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Combining acoustic and CUFES data for the quality control of fish-stock survey estimates

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Abstract:

Fish behaviour may cause bias in the acoustic estimates of fish stocks, which are difficult to assess using acoustic data alone. In contrast, fish eggs are passive particles that can be sampled with little avoidance. The combination of CUFES (continuous, underway, fish-egg sampler) data with acoustic sampling has the potential to cross-validate methods and address the question of relative bias. For anchovy in the Bay of Biscay, a CUFES has been used in conjunction with acoustics along the transect lines of IFREMER's spring acoustic survey since 2001. Subsurface CUFES egg concentrations were converted to vertically integrated egg abundances using a biophysical model of egg vertical distribution. Then, a procedure similar to the daily egg production method (DEPM) was applied to map an index of daily egg production. Maps of fish abundance and egg production were combined to derive a second index of daily specific fecundity over the survey area, which served as a quality-control indicator of the survey estimate. Over the series of surveys analysed, the quality-control indicator provided two warnings and in both cases the reasons for these were identified.

Keywords: abundance, acoustics, anchovy, bias, Biscay, CUFES

1. Introduction

A prime objective of acoustic surveys is to map fish stocks and estimate their abundance. Precision of the abundance estimate is determined by the data variability around their mean (e.g. Petitgas, 2001). The deviation between the mean estimate and the real field value is the bias (systematic error). A major cause of bias is fish behaviour and therefore bias may not be constant across years. Fish behaviour affects accessibility of the survey to the fish, avoidance of the fish to the vessel and catchability of the gear (e.g. Simmonds and MacLennan, 2005), as well as interpretation of echotraces. Statistically significant interannual variations in stock-size estimates above the level of survey precision can be misinterpreted because of interannual variations in survey bias. Therefore, to correctly interpret variations in stock-size estimates, detecting variations in the bias is a key requirement. But bias is impossible to assess using the data alone. For that reason, combining the acoustic survey with another method provides the potential to compare estimates and in this manner increases the reliability of the estimation. Fish eggs of most species are pelagic passive particles that can be sampled without avoidance. For that reason it is useful to cross-validate fish-stock estimates derived from acoustic and egg surveys (e.g. Hampton, 1996). In contrast to studies that used separate egg and acoustic surveys, we here demonstrate the possibility of combining an egg survey jointly with an acoustic survey on board the same vessel by using a subsurface pump CUFES (continuous underway fish egg sampler; Checkley *et al.*, 1997). In addition to comparing global estimates of abundance over the survey area, the spatial patterns in the eggs spawned and the spawning adults can be compared. Both methods provide high-resolution distribution maps, allowing further understanding of the variation in the bias when it occurs.

Because a CUFES collects samples underway at a fixed depth (e.g. 3 m) along the acoustic-survey transects, the conversion of subsurface egg concentration to vertically integrated egg abundance relies on a model output for the vertical distribution of the eggs (e.g. Petitgas *et al.*, 2006). Curtis *et al.* (2007) and Pépin *et al.* (2007) demonstrated the ability to convert CUFES data to egg abundance using a vertical distribution model. We followed a similar approach, but rather than using egg abundance, we related egg production to the acoustically estimated spawning biomass. In this manner egg abundance was converted to egg production. This was achieved by fitting a mortality curve to the egg abundance by age, as in the daily egg production method (DEPM: Lasker, 1985; and Stradoudakis *et al.*, 2006).

Since 2001, IFREMER operated a CUFES during its spring acoustic survey of the pelagic ecosystem of the Bay of Biscay (PelGas), which now provides a consistent series of data using a constant survey design. The present work on Bay of Biscay anchovy describes a procedure to cross-validate the acoustic estimate of abundance with an egg-production index based on CUFES data. Anchovy is a daily batch spawner (Motos, 1996), which has its peak spawning time in spring and its pelagic eggs are mostly found at subsurface depths. These biological facts make cross-validation between CUFES and acoustic methods possible.

CUFES subsurface egg concentrations by stage were converted into an index of daily egg production using the vertical model of Petitgas *et al.* (2006), the egg buoyancy relationship with sea-surface salinity of Goarant *et al.* (2007), the temperature-dependent ageing procedure of Lo (1981) and fitting a exponential mortality curve to the egg-abundance -by-age data. Acoustic estimates of abundance were derived using standard acoustic procedures for echo integration and species allocation to echotraces described in Massé (1996) and Petitgas *et al.* (2003). An index of daily specific fecundity was estimated by taking the ratio between the acoustic-abundance estimate and the CUFES-based egg production. The departure of the daily fecundity index from published reference values (Somarakis *et al.*, 2004) was used as a quality-control indicator, which served to warn of the incoherent joint estimation of egg production and fish abundance and thus resulting in potential bias. Warning signals were detected on two occasions. In both cases the spatial patterns in the egg production and adult fish distributions also differed. To our knowledge this is the first time that jointly collected CUFES and acoustic data have been quantitatively combined to derive a quality index of the survey estimate.

2. Material and methods

2.1. Survey scheme

The data were collected during the May–June PelGas cruises from 2001 to 2006 on board the RV "Thalassa". The survey design was parallel transects, oriented perpendicular to the isobaths that were regularly spaced at 12 nautical miles from 43.4°N to 48°N, from the coast to the shelf break (Petitgas *et al.*, 2003). Along the transects, CUFES samples and acoustic records were collected continuously by day, at a speed of 10 knots. During night-time, conductivity-temperature-depth (CTD) profiles were performed on a grid of stations (Figure 1).

2.2. Acoustic equipment and data

The acoustic equipment was a hull-mounted Simrad ER60 38 kHz echosounder with a nominal beam angle of 7°. The pulse duration was 1 ms. The ping-repetition rate was varied from 0.35 to 0.7 s depending on the bottom strata. The backscattered acoustic signal was digitized, providing acoustic samples of 20 cm in height and less than 5 m in length, which formed the echogram. Echogram processing is described in ICES (2006a). Acoustic samples were cleaned to exclude bottom echoes and parasites. Samples with a mean volume- backscattering strength (Sv; dB re 1 m^{-1}) higher than –60 dB were echo integrated in predefined layers using the MOVIES software (Weill *et al.*, 1993) as well as by echotrace. Fish echotraces were classified visually in six expert-defined categories named echotypes, which were characteristic of groups of species. The echo-integration procedure resulted in a nautical-area-scattering coefficient (s_A; m^2 nm^{-2}) by ESU (elementary sampling unit) of one nautical mile in length for each echotype. To facilitate species identification, each echotype in each ESU was associated by an expert with one identification trawl haul (Petitgas *et al.*, 2003). When many species were present, the s_A in each ESU was apportioned into a s_A per species using the standard equation (Simmonds and MacLennan, 2005). Species-specific s_As were further converted to abundances using the target strength (TS) corresponding to the mean length of the particular species in the catch. This procedure allowed estimation of anchovy abundance (g m^{-2}) for every nautical mile along the transects. From May to June, when the surveys were conducted, all the anchovy were mature and spawning (Motos, 1996) and considered to be in a similar reproductive state. The estimated abundance is for these reasons considered an index of spawning-stock biomass.

2.3. CUFES equipment and data

The CUFES (Model C-100, Ocean Instruments Inc.) installation on board RV "Thalassa" is described in ICES (2007). The pump was operated at 3 m depth at the end of a pipe installed externally on the vessel, approximately one metre away from the hull. The mesh size of the concentrator and collector was 500 µm. The flow rate was continuously monitored with a flowmeter (Promag) and it was approximately 490 l min^{-1}. Samples were taken every three nautical miles. Eggs from the CUFES samples were sorted on board, counted by species and stored in a 4% formalin–

seawater solution for later staging in a laboratory. Anchovy-egg concentrations along the survey transects were recorded as numbers of eggs per 10 m^3 at 3 m depth, integrated every three nautical miles.

2.4. Egg abundance

We used a validated biophysical model of egg vertical distribution that was adapted to the conditions of saline thermal stratification that often occur on the Biscay shelf (Petitgas *et al.*, 2006). This model was run at each CTD station. Each CUFES sample was associated with its closest CTD station. Inputs for the model were wind, tide, temperature and salinity vertical profiles and egg parameters (diameter and buoyancy). Maximal tidal current at the sampling location and day for each CTD station was derived from a M2 tide model of the Bay of Biscay. Wind velocity and direction were the averages of the recorded values for the CUFES samples associated with the closest CTD cast. Egg buoyancy was predicted at each CTD station using its relationship with sea-surface salinity (Goarant *et al.*, 2007). Egg-equivalent spherical diameter was taken as a constant (0.4 mm: Goarant *et al.*, 2007). The vertically integrated egg abundance (egg m^{-2}) was estimated by dividing the CUFES concentration by the model-predicted percentage abundance at 3 m depth. When the CUFES sample was empty, there was uncertainty whether there was no egg in that sample (true zero) or whether it was a consequence of the vertical distribution. In that case, we used the following procedure to resolve such uncertainty. The minimum CUFES concentration of 0.07 egg m^{-3} for the entire survey series (2001–2006) was considered the detectability threshold. For each “empty” CUFES sample, the nil value was replaced by this minimum. Then the vertical model was run and the vertically integrated abundance estimated. If the abundance remained less than one egg, a true-zero value was assigned, otherwise no value was assigned and that CUFES sample was omitted from the data set.

2.5. Egg staging and ageing

Eggs were staged in three categories according to the eleven reference stages of Moser and Ahlstrom (1985): no embryo (stages I–III); early embryo (stages IV–VI); and late embryo (stages VII–XI). The egg abundance at each CUFES sample was split into egg abundances by stage categories proportionally to the stage-category percentages in the sample. The incubation temperature for each CUFES sample was estimated at the associated CTD station by weighting the temperature profile by the predicted egg profile. The same egg vertical profile was considered for all egg categories, because egg buoyancy varied little during egg development (Coombs *et al.*, 2004). For each stage category, the average age was estimated with the age–temperature relationship of Lo (1985). In this manner egg abundance in each stage category (N_1, N_2, N_3) and mean age (d_1, d_2, d_3) were obtained for each CUFES sample. The suite of calculations required to progress from the CUFES samples to an index of egg production is summarized in Figure 2.

2.6. Estimates of egg production and fish abundance

A grid layout was designed over the survey area using block dimensions 0.4° × 0.4° in latitude and longitude. Egg-abundance-by-age was block averaged using the CUFES samples for each block. An exponential mortality curve $P_t(x) = P_0(x)\exp(-Z(x)\,t)$ was fitted for each block *x* on the block-averaged data, which resulted in estimates for each block of the parameters P_0 (daily egg production: egg day^{-1} m^{-2}) and *Z* (mortality: day^{-1}). However that model-based approach could not be used for all blocks. Those with less than three CUFES samples or more than 70 % of nil-valued CUFES samples were not considered. There was a linear relationship between the block average egg abundance *N(x)* and the block-estimated $P_0(x)$ (not shown). For blocks in which the estimate of Z was negative, the estimate of $P_0(x)$ was not based on the mortality curve but on the relationship between $N(x)$ and $P_0(x)$. Acoustic fish concentrations were block averaged using the same grid to obtain fish-abundance estimates by block $B(x)$ in g m^{-2}. The estimates were conditional to the grid-block size and origin. To decondition the estimate relative to the grid origin, the coordinates of the grid origin were randomly sampled 50 times with replacement from a uniform distribution within the block origin (lower left corner). The procedure of block estimation of $P_0(x)$ and $B(x)$ was repeated 50 times using the 50 grids with 50 different origins. The final maps $\overline{P}_0(x)$ and $\overline{B}(x)$ were obtained by taking the average value in each block over the 50 realizations.

2.7. Variance of the global estimates

The variance of the global estimate could be calculated because the grid origin had been randomized. Global means and variances were computed conditional to the grid origin and combined. The variance of the global estimate equalled the variance of the conditional means plus the mean of the conditional variances:

$$V(Y) = E[V(Y_{x,g} / grid)] + V[E(Y_{x,g} / grid)] \quad (1)$$

where E is expectation, V is variance and $Y_{x,g}$ is the block estimate (either $P_0(x,g)$ or $B(x,g)$) in block x for the grid with origin g:

$$E(V(Y / grid)) = \frac{1}{k}\sum_{g=1}^{k} \sigma_g{}^2 \text{ , } (2)$$

where $\sigma_g{}^2$ is the variance of $Y_{x,g}$ over the blocks for grid g and k the number of grid realizations ($k = 50$):

$$V(E(Y / grid)) = \frac{1}{k}\sum_{g=1}^{k} (\overline{Y} - Y_g)^2 \text{ , } (3)$$

where Y_g is the spatial average over the blocks for grid g and $\overline{Y}$ is the average of Y_g over the k grid realizations.

2.8. Daily specific fecundity

An index of daily specific fecundity (DF: egg day^{-1} g^{-1}) over the survey area was estimated as the ratio $DF = \frac{\boldsymbol{P_0}}{\boldsymbol{B}}$, where P_0 and B were the summed values of $\overline{P}_0(x)$ and $\overline{B}(x)$ over all their respective positive blocks. The variance of DF was calculated as:

$$\sigma_{DF}{}^2 = \left[\frac{\mathrm{P}_0}{\mathrm{B}}\right]^2 \left[\frac{\sigma_{P_0}{}^2}{P_0{}^2} + \frac{\sigma_B{}^2}{B^2}\right]. \ (4)$$

2.9. Spatial patterns

The yearly spatial distributions in the egg daily production $\overline{P}_0(x)$ and spawning biomass $\overline{B}(x)$ were compared using indicators that summarized location, dispersion and overlap of these distributions. The spatial indicators used (Woillez *et al.*, 2007) were the gravity centre CG of the distribution, the inertia I and the global index of collocation:

$$GIC = 1 - \frac{\Delta_{CG}{}^{2}}{\Delta_{CG}{}^{2} + I_{P_0} + I_B} \text{ where } \Delta \text{ is distance. (5)}$$

The GIC ranged from 0 (no overlap) to 1 (coincidence in CGs). The overlap may be attributable to close CGs or large inertia or a combination of both factors. The daily egg production and the biomass data were double-root transformed before calculating the indicators to dampen the influence of high values on the indicators.

3. Results

3.1. Validation of CUFES-based total egg-production estimate

Anchovy-egg surveys (BIOMAN survey series) following a standard protocol using discrete, vertically integrated CalVET tows (vertical-tow egg sampler) are also performed in the area in May by AZTI-Tecnalia (Organisation for Food and Marine Research, Basque Country, Spain) . The BIOMAN survey data are used to estimate total egg production and provide a DEPM estimate of anchovy biomass (e.g. ICES, 2004a). The DEPM-based egg production P_0 reported to ICES (ICES, 2006) was used as reference to validate our CUFES-based P_0 estimate. CUFES-based P_0 estimates from our study showed an acceptable linear relationship with the DEPM estimates ($r^2 = 0.9$, Figure 3).

3.2. Daily specific fecundity as a quality control criteria

The *daily specific fecundity* (*DF*) varied between 34 and 92 egg day^{-1} g^{-1}, which was in the range of variability of 27 DEPM investigations of European anchovy (Mediterranean and Biscay) anchovy (Somarakis *et al.*, 2004). The authors concluded that an isometric relationship exists between P_0 and *DF* ($P_0 = 1.08\, DF^{0.99}$). They also documented low interannual variability in the adult-fecundity parameters at peak spawning (survey time) in the Bay of Biscay. For that reason, large departures from this isometric relationship can indicate unusual estimated fish biomass. We used the departure of our estimates from the isometric relationship as a quality-control criterion. The *DF* values for the 2003 and 2005 surveys were unusually high, demonstrating an abnormal departure from the expected isometric line (Figure 4). For that reason the estimates of egg production and fish abundance were incoherent for the 2003 and 2005 surveys.

3.3. Spatial patterns in the daily egg production and the spawning-fish abundance

The spatial distributions (2001–2006) of the daily egg production and fish abundance were summarized using the spatial indicators (Figure 5). The distributions overlapped greatly in each year; the global index of collocation (*GIC*) ranged between 0.89 and 1. But the distributions also revealed consistent differences across the time-series; the *CG* of the fish distribution was consistently more coastal and towards the southeast than that of the egg production. No pattern across the years was identified for the inertia (*I*) or the *GIC*. In contrast, for the two years in which the fish abundance and the egg production were not estimated coherently (i.e. 2003 and 2005), the distance between the *CG*s of the spatial distributions was greatest. The distribution of the egg production was situated unusually farther northwest than that of the fish abundance in those two particular years.

4. Discussion and conclusion

4.1. Explaining the discrepancies in the estimates of egg production and fish abundance in 2003 and 2005

In agreement with Somarakis *et al.* (2004), ICES (2006) reported consistent fecundity parameters across the time-survey series based on gonad analysis. For that reason a change in the individual fish fecundity at survey time was rejected as an explanatory hypothesis. Because the CUFES-based estimates of P_0 agreed across the series with the standard DEPM, the CUFES-based estimate of P_0 are considered reliable. This means the acoustic estimate of fish abundance was too low. Indeed, underestimation of fish abundance has to be assumed for both years, because of the unusual situations of catchability in relation to the trawl and accessibility to the survey. During the 2003 survey, an unusual number of small schools were observed at the surface in the northwest part of the survey area in contrast to other years. These schools were not identified appropriately by trawling during this survey, when anchovy eggs were collected by the CUFES (ICES, 2004b). The allocation of acoustic echotraces to anchovy may have been too conservative in the north-western area, resulting in underestimates of fish abundance. For the 2005 survey, the abundance of age 2 fish in 2006 was estimated as being greater than that of age 1 fish in 2005 (ICES, 2006b). This indicates that fish abundance had been underestimated for 2005. As the age 2 fish in 2006 displayed an unusually large proportion of small individuals, part of the age 1 cohort in 2005 might have been in shallow coastal waters inaccessible to the survey.

4.2. Combination of CUFES and acoustic data for the quality control of survey estimates

The acoustic-survey series PelGas was designed as a platform for ecosystem monitoring in the Bay of Biscay. Acoustic and CUFES were jointly operated, both being underway continuous samplers. Realistic daily egg-production indices were obtained that compared well with proper DEPM survey indices. For that reason, although complex, the suite of calculations used to convert CUFES egg subsurface concentrations into maps of daily egg production were considered appropriate. The quantitative combination of acoustic and CUFES data resulted in a daily specific-fecundity index. Unusual values in that index, compared with values established by gonad analyses, provided reliable warnings of bias in the acoustic-survey estimate. The spatial patterns in the egg production and fish abundance varied coherently with the daily specific fecundity, which increased the reliability of the warning.

The quality-control scheme proposed here is based on a reference for daily fecundity that had to be established beforehand by gonad analyses. In this manner, DEPM surveys are complementary to acoustic surveys and can be seen as establishing reference values for fecundity and egg production parameters. In addition to the series of acoustic estimates and its precision, combined acoustic-CUFES surveys can provide a series of quality criteria based on daily specific-fecundity estimates. The CUFES-acoustic-based estimate of daily specific fecundity helped to diagnose changes in acoustic-survey catchability, but no attempts were made to correct acoustic estimates.

Daily fecundity could not be estimated at the small scale of the grid layout used to map egg production, as the maps of egg production and fish abundance did not coincide sufficiently. There were blocks with high egg production and low fish abundance and *vice versa*, a situation that is not uncommon and was reported by Zwolinski *et al.* (2006). Daily specific fecundity was for that reason globally estimated over the survey area. Precise comparisons of spatial patterns may reveal fine-scale movements of eggs (dispersion) and fish (migrations over the 24 h cycle) that may be important for improving survey designs in space and time.

The calculation of daily specific fecundity and its use to detect changes in the acoustic-survey catchability as proposed here assumes that particular conditions are met. This may not apply for all areas and species. In our study, eggs were more often than not found in the upper layers and were therefore accessible to the CUFES pump. However, a vertical model was still required to estimate egg abundance, because of deeper distributions or subsurface peaks that occurred for particular turbulence conditions or hydrological structures. Adult fish-fecundity parameters and their interannual variability had already been documented and this allowed interpretation of variations in the combined acoustic–CUFES daily specific fecundity in terms of changes in the acoustic estimate. In other situations, where interannual variation in adult parameters and egg vertical distribution are less optimal, differences in the spatial distributions of the acoustic and CUFES data could perhaps serve as preliminary warning indicators, before applying the full procedure as proposed here.

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Figures

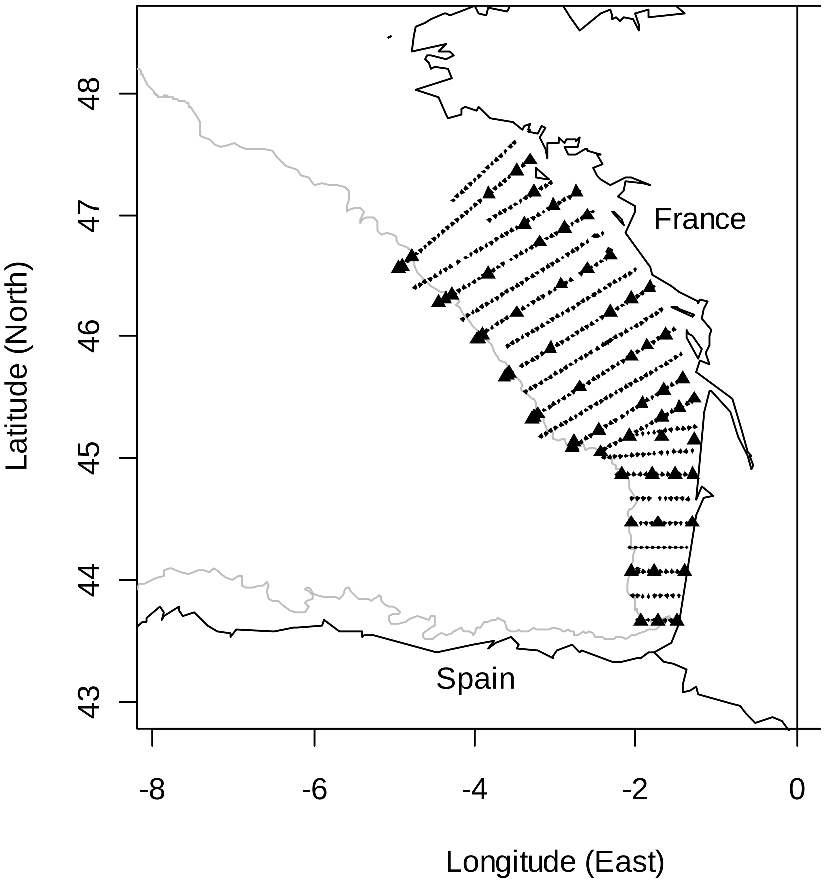

Figure 1
Figure 1. Sampling scheme of the PelGas research cruises showing the CUFES samples (black spots) and the CTD stations (triangles). CUFES samples are collected along the acoustic-transect lines. The 200m isobath is shown.

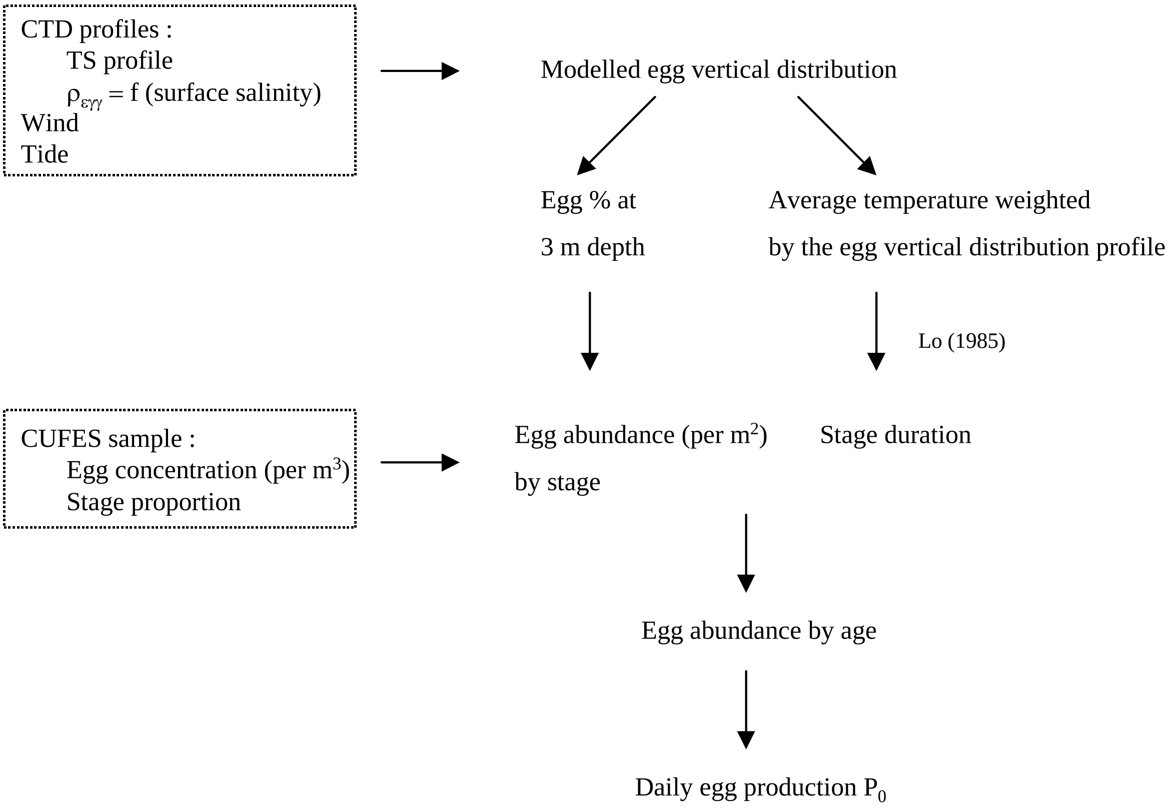

Figure 2

Figure 2. Scheme of the data processing to convert CUFES subsurface egg concentrations to vertically integrated egg abundances and daily egg production.

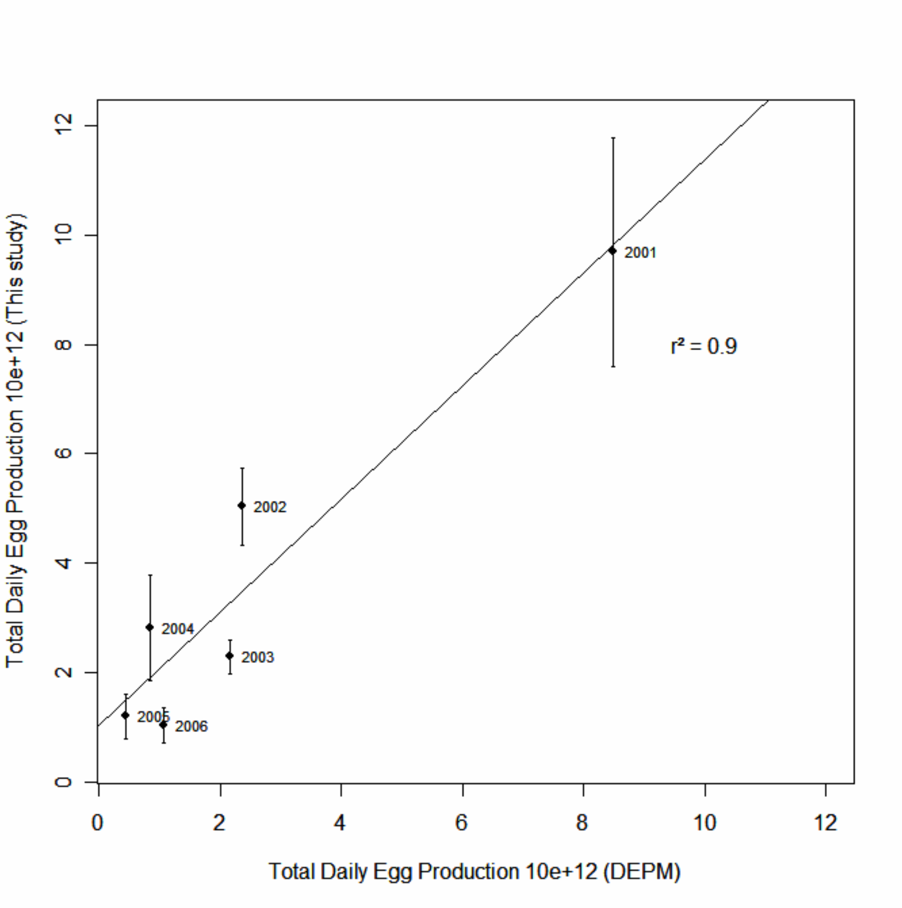

Figure 3

Figure 3. Comparison of the total daily egg production (P_0 × spawning area) estimates between the CUFES-based estimate (this study) and the DEPM-based estimate (ICES 2006b). The linear relationship between the two methods is: $y = 1.035\,x + 1.028\,10^{12}$. The bars represent ± two standard deviations around the DEPM estimate.

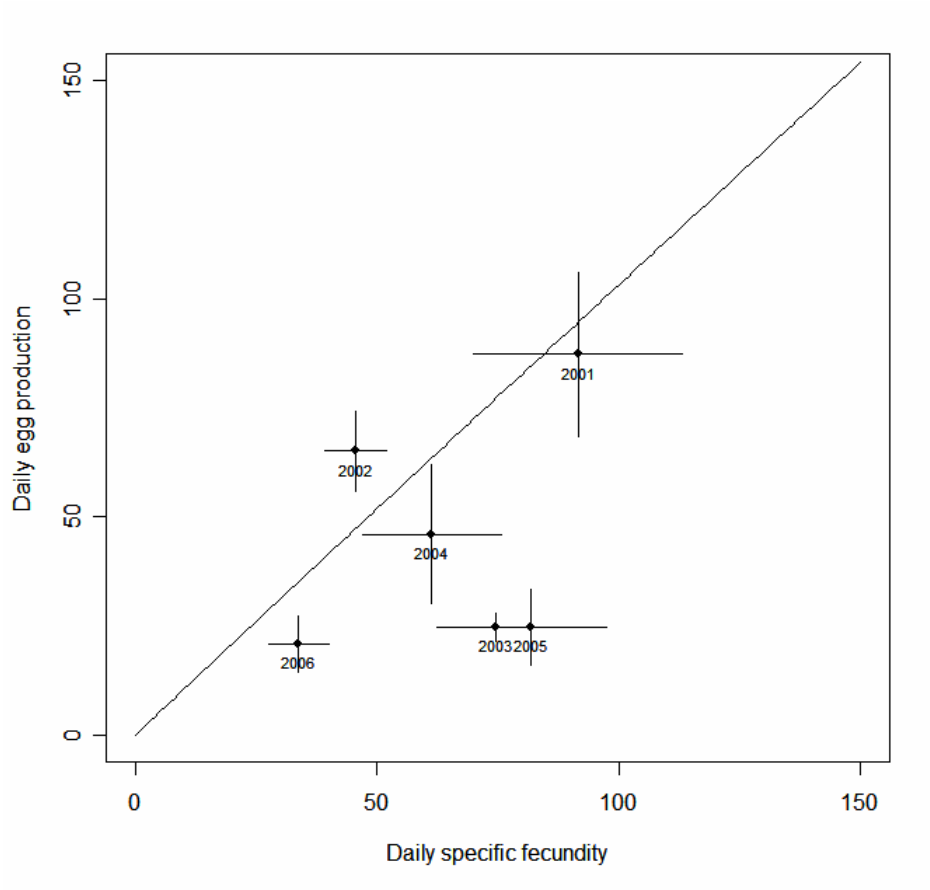

Figure 4

Figure 4. Daily egg production (CUFES-based) vs. daily fecundity (acoustic and CUFES-based). The line represents the isometric relationship of Somarakis *et al.* (2004) for the European anchovy populations (Mediterranean and Bay of Biscay). The bars represent ± two standard deviations around the estimates.

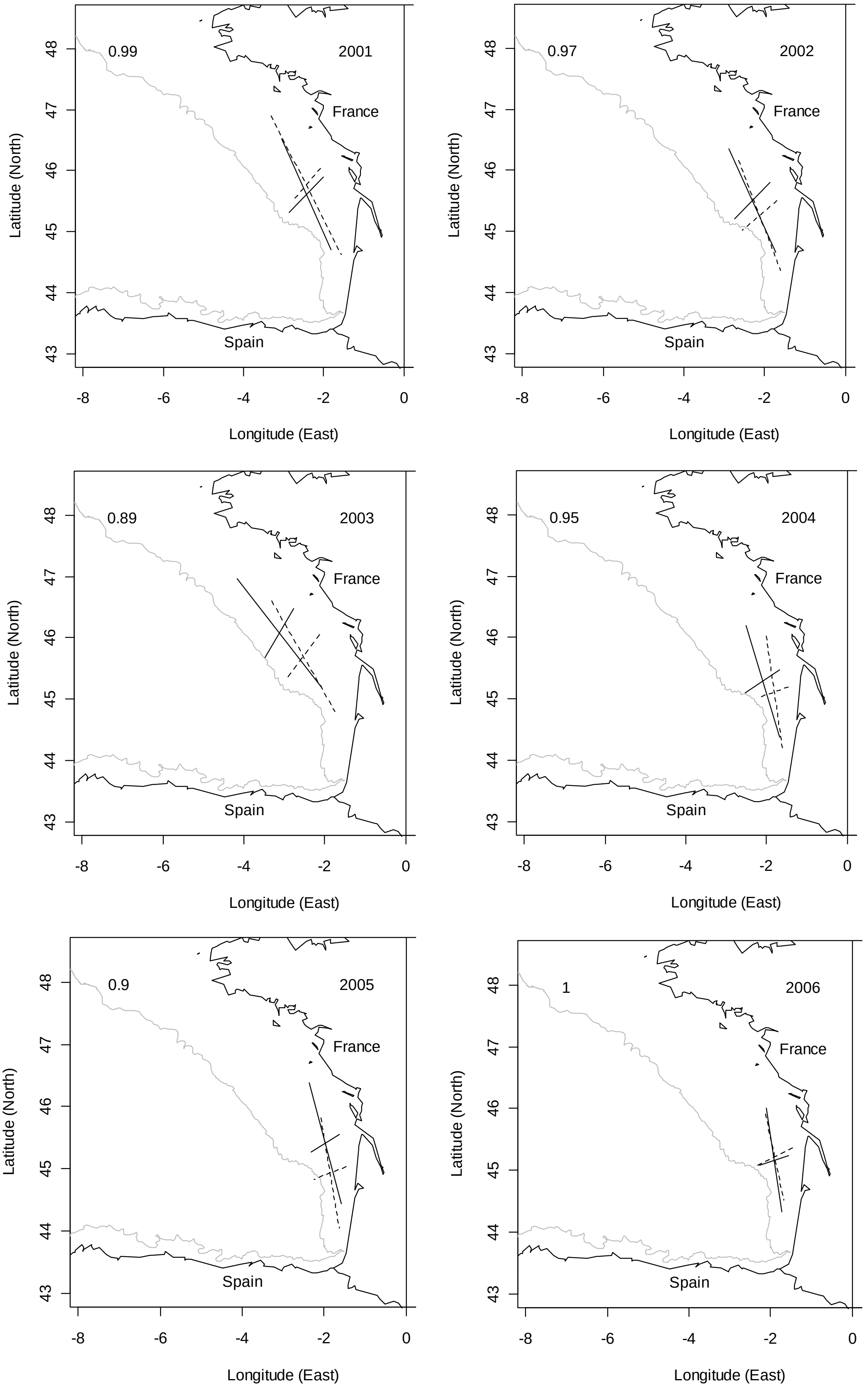

Figure 5

Figure 5: Centre of gravity and inertia of the distributions of the acoustic-derived fish abundance (dotted line) and the CUFES-based daily egg production (solid line). The

Global Index of Collocation is indicated in the top left corner of the maps. top: 2001–2002, middle: 2003–2004, bottom: 2005–2006. The 200m isobath is shown.