and marine biology*, 123-202

Holme, N. A. (1974). The biology of Loligo forbesi Steenstrup (Mollusca: Cephalopoda) in the Plymouth area. *Journal of the Marine Biological Association of the United Kingdom, 54(2),* 481-503.

ICES. (2011). Report of the Working Group on Cephalopod Fisheries and Life History (WGCEPH). ICES CM 2011/SSCEF:03, 122 pp.

ICES. (2017). Interim Report of the Working Group on Cephalopod Fisheries and Life History (WGCEPH). In : . 2017. p. 135.

ICES. (2020). Working Group on Cephalopod Fisheries and Life History (WGCEPH; outputs from 2019 meeting). ICES Scientific Reports. 2:46. 121 pp. http://doi.org/10.17895/ices.pub.6032

ICES. (2023). Working Group on Cephalopod Fisheries and Life History (WGCEPH; Outputs from 2022 meeting). ICES Scientific Reports. 5:01. 163 pp. https://doi.org/10.17895/ices.pub.2197671

Kerr, L. A., Cadrin, S. X., & Secor, D. H. (2010). The role of spatial dynamics in the stability, resilience, and productivity of an estuarine fish population. *Ecological Applications, 20(2),* 497-507.

Knijn, R. J., Boon, T. W., Heessen, H. J., & Hislop, J. R. (1993). Atlas of North Sea fishes-Based on bottom-trawl survey data for the years 1985-1987. ICES Cooperative Research Reports (CRR).

Laptikhovsky, V., Allcock, A. L., Barnwall, L., Barrett, C., Cooke, G., Drerup, C., .Firmin, C., Lozach, S., MacLeod, E., .Oesterwind, D., Petroni, M., Robin, J.P., Sheerin, E., Power, A.M., Pierce, G. J (2022). Spatial and temporal variability of spawning and nursery grounds of *Loligo forbesii* and *Loligo vulgaris* squids in ecoregions of Celtic Seas and Greater North Sea. ICES Journal of Marine Science, 79(6), 1918-1930.

Lima, A. R., Baltazar-Soares, M., Garrido, S., Riveiro, I., Carrera, P., Piecho-Santos, A. M., ... & Silva, G. (2022). Forecasting shifts in habitat suitability across the distribution range of a temperate small pelagic fish under different scenarios of climate change. *Science of the Total Environment*, *804*, 150167.

Lordan, C., & Casey, J. (1999). The first evidence of offshore spawning in the squid species Loligo forbesi. *Journal of the Marine Biological Association of the United Kingdom*, *79*(2), 379-381

Mahevas, S., Trenkel, V.M., Doray, M. and Peyronnet, A. (2011) Hake catchability by the French trawler fleet in the Bay of Biscay: estimating technical and biological components. *ICES Journal of Marine Science.* 1 janvier 2011. Vol. 68, n° 1, p. 107-118. (doi 10.1093/icesjms/fsq140).

McLean, M., Mouillot, D., Lindegren, M., Engelhard, G., Villéger, S., Marchal, P., ... & Auber, A. (2018). A climate-driven functional inversion of connected marine ecosystems. *Current Biology*, *28*(22), 3654-3660.

Moreno A., Pereira J., Arvanitidis C., Robin J.P., Koutsoubas D., Perales-Raya C., Cunha M.M., Balguerias E., Denis V., (2002). Biological variation of *Loligo vulgaris* (Cephalopoda Loliginidae) in the Eastern Atlantic and Mediterranean. Bulletin of Marine Science 71 (1):3-7, 515-534.

Moreno, A., Azevedo, M., Pereira, J. M. F., Pierce G. J., (2007). Growth strategies in the European squid *Loligo vulgaris* from Portuguese waters. Marine Biology Research, 3: 49–59.

Morrison, W.E., and V. Termini. (2016) A Review of Potential Approaches for Managing Marine Fisheries in a Changing Climate. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OSF-6, 35 p.

Moullec, F., Asselot, R., Auch, D. et al. Identifying and addressing the anthropogenic drivers of global change in the North Sea: a systematic map protocol. Environ Evid 10, 19 (2021). https://doi.org/10.1186/s13750-021-00234-y

National Research Council. (2000.) Improving the collection, management and use of marine fisheries data. National Academy Press, Washington, D.C. https://doi.org/10.17226/9969

Oesterwind, D., Barrett, C. J., Sell, A. F., Núñez-Riboni, I., Kloppmann, M., Piatkowski, U., ... & Laptikhovsky, V. (2022). Climate change-related changes in cephalopod biodiversity on the North East Atlantic Shelf. Biodiversity and Conservation, 31(5-6), 1491-1518.

Pierce, G. J., Boyle, P. R., Hastie, L. C., & Key, L. (1994). The life history of *Loligo forbesi* (Cephalopoda: Loliginidae) in Scottish waters. Fisheries Research, 21(1-2), 17-41.

R Development Core Team. (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org

Rijnsdorp, A. D., W. Dekker, and N. Daan. (2006). Partial fishing mortality per fishing trip: a useful indicator for effective fishing effort in management of mixed demersal fisheries. ICES Journal of Marine Science 63:556-566.

Roa-Ureta, R. H. (2012). Modeling in-season pulses of recruitment and hyperstability-hyperdepletion in the Loligo gahi fishery of the FalklandI slandswith generalized depletion models. ICES Journal of Marine Science, 69: 1403–1415.

Robin, J. P., & Boucaud-Camou, E. (1995). Squid catch composition in the English Channel bottom trawl fishery: proportion of *Loligo forbesi* and *Loligo vulgaris* in the landings and length-frequencies of both species during the 1993–1994 period. ICES CM 1995/K: 36*,* 12pp.r

Robin, J. P., & Denis, V. (1999). Squid stock fluctuations and water temperature: temporal analysis of English Channel Loliginidae. Journal of Applied Ecology, 36(1), 101-110.

Rodhouse, P. G., Pierce, G. J., Nichols, O. C., Sauer, W. H., Arkhipkin, A. I., Laptikhovsky, V. V., ... & Downey, N. (2014). Environmental effects on cephalopod population dynamics: implications for management of fisheries. *Advances in marine biology,* 67, 99-233.

Rosenberg, A.A., Kirkwood, G.P., Crombie, J.A. and Beddington, J.R., 1990. The assessment of stocks of annual squid species. *Fisheries Research*., 8: 335-350.

Royer, J. (2002) Modélisation des stocks de céphalopodes de Manche. PhD thesis, University of Caen, 243pp.

Royer, J., Périès, P., & Robin, J. P. (2002). Stock assessments of English Channel loliginid squids: updated depletion methods and new analytical methods. *ICES Journal of Marine Science, 59(3),* 445-457.

Sims, D. W., Genner, M. J., Southward, A. J., & Hawkins, S. J. (2001). Timing of squid migration reflects North Atlantic climate variability. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *268*(1485), 2607-2611.

Southward, A. J., Butler, E. I., & Pennycuick, L. (1975). Recent cyclic changes in climate and in abundance of marine life. Nature, 253(5494), 714-717.

Southward, A. J., Hawkins, S. J., & Burrows, M. T. (1995). Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. Journal of thermal Biology, 20(1-2), 127-155.

Thorson JT, Cunningham CJ, Jorgensen E, Havron A., Hulson PJF, Monnahan CC., von Szalay P. (2021). The surprising sensitivity of index scale to delta-model assumptions: Recommendations for model-based index standardization. *Fisheries Research, 233,* 105745. https://doi.org/10.1016/J.FISHRES.2020.105745

Thorson, JT. (2019). Guidance for decisions using the Vector Autoregressive Spatio-Temporal (VAST) package in stock, ecosystem, habitat and climate assessments. *Fish. Res.* 210: 143-161.

Tinbergen, L., & Verwey, J. (1945). Zur Biologie von *Loligo vulgaris* Lamarck. *Archives Néerlandaises Zoologie*, *7*, 186-213.

van der Hammen, T.; Poos, J.J.; Quirijns, F.J. (2011). Data availability for the evaluation of stock status of species without catch advice: Case study: turbot (Psetta maxima) and Brill (Scophthalmus rhombus). IJmuiden: IMARES, (Report C109/11) - p. 35.

Vaz, S., Martin, C. S., Eastwood, P. D., Ernande, B., Carpentier, A., Meaden, G. J., & Coppin, F. (2008). Modelling species distributions using regression quantiles. *Journal of Applied Ecology*, 204-217.

Waluda, C. M., & Pierce, G. J. (1998). Temporal and spatial patterns in the distribution of squid *Loligo spp.* in United Kingdom waters. African Journal of Marine Science, 20.

Wang, J., Pierce, G. J., Boyle, P. R., Denis, V., Robin, J. P., & Bellido, J. M. (2003). Spatial and temporal patterns of cuttlefish (*Sepia officinalis*) abundance and environmental influences–a case study using trawl fishery data in French Atlantic coastal, English Channel, and adjacent waters. ICES Journal of Marine Science, 60(5), 1149-1158.

Figure captions

Figure 1. Loliginid landings in the English Channel from 2000 to 2021 by national fleet (Data from ICES, 2023)

Figure 2. The 33 ICES rectangles of the English Channel (division 7E and 7D). Four rectangles (30E6, 30E7, 30E8 in the English coast and 27F0) were excluded from the analysis because very few data were available. Rectangle 27E8 overlaps into ICES division (27E8.E and 27E8.D) and because of this, is split into two distinct rectangles. In total, 30 rectangles were considered in the analysis. Red crosses represent the barycentres associated with each rectangle.

Figure 3. CGFS indices (kg/km^2; in red), LPUE$_{basic}$ (kg/h; in green), LPUE$_{vessel}$ (kg/h; in blue) and LPUE$_{VAST}$ (kg/h; in purple) in October from 2000 to 2021. LPUE indices are plotted against the left vertical axis and CGFS indices against the right axis.

Figure 4. Squid biomass indices in the English Channel for two years: 2012 (a and b) and 2017 (c and d) in two seasons: summer (a and c) and in winter (b and d).

Figure 5. Seasonal and global trends in the squid biomass index in the English Channel between 2000 and 2021 with (a) the original time series decomposed in three components: (b) the global trend, (c) the seasonal component and (d) the remainder component.

Figure 6. The monthly average biomass squid index in the English Channel over all years (a) and between 2000 and 2021 (b).

Figure 7. Time series clustering of the biomass index using time series of the biomass index for each ICES rectangle. The dendrogram (a) reveals two main clusters of rectangles and the map (b) shows the location of each group of rectangles within the English Channel. For each cluster seasonal time series decompositions are shown in c and d and are as described in fig. 5.

Figure 8. Centre of gravity for squid biomass indices: (a) for each month for all years (2000-2021) and (b) the average location of gravity centre for each month using symbol size scaled according to the monthly biomass indices averaged over the 22 years.

Figure 9. Location of the average centre of gravity by year for squid biomass indices in the English Channel