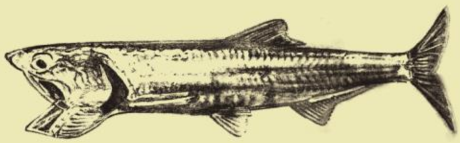

PhD Thesis 2017

ACOUSTIC ABUNDANCE OF JUVENILE ANCHOVY FOR PREDICTING RECRUITMENT

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Abundancia acústica de anchoa juvenil para la predicción del reclutamiento

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Foto: Cerquero Divino Jesús de Praga, JUVENA 2003 (Fuente: propia).

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Resumen extendido

El objetivo de este trabajo es desarrollar un índice para la predicción del reclutamiento de anchoa en el Golfo de Vizcaya varios meses antes de la actividad pesquera para mejorar la gestión de su pesquería. Dicho índice se basa en la estimación de la abundancia de anchoa juvenil cuatro meses después de la época de puesta, una vez que termina la fase de mortalidad mayor y más variable de la especie. De esta manera se espera que la abundancia de juveniles en ese momento proporcione una indicación fiable de la tasa de supervivientes que se incorporará a la población al año siguiente.

Elección de la tecnología adecuada

Para llevar a cabo dicho objetivo, en primer lugar se seleccionó la tecnología adecuada para realizar la estima de abundancia de juveniles en el Golfo de Vizcaya. Entre los años 1998 y 1999se realizaron una serie de campañas experimentales (JUVESU) comparando la adecuación de la metodología acústico-pesquera (Simmonds and Maclennan, 2005), realizada a bordo de embarcaciones pesqueras y oceanográficas, con el uso de sensores LIDAR aerotransportados (Churnside and Hunter, 1996), para la estimación de abundancia de juveniles de varias especies de pequeños pelágicos del sudoeste europeo.

La comparación de metodologías se realizó en tres zonas distintas cada año: la costa de Portugal, las rías bajas gallegas y el Golfo de Vizcaya, empleando para ello una avioneta dotada de un LIDAR pesquero que sobrevolaba consecutivamente las tres áreas que se estaban muestreando simultáneamente con embarcaciones oceanográficas y pesqueras. Se seleccionaron las áreas de máxima superposición espacio-temporal entre muestreo LIDAR y acústico, y en ellas se realizaron comparaciones de mapeos espaciales y regresiones lineales. Además, se realizaron estudios de autocorrelación espacial de los registros LIDAR y acústicos para establecer el diseño de muestreo óptimo en términos de distancia inter-radial y área potencial de muestreo. La extensión vertical de anchoa juvenil encontrada se empleó para considerar posibles métodos de pesca para identificación de especies y obtención de muestras para análisis biológicos. El resultado de este estudio estableció la campaña acústico-pesquera como el mejor método para los objetivos propuestos.

Desarrollo de la metodología: la campaña JUVENA

Una vez elegida la tecnología, se desarrolló metodología. La metodología desarrollada consistió en una campaña acústico-pesquera (Simmonds and Maclennan, 2005b) para estimar la abundancia de anchoa juvenil a final de verano, adecuada a las particularidades de la especie objetivo y el período de interés. La metodología acústico-pesquera utiliza ecosondas científicas calibradas para caracterizar la distribución espacial de biomasa y pescas para la identificación de las especies.

Se puso en marcha una serie temporal de campañas científicas para producir estimaciones anuales de anchoa juvenil en otoño desde el año 2003 ininterrumpidamente hasta el año 2015. Las campañas presentaban una estrategia de muestreo adaptativa en la que la extensión del muestreo se extendía hasta cubrir el área total de ocupación de la anchoa juvenil. Basándose en dichas estimaciones se desarrolló un índice de abundancia de anchoa juvenil. La información que se iba obteniendo en las sucesivas campañas se empleó para obtener también una idea de la distribución espacial de la anchoa juvenil del Golfo de Vizcaya y se fue empleando para mejorar la metodología de las campañas subsiguientes.

La capacidad del índice de juveniles para predecir el reclutamiento del año siguiente se testeó por comparación de la biomasa de juveniles en otoño frente a la abundancia de reclutas en la primavera siguiente obteniendo una relación significativa entre ambos. En el período de estudio se encontró un amplio rango de niveles de reclutamiento, desde el reclutamiento extremadamente bajo que condujo al colapso de la población en 2005 hasta los reclutamientos muy altos que proporcionaron la recuperación del recurso en los años 2010 y 2011. La relación entre los índices de juveniles y reclutamiento no resulta dependiente de ningún punto particular de la serie, ni el máximo ni el mínimo. La relación es significativa independientemente del modelo de regresión elegido.

Incertidumbres del índice JUVENA

Para estimar las principales fuentes de incertidumbre de la campaña acústica de anchoa juvenil relacionadas con las asunciones varias y especificidades metodológicas. Se analizaron errores sistemáticos y aleatorios, centrándose específicamente en errores de interpolación del muestreo usando técnicas geoestadísticas, error del campo cercano, intercalibración entre embarcaciones, cobertura horizontal y vertical, identificación de especies y asignación de edad. Los errores obtenidos fueron usados para construir intervalos de confianza de las estimaciones de abundancia de anchoa juvenil.

En general las incertidumbres obtenidas mostraron un impacto pequeño en el objetivo principal de la campaña (proporcionar un indicador temprano del reclutamiento) debido a: (i) la alta tasa señal-ruido (2.5) de las incertidumbres aleatorias estimadas; (ii) la pequeña diferencia entre estimas alternativas comparadas con las diferencias entre niveles de biomasa interanuales y (iii) la capacidad de predicción del reclutamiento altamente significativa mostrada por el índice JUVENA para todas las estimaciones alternativas empleadas (sin corregir o empleando las correcciones propuestas).

Implicaciones para la gestión

El índice JUVENA presenta relaciones significativas con las abundancias de reclutas obtenidas mediante el BBM (Ibaibarriaga et al., 2008), tanto si tenemos en cuenta los años iniciales (2003-2010) publicados, como si añadimos el resto de la serie, lo que valida su uso robusto y estable como índice anticipado del reclutamiento. Este índice se ha incluido dentro del consejo científico para la gestión de la pesquería de manera paulatina. En el año 2009 el ICES usó las buenas perspectivas de reclutamiento proporcionadas por JUVENA (entre otras fuentes) para reabrir la pesquería de anchoa del Golfo de Vizcaya con una pequeña cuota de 5000 toneladas tras un cierre que databa desde el año 2005. El índice JUVENA ha sido sistemáticamente tenido en cuenta desde entonces para acomodas las cuotas de pesca a las perspectivas de reclutamiento que proporcionaba.

Finalmente en el año 2014 el consejo científico para la gestión de la anchoa, realizado en el contexto del grupo de trabajo del ICES HANSA, se actualizó a un nuevo índice sintético, denominado CBBM (ICES, 2014) que incluye también JUVENA como una de las fuentes de información, combinada con las capturas y los resultados de las campañas de anchoa de primavera. Con la inclusión de JUVENA en el CBBM se ha cambiado también el momento de estimación del índice sintético de abundancia, que ahora se realiza en diciembre, con lo que proporciona una estima del reclutamiento varios meses antes del inicio de la actividad pesquera. Esto ha permitido mejorar notablemente la gestión de la pesquería, ya que proporciona un margen de actuación para la toma de medidas en caso necesario.

Dinámica espacial de anchoa juvenil en el Golfo de Vizcaya

Por último se realizó un estudio de la dinámica espacial de anchoa juvenil en el Golfo de Vizcaya basándose en los datos recogidos en las campañas acústicas. La dinámica horizontal de anchoa juvenil se estudió comparando la distribución espacial de dos campañas que se centraban en el estudio de la anchoa juvenil, y que se realizaron consecutivamente en el año 2009: la campaña JUVENA 2009 y la campaña PELACUS10 2009 realizada por el Instituto Español de Oceanografía. La comparación de las distribuciones verticales y horizontales de anchoa juvenil en ambas campañas proporcionó dos “fotografías” consecutivas con 20 días de demora, a partir de las cuales se obtuvo la dinámica espacial de los juveniles para esas fechas y durante ese año. Los resultados se analizaron en el contexto ambiental de los juveniles obtenido a partir de perfiles de CTD, datos de satélite y mediciones de temperatura y salinidad en continuo a bordo de las embarcaciones.

La anchoa juvenil mostró una distribución espacial predominante en aguas oceánicas, aunque cambió su comportamiento dependiendo del área en que se encontraba. En el sector español del Golfo de Vizcaya, los juveniles migraron unas 20 millas náuticas hacia la costa, permaneciendo en todo momento fuera de la plataforma y cerca de la superficie. A medida que avanzaban hacia la plataforma, su área de distribución decreció y su densidad aumentó, agregándose en un número menor de bancos más densos. Por otro lado, en el sector francés, los juveniles también migraban hacia la costa pero cruzando el cantil para ocupar la plataforma continental, donde incrementaron significativamente su profundidad media hasta adoptar las típicas migraciones nictimerales de la anchoa adulta. La talla media de los juveniles de esta zona era significativamente mayor que en la española lo que da pie a conjeturar que la talla pueda ser relevante para acometer este cambio. Los diferentes gradientes de temperatura encontrados en la zona francesa (más fuertes) y la española (más débiles) pudieron haber influido en los distintos patrones de distribución espacial y comportamiento observados en ambas zonas.

El predominio de la anchoa juvenil en aguas oceánicas encontrado es consistente con las observaciones generales de la serie JUVENA. Además coincide con las observaciones realizadas por varios autores que también observaron la preferencia de la anchoa juvenil en áreas de menor disponibilidad de alimento pero mayor temperatura (Bachiller *et al.*, 2013; Irigoien *et al.*, 2007). Estas observaciones serían consistentes con una estrategia de reclutamiento de la anchoa basada en el aprovechamiento de un compromiso entre alta temperatura sumado a la (relativamente) baja depredación y alta disponibilidad de alimento fuera del cantil para incrementar sus posibilidades de supervivencia invernal.

Hipótesis de la tesis

La hipótesis de esta tesis es que el índice de abundancia de anchoa juvenil a principios de otoño, unos cuatro meses después de la puesta proporciona un índice válido (y por tanto una estima anticipada a la "costera" de la anchoa, con ocho meses de antelación) del reclutamiento que se producirá al año siguiente. El testeo de la hipótesis se realizó estableciendo modelos de regresión estadísticos, paramétricos y no-paramétricos, entre las series temporales de biomasa de juveniles y reclutas de anchoa. La existencia de una correlación altamente significativa entre los índices de juveniles y reclutamiento, independientemente de los varios modelos ensayados, y su insensibilidad a cualquier punto particular de la serie demostró la validez de la hipótesis.

Extended summary

The objective of this work is to develop an index to predict the anchovy recruitment in the Bay of Biscay, various months before the fishing activity to improve the management of the fishery. In order to achieve this objective, first, the appropriate technology to conduct the estimation of abundance of juvenile anchovy in the Bay of Biscay was chosen. Second, a methodology was set up to estimate juvenile anchovy abundance, adequate to the particularities of the objective species and survey period. Afterwards, a series of scientific surveys were carried out to produce annual estimations of juvenile anchovy in Autumn. Based on these estimations, an index of recruitment was developed. The capacity of the juvenile index to forecast next year recruitment was tested by comparing the biomass of juveniles in Autumn with the biomass of recruits the next spring. An estimation of the uncertainties of the estimates allowed assigning confidence intervals to the biomass estimations and their predictions. Finally, a study was conducted on the spatial dynamics of juvenile anchovy in the Bay of Biscay, based on the data registered in the acoustic surveys.

Election of the technology

The feasibility of using airborne LIDAR (Light Detection and Ranging) was studied to assess the early juvenile fractions of the main pelagic fish species that occur in the coastal Atlantic waters of southern Europe (i.e., anchovy, sardine, mackerel, and horse mackerel). Field comparisons with more established acoustic methods were undertaken in the summers of 1998 and 1999 during the recruitment

period of sardine and anchovy in the selected areas and in the presence of a variety of oceanographic and environmental conditions. Backscattered energy as well as the typology of the targets collected by both devices was compared. The distribution of energy and observed typologies were generally similar for both techniques, with moderate numerical correlation between sensors, proving the potential of LIDAR for assessment of three of the targeted species of juveniles, namely anchovy, sardine, and mackerel. However, differences in received backscattering energy were found, especially in the presence of certain plankton structures (more visible for LIDAR) and isolated thick schools. Experimental ad hoc optical reflectivity measurements of fish and plankton are proposed to discriminate these two types of targets. In addition, an improvement on LIDAR implementation and data processing is suggested to achieve fish abundance estimates.

Development of the methodology: the JUVENA survey

A series of acoustic surveys (JUVENA) began in 2003 targeting juvenile anchovy (*Engraulis encrasicolus*) in the Bay of Biscay. A specific methodology was designed for mapping and estimating juvenile abundance annually, four months after the spawning season. After eight years of the survey, a consistent picture of the spatial pattern of the juvenile anchovy has emerged. Juveniles show a vertical and horizontal distribution pattern that depends on size. The younger individuals are found isolated from other species in waters closer to the surface mainly off the shelf within the mid-southern region of the bay. The largest juveniles are usually found deeper and closer to the shore in the company of adult anchovy and other pelagic species. In these eight years, the survey has covered a wide range of juvenile abundances, and the estimates show a significant positive relationship between the juvenile biomasses and the 1-year-old recruits of the following year. This demonstrates that the JUVENA index provides an early indication of the strength of next year's recruitment to the fishery and can therefore be used to improve the management advice for the fishery of this short-lived species.

Uncertainties of the JUVENA index

This chapter details the assessment of main error sources involving the estimation of juvenile anchovy biomass along the temporal series of JUVENA surveys, to check their impact in the recruitment prediction capacity. In general, the resulting uncertainties have a small impact in the main objective of the survey (providing an early indicator of recruitment) due to (i) the high SNR of the random uncertainties estimated (2.5); (ii) the small difference between alternative estimates compared to the difference between annual biomass levels, (iii) and the highly significant prediction capability of the JUVENA index for all the alternative juvenile biomass estimates (uncorrected or with any of the proposed corrections).

Implications for management

This chapter presents the update of the index of recruitment based on the acoustic estimates of juvenile anchovy in the Bay of Biscay provided by the JUVENA survey, after the inclusion of two more years of surveys. The main aim of these surveys was to test whether the abundance of juveniles in autumn constitutes a reliable indicator of the strength of recruitment to the adult stock each year in the Bay of Biscay. The hypothesis has been confirmed by the significant positive correlations between the biomass estimates of juveniles and the next year's age-1 recruits. Boyra et al (2013) showed that there exists a significant correlation between juvenile and recruitment indices, thus supporting the reliability of the JUVENA index to anticipate abundance trends in the Bay of Biscay anchovy. In the present work, after the addition of two more recruitment years, the correlations between juvenile and recruitment are still significant, further supporting the validity of the JUVENA index. Since year 214, the JUVENA index forms part of the new CBBM synthetic abundance index used by ICES to manage the anchovy fishery.

Spatial dynamics of juvenile anchovy in the Bay of Biscay

In autumn 2009, the implementation of two successive acoustic surveys targeting juvenile anchovy (Engraulis encrasicolus) in the Bay of Biscay allowed us to monitor the changes in the spatial distribution and aggregation patterns of juveniles of this species during 45 days under fairly stable meteorological conditions. Juvenile anchovy changed its biological condition and behavior in a different manner in two distinct areas. In the Spanish sector the juveniles migrated 20 n.mi. toward the coast, but they remained off the shelf and near the surface during the whole surveyed period. As the advance towards the shelf break progressed, their area of distribution decreased, their density increased and the juveniles spread in fewer but heavier shoals. In the French sector the juveniles migrated also from slope waters toward the coast at similar velocity, but they crossed the shelf break into the continental shelf, where they increased significantly their mean depth until gradually adopting the typical nyctemeral migrations of adult anchovy. The mean length of the juveniles that adopted the nyctemeral migrations was significantly higher than that of the juveniles remaining at the surface, suggesting that body size is relevant to accomplish this change. Besides, the stronger temperature gradients between shelf and oceanic waters in the Spanish sector, favored by a narrow shelf, may have acted as a barrier influencing the distinct observed spatial patterns in the two areas


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Foto: Cerquero Nuevo Erreñezubi, JUVENA 2004 (Fuente: propia).

Introducción general

Contexto

Marco geográfico: El Golfo de Vizcaya

Este estudio está enmarcado en el Golfo de Vizcaya, una porción del océano Atlántico delimitada al este por la costa francesa y al sur por la costa cantábrica. El Golfo de Vizcaya se extiende desde el cabo Ortegal en Galicia hasta el Punto de Penmarch en Bretaña (Figura **1**). El litoral de la vertiente sur, la costa cantábrica, es relativamente recto pero escarpado, con abundantes acantilados alternados con playas y bahías, situadas generalmente en las desembocaduras de los ríos. Por otra parte, el litoral de la vertiente este, la costa francesa, es recto, llano y arenoso, salvo el tercio norte, la costa de Bretaña, en la que también abundan los tramos escarpados y rocosos.

En cuanto a la batimetría, el Golfo de Vicaya presenta dos tramos de plataforma continental, una asociada a la costa cantábrica y otra asociada a la costa francesa, separadas por el cañón de Capbretón, un estrecho valle submarino de unos 150 km de largo y 2000 m de profundidad situado en el vértice entre España y Francia en el sudeste del golfo. La plataforma de la costa cantábrica es bastante estrecha, de unos 20 km de anchura, mientras que la plataforma francesa se ensancha considerablemente superando los 150 km de ancho en su parte norte.

En primavera y verano predominan los vientos suaves de componente este o noreste, mientras que en invierno imperan oestes y noroestes de mayor intensidad (Borja *et al.*, 1998). Dada su orientación, el golfo de Vizcaya está expuesto durante el período invernal a fuertes temporales provenientes del Atlántico Norte.

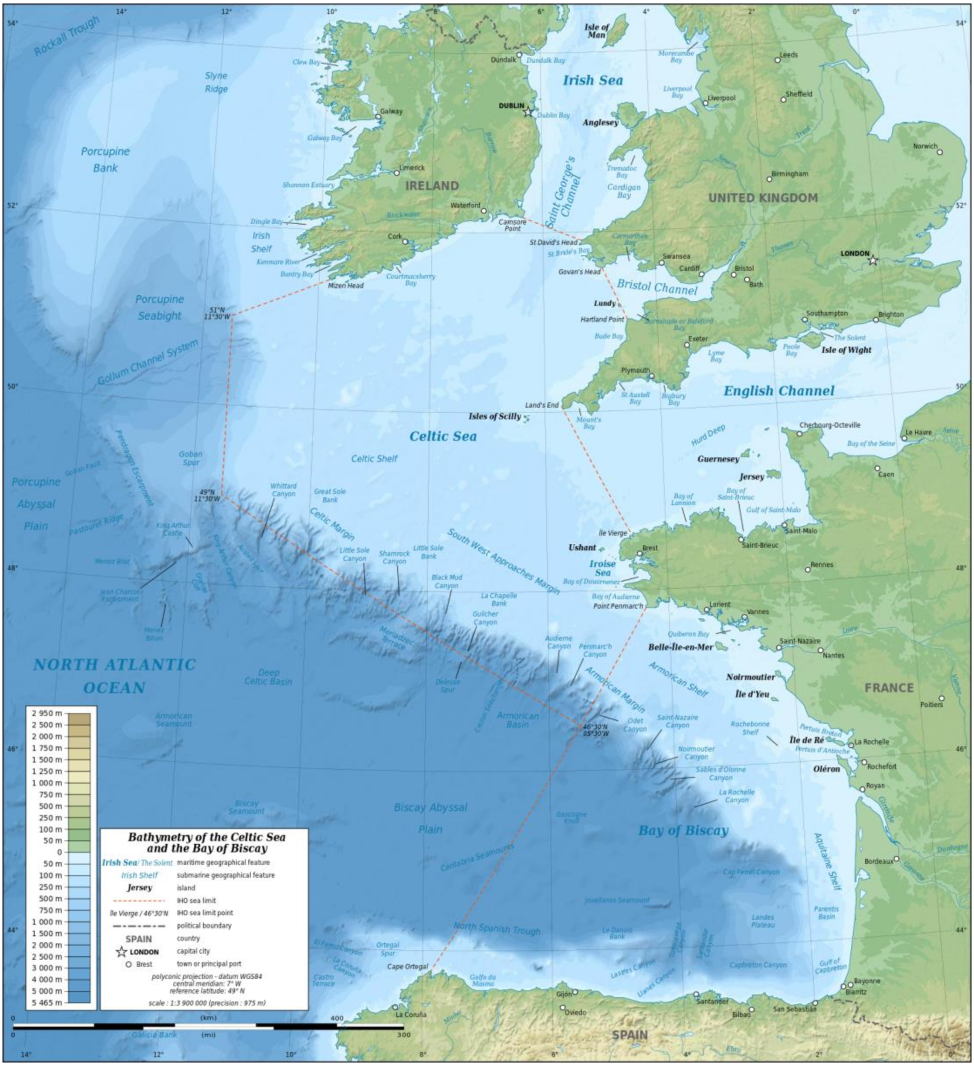

Figura 1. Mapa batimétrico del Golfo de Vizcaya. Fuente: Wikipedia.

La corriente predominante en el golfo es un flujo de aguas templadas superficiales que recorren el litoral del golfo en sentido antihorario, contribuyendo a mantener las temperaturas moderadas a lo largo de todo el año. En el sureste del golfo, la interacción de estas corrientes con las irregularidades batimétricas en la zona del cantil provocan la aparición de surgencias de aguas profundas a la superficie así como de giros de agua ciclónicos y anticilónicos que persisten desde la primavera hasta bien entrado el otoño y estabilizan las masas de agua provocando que en verano y otoño la temperatura sea más elevada en aguas oceánicas que en la plataforma (Koutsikopoulos and Le Cann, 1996; Pingree and Le Cann, 1992).

Especie objetivo: La anchoa

La especie objetivo de este trabajo es la anchoa, *Engraulis encrasicholus* (Linnaeus, 1758), del Golfo de Vizcaya (Figura 2). La anchoa es un clupeiforme de la familia de los engráulidos y constituye un ejemplo típico de pequeño pelágico, ostentando muchos de los rasgos distintivos de este grupo. Los pequeños pelágicos, como su propio nombre indica, son especies de pequeño tamaño; en concreto la anchoa presenta una talla media de unos 15 cm y una talla máxima que ronda los 20 centímetros. Además, se trata de especies que habitan en la zona pelágica, es decir, entre aguas, no encontrándose asociadas ni a la superficie ni al fondo. En concreto, la anchoa es una especie epi-pelágica ya que habita en la capa más superficial de la zona pelágica, que va desde la superficie hasta los 200 metros de profundidad. Las anchoas forman densos cardúmenes que normalmente se mantienen unos 10 metros por encima del fondo marino durante el día y ascienden cerca de la superficie durante la noche (Massé, 1996).

Como el resto de pequeños pelágicos, la anchoa se encuentra en un punto intermedio de la cadena trófica marina. Se alimenta de plancton, tanto animal como vegetal, siendo su presa favorita los copépodos (Bachiller *et al.*, 2013). La anchoa constituye lo que en inglés se conoce como un "forage fish", y que aquí he traducido libremente como "presa universal": dado su pequeño tamaño es presa de muchas de las otras especies pelágicas más grandes (como chicharros, merluzas o atunes) con las que comparte el ecosistema pelágico (Bachiller, 2012). Lógicamente, también es presa del resto de depredadores superiores de la cadena trófica marina, como cetáceos o aves marinas.

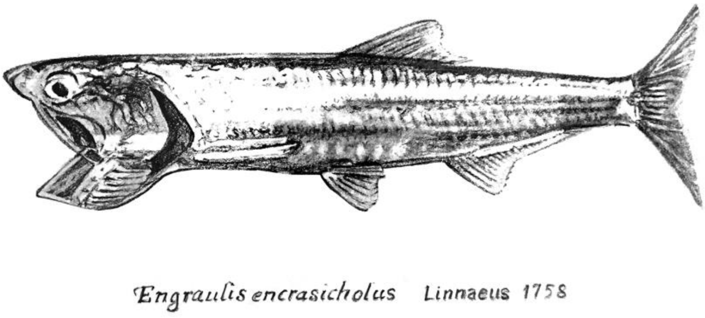

Figura 2: Ilustración de una anchoa. Fuente: Xohan.

En lo que se refiere a alimentación, la anchoa está relativamente especializada en la caza y se alimenta activamente, sobre todo en la etapa juvenil, cuando todavía no ha desarrollado completamente los sistemas de alimentación por filtrado pasivo, que resultan aún poco eficientes. En la etapa adulta, por el contrario, sus sistemas de filtrado se encuentran completamente desarrollados y la anchoa se vuelve más flexible, pudiendo alimentarse tanto activa como pasivamente (Van Der Lingen *et al.*, 2006). Durante la fase juvenil, para realizar la caza selectiva del zooplancton, dispone de unos órganos visuales únicos entre los vertebrados, capaces de concentrar información de color y polarización en la retina (Kondrashev *et al.*, 2012; Novales Flamarique, 2011), que le permiten localizar a sus presas, especialmente en aguas con buena visibilidad. Esta condición, la buena visibilidad, es precisamente una de las características de las aguas oceánicas del Golfo de Vizcaya y es probable que haya contribuido a que la anchoa del golfo haya optado, como veremos después, por una estrategia de ciclo de vida en la que pasa buena parte de su vida juvenil en aguas oceánicas, a diferencia de la mayor parte de los pequeños pelágicos, que pasan dichas fases en aguas de la plataforma continental.

La importancia del reclutamiento

En biología marina se denomina reclutamiento a la entrada de individuos jóvenes a una población. La anchoa, en este sentido, es una especie famosa por su precocidad, ya que madura y se reproduce, reclutándose a la población de adultos, para su primer cumpleaños (Motos *et al.*, 1996a). La anchoa también destaca por su corta vida: raramente alcanza los 3 años de edad (Cort *et al.*, 1977). Como consecuencia, los reclutas suelen constituir más de un 70% de la población (Uriarte *et al.*, 1996) lo que provoca que su abundancia dependa muy fuertemente de la mayor o menor tasa del reclutamiento anual. Este hecho ocasiona que su abundancia esté sujeta a fuertes altibajos, ya que, al no existir más que anchoas de tres generaciones (1, 2 o 3 años de edad), la consecución de varios (dos o más) años de malos reclutamientos suele dar como resultado una disminución drástica de su abundancia, como ocurrió en el año 2005, en el que, tras cuatro años seguidos de pobres reclutamientos, se produjo un colapso de su población (Figura 3) que llevó al cierre de la pesquería durante cinco años.

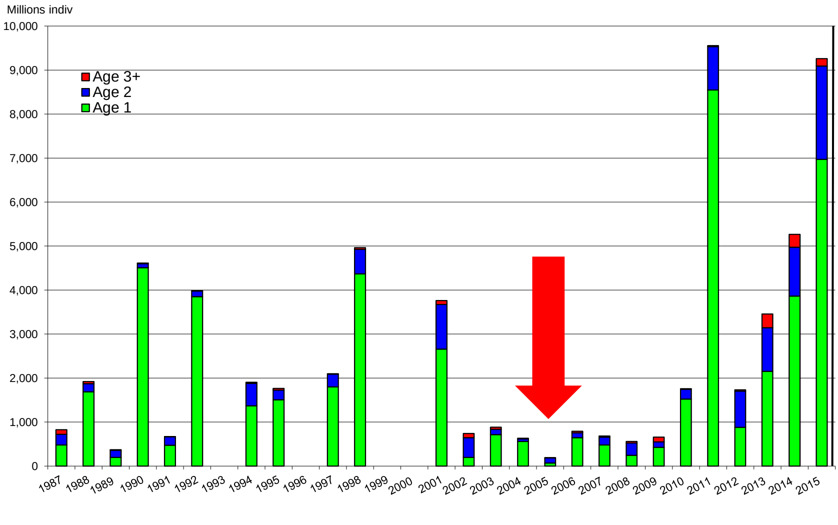

Figura 3. Serie temporal de abundancias por edad de anchoa del Golfo de Vizcaya de acuerdo a la estima sintética del CBBM (Ibaibarriaga et al., 2008, ICES, 2015). La flecha roja señala el año del colapso de la población ocurrido en 2005.

Ciclo de vida de la anchoa del Golfo de Vizcaya

La época de puesta de la anchoa ocurre en primavera y tiene lugar principalmente en la periferia de las pluma del río Garona y Adour (Motos *et al.*, 1996, ver Figura 1) y la zona de cantil (Figura 4). Tras la puesta y a lo largo del verano, los huevos y larvas de anchoa se dispersan y son arrastrados por las corrientes, normalmente desde las zonas costeras de puesta en dirección al suroeste, hacia aguas oceánicas (Cotano et al, 2008, Uriarte *et al.*, 2001b). Durante este proceso, que dura varias semanas, el huevo se va transformando en larva, post-larva y, finalmente, en juvenil.

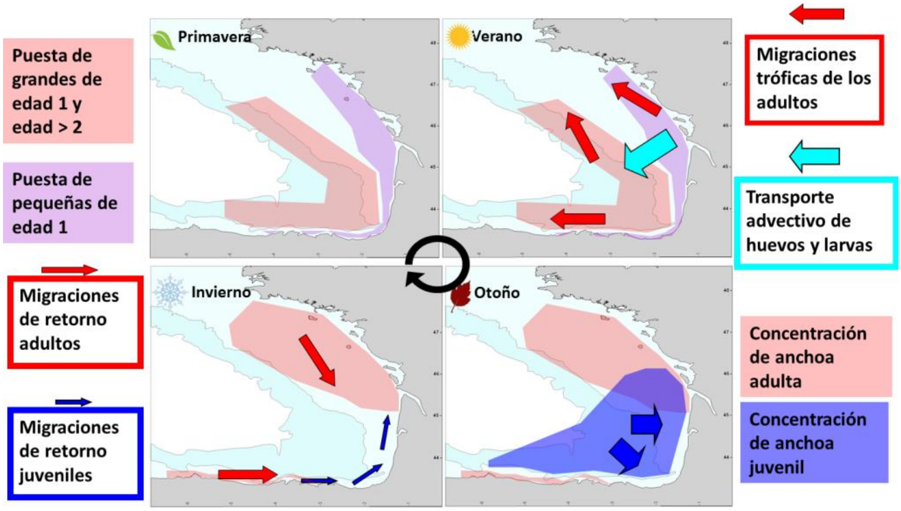

Figura 4. Ciclo de vida de la anchoa del Golfo de Vizcaya.

En sus primeros estadios de desarrollo, la anchoa (como el resto de las especies pelágicas) atraviesa una fase planctónica, es decir, en la que todavía no es capaz de nadar por sí misma. Su supervivencia depende en gran medida, por tanto, de que las corrientes la lleven a zonas donde haya alimento disponible. La velocidad en desarrollarse influye además en la mortalidad, ya que en estas fases constituye presa potencial de prácticamente toda la comunidad pelágica incluidos larvas y juveniles de otras especies piscívoras y gran parte de la comunidad del macrozooplankton (e incluida la propia anchoa adulta, Albaina et al., 2015). Así pues sufre en este período las mayores tasas de mortalidad de todo su ciclo de vida. Esta elevada mortalidad hace que la anchoa siga (a semejanza de otros pequeños pelágicos) una estrategia reproductiva consistente en realizar una puesta lo suficientemente grande como para compensar la extremadamente baja probabilidad de supervivencia de cada huevo.

En el momento en el que se comenzó el presente trabajo, no se conocía demasiado de la fase juvenil de la anchoa. Es precisamente gracias a la campaña que se desarrolló durante este proyecto, la campaña JUVENA, que se ha avanzado principalmente en su conocimiento. La información disponible anteriormente provenía de las pesquerías artesanales de atún del Golfo de Vizcaya, que emplean anchoa juvenil como cebo vivo (Cort *et al.*, 1977). Gracias a ellas sabíamos por ejemplo que durante la fase de juvenil, a principios de otoño, la anchoa se concentraba en zonas de aguas oceánicas del centro y oeste del Golfo de Vizcaya (Uriarte *et al.*, 2001b; Figura 4). Durante la realización de la campaña JUVENA hemos ido conociendo más cosas.

Por ejemplo, que mientras habita en aguas oceánicas, la anchoa juvenil aprovecha las condiciones de temperatura templada, ausencia relativa de depredadores y disponibilidad de alimento asequible y nutritivo (Bachiller *et al.*, 2013), para alimentarse y crecer a la mayor velocidad posible (Aldanondo *et al.*, 2010). Cuanto más crezca, mayores serán sus probabilidades de supervivencia invernal, ya que disminuirá su rango de depredadores potenciales, aumentando el de las posibles presas. Igualmente la velocidad de crecimiento es importante para disminuir el periodo de vulnerabilidad ante sus potenciales depredadores durante las fases tempranas de desarrollo. Una vez los juveniles desarrollan sus capacidades motrices adquiriendo capacidad natatoria, comienzan un regreso paulatino hacia las zonas costeras (Aldanondo *et al.*, 2010).

Con la llegada del régimen invernal, hacia finales de octubre, la paulatina migración de la anchoa hacia costa se precipita. Durante unas semanas es típico que aparezcan anchoas varadas en las playas y estuarios de la costa cantábrica. Y, a partir de un cierto momento, cesan sus detecciones en las ecosondas de pescadores y científicos. Desde ese momento y a lo largo del invierno sólo podemos inferir que la anchoa continúa su migración hacia costa y hacia aguas de la plataforma francesa (Irigoien *et al.*, 2008a) hasta que eventualmente se encuentra con la anchoa adulta, produciéndose en ese momento el reclutamiento. Llegada la primavera, los reclutas se distribuyen en la proximidad de los ríos que desembocan en el Golfo de Vizcaya y, cuando la temperatura asciende lo suficiente, comienzan a poner huevos, cerrándose así el ciclo vital de la especie y comenzando un nuevo ciclo.

La pesquería de la anchoa y su gestión

Hemos mencionado más arriba que la anchoa está considerada como una presa universal para la mayor parte de la comunidad pelágica con la que comparte el ecosistema pelágico. Pero no son sólo las especies marinas las que se alimentan de la anchoa: también lo hace el hombre. La anchoa constituye una de las especies comerciales más apreciadas del Golfo de Vizcaya, existiendo una importante pesquería e industria establecidas a su alrededor y dependientes del buen estado del recurso. La "costera" (la actividad pesquera comercial) de la anchoa comienza normalmente durante la época de puesta, en primavera, extendiéndose a lo largo del verano.

Para tratar de asegurar la sostenibilidad del recurso, la pesquería de la anchoa en el Golfo de Vizcaya se gestiona apoyándose en un consejo científico fundamentado, desde el año 1987, en la información proporcionada por las campañas de evaluación de abundancia que se realizan en primavera, en el momento de la puesta. Estas campañas son BIOMAN (Santos, 2016), realizada por AZTI mediante el Método de Producción Diario de Huevos (MPDH), y PELGAS (ICES, 2016), campaña realizada por IFREMER usando metodología acústico-pesquera. Hasta el año 2014, la información proporcionada por las campañas se combinaba con las capturas de la flota comercial a través de un modelo Bayesiano (Bayesian-Based Model o BBM, Ibaibarriaga et al., 2008) para generar una estima sintética (es decir, obtenida como síntesis a partir de varias fuentes) de abundancia de anchoa. Esta estima sintética de abundancia se obtenía y validaba en el contexto del grupo de trabajo del ICES

WGHANSA (ICES, 2012) y después se empleaba como consejo científico para la gestión de la pesquería. El sistema de estima sintética resulta muy robusto, al combinar la información de las capturas de la flota con la de dos estimas independientes de la pesquería (e independientes entre sí), lo que estabiliza la serie temporal de estimas y la hace más insensible a potenciales errores de alguna de las tres fuentes.

Sin embargo, el sistema del BBM en esta versión presentaba una limitación importante: la estima sintética de abundancia estaba disponible sólo a finales de junio de cada año, con la costera de la anchoa ya iniciada, lo que limitaba su potencialidad para tomar medidas correctoras para el primer semestre del año en caso de reclutamientos inesperadamente altos o bajos. Esta eventualidad se venía anticipando desde los años noventa y se puso de manifiesto ya en las crisis de la pesquería ocurridas en esos años. Así pues, se planteó la necesidad de tratar de obtener por algún medio una información anticipada de la abundancia del recurso, antes del comienzo de la costera.

Se plantearon distintas alternativas. En primer lugar se intentó usar la abundancia de anchoa un año dado para tratar de predecir la magnitud de reclutamiento del año siguiente. Sin embargo, dada la alta variabilidad de la mortalidad entre años, no se obtuvieron correlaciones significativas entre la cantidad de anchoas desovantes y la fracción de supervivientes de la puesta (Figura 5).

Para tratar de mejorar esta relación se hizo uso de variables ambientales que trataran de explicar la variabilidad del reclutamiento interanual, aumentando la correlación entre la puesta y el reclutamiento (Borja, 1998, Borja *et al.*, 2008; Fernandes *et al.*, 2010). Sin embargo, aunque mejoraban notablemente en algunos años, en otros años no eran capaces de predecir los reclutamientos obtenidos, por lo que no proporcionaban una información fiable de cara a la gestión.

Como segunda alternativa, se propusieron métodos basados en modelos hidrodinámicos del Golfo de Vizcaya, que eran capaces de predecir la deriva de la hueva, estableciendo así proyecciones de supervivencia en función de que los modelos pronosticaran la llegada de la anchoa a zonas favorables para la supervivencia (Allain *et al.*, 2001). Sin embargo dada la complejidad del ecosistema del Golfo de Vizcaya, estos modelos tampoco funcionaron. El motivo de ello fue que, a diferencia por ejemplo de los ecosistemas de afloramiento, como el Golfo de Bengüela o la plataforma peruana, que se basan prácticamente en una sola variable con mucha influencia (la intensidad del afloramiento), el Golfo de Vizcaya es un ecosistema que carece de variables de influencia predominante y funciona por acumulación de pequeños factores, por lo que no resulta sencillo pronosticar cuáles serán realmente las zonas favorables para la supervivencia (Irigoien *et al.*, 2008b).

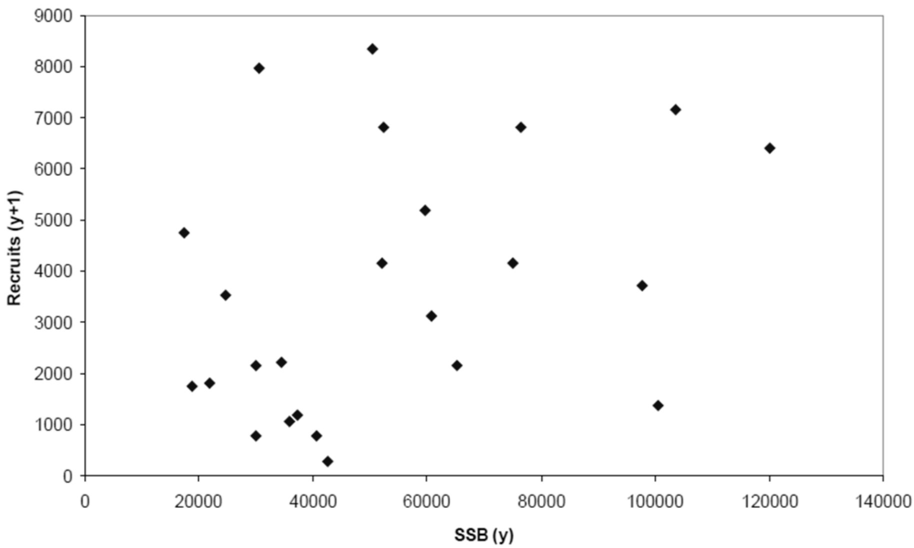

Figura 5. Relación entre biomasa de anchoa y reclutamiento al año siguiente para la anchoa del Golfo de Vizcaya (extraído de Petitgas et al., 2011). Se puede intuir una correlación positiva entre ambas variables, pero sujeta a una muy alta variabilidad (los puntos se disponen en una nube en vez de alineados).

Como tercera posibilidad para tratar de obtener una información anticipada del reclutamiento, se propuso la idea de añadir una nueva campaña oceanográfica de prospección, enfocada al consejo científico de la gestión de la pesquería, que estimara la abundancia de anchoa juvenil, es decir, cuyo objetivo fuera la estimación de la fracción de hueva que sobrevive durante el verano y llega a la fase juvenil a principios de otoño, unos cuatro meses después de la puesta. Si la anchoa en fase juvenil ha superado ya las etapas de mortalidad más variable, su abundancia podría dar una estima fiable de la anchoa que sobrevivirá el invierno y se reclutará a la pesquería la primavera siguiente. Así pues, la idea es usar dicha abundancia de anchoa juvenil como estima anticipada del reclutamiento, varios meses antes de que éste se produzca y del inicio de la actividad pesquera

Objetivos

- El primer objetivo de la presente tesis doctoral consiste en el diseño y puesta a punto de una campaña de prospección de recursos pesqueros para obtener un índice de abundancia anual de anchoa juvenil.
- El segundo objetivo consiste en chequear la efectividad de la estima de abundancia de anchoa juvenil como índice predictivo del reclutamiento del año entrante. Esto se realizará correlacionando la abundancia de anchoa juvenil con la abundancia de anchoa de un año de edad la primavera siguiente (según la estima del BBM, Ibaibarriaga *et al.*, 2008) a lo largo de 10 años ininterrumpidos de campañas de evaluación.
- El tercer objetivo es explorar la distribución espacial y la dinámica de la anchoa juvenil en el Golfo de Vizcaya, así como su posible influencia en el éxito del reclutamiento de la especie.

Hipótesis de la tesis

La hipótesis (H0) de esta tesis doctoral es que la variabilidad en la mortalidad de juveniles de anchoa durante el invierno no es suficiente como para eliminar la relación entre la abundancia de juveniles y la de reclutas. La hipótesis alternativa (H1) es que la variabilidad en la mortalidad invernal de reclutas es lo suficientemente alta como para que desaparezca esa relación. Si se acepta la hipótesis, el índice de abundancia de anchoa juvenil a principios de otoño, unos cuatro meses después de la puesta proporciona un índice válido (y por tanto una estima anticipada a la "costera" de la anchoa, con ocho meses de antelación) del reclutamiento que se producirá al año siguiente. El testeo de la hipótesis se realizará estableciendo modelos de regresión estadísticos, paramétricos y no-paramétricos, entre las series temporales de biomasa de juveniles y reclutas de anchoa. Una correlación significativa probaría la validez de la hipótesis.

Estructura de la tesis

Este trabajo se acoge a una estructura formal de tesis por compendio de contribuciones científicas basada en cinco capítulos (cada uno de ellos correspondiente a un artículo publicado en revistas incluidas en el *Science Citation Index* o un capítulo de libro) más unas conclusiones generales. Los capítulos son los siguientes:

Capítulo 1: Selección de la tecnología apropiada para la estimación de abundancia de anchoa juvenil. En él el doctorando realizó el grueso de los análisis de correlación entre abundancia acústica y LIDAR en las zonas de simultaneidad espacio-temporal, así como la coordinación de la discusión.

Capítulo 2: Desarrollo de metodología de campaña acústico-pesquera para estimar abundancia de anchoa juvenil. Serie temporal de estimas JUVENA 2003-2010 y predicción del reclutamiento.

Capítulo 3: Cálculo del error de las estimas de biomasa realizadas en la campaña JUVENA entre los años 2003 y 2010.

Capítulo 4: Actualización del índice de reclutamiento empleando 2 años más de estimas de juveniles y reclutas. Incluye un Addendum con la actualización del índice hasta el año 2016 y estado de la gestión de la pesquería tras la incorporación del índice JUVENA.

Capítulo 5: Dinámica espacial de los juveniles en el período de la campaña basado en la comparación de dos campañas sucesivas en el año 2009.

Conclusiones generales: Las conclusiones generales se estructuran por capítulos. Al final de la sección se incluye la validación de la hipótesis de la tesis doctoral.

Lista de artículos

La siguiente lista de artículos científicos constituye la base de esta tesis doctoral:

- Comparison of airborne LIDAR with echosounders: a case study in the coastal Atlantic waters of southern Europe. Carrera, P., Churnside, J. H., Boyra, G., Marques, V., Scalabrin, C. and Uriarte, A. (2006). ICES Journal of Marine Science, 63, 1736-1750 (Chapter 1)
- Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. ICES Journal of Marine Science, 70: 1354–1368. (Chapter 2)
- Uncertainties and alternative estimates of the JUVENA index according to its special methodology and assumptions. G. Boyra, U. Martínez, U. Cotano, M. Santos, X. Irigoien and A. Uriarte. Suplementary information for ICES Journal of Marine Science, 70: 1354–1368. (Chapter 3)
- Anchovy juvenile acoustic surveys JUVENA 2003-2012. Boyra, G. 2016. In "Pelagic Surveys series for sardine and anchovy in ICES Areas VIII and IX (WGACEGG) - Towards an ecosystem approach". Massé, J. and Uriarte, A. (ed.) ICES CRR. (in press). (Chapter 4)
- Spatial dynamics of juvenile anchovy in the Bay of Biscay. 2016. Boyra, G., Peña, M., Cotano, U., Irigoien, X., Rubio, A. and Nogueira, E. Fisheries Oceanography, in press. (Chapter 5)

Los siguientes artículos, aunque no forman parte directa de esta tesis doctoral, cuentan con la autoría del doctorando y se han podido realizar gracias a la puesta en marcha de la campaña JUVENA:

- Interannual differences in growth and hatch-date distributions of early juvenile European anchovy in the Bay of Biscay: implications for recruitment. Naroa Aldanondo, Unai Cotano, Nerea Goikoetxea, Guillermo Boyra, Leire Ibaibarriaga and Xabier Irigoien. (2016) Fisheries Oceanography, 2:147-163.
- Spatial distribution of the stomach weights of juvenile anchovy (Engraulis encrasicolus L.) in the Bay of Biscay. Eneko Bachiller, Unai Cotano, Guillermo Boyra and Xabier Irigoien. ICES Journal of Marine Science, 70 (7), 362-378. 2012
- Growth and movement patterns of early juvenile European anchovy (Engraulis encrasicolus) in the Bay of Biscay based on otolith microstructure and chemistry. Aldanondo, N; Cotano, U; Tiepolo, M; Boyra, G and Irigoien, X. 2010. Fish. Oceanogr. 19:3, 196–208, 2010
- Spatial-temporal variability of albacore (Thunnus alalunga) prey fields in the Bay of Biscay as inferred from acoustic surveys. A. Lezama, G. Boyra, N. Goñi and H. Arrizabalaga. Progress In Oceanography, 86(1-2), 105-114. 2010.
- From egg to juvenile in the Bay of Biscay: spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P. Otheguy, P., Etxebeste, E., Uriarte, A., Ferrer, L.and Ibaibarriaga, L. Fish. Oceanogr. 17:6, 446–462, 2008.
- Could Biscay Bay Anchovy recruit through a spatial loophole? X. Irigoien, Ø. Fiksen, U. Cotano, A. Uriarte, P. Alvarez, H. Arrizabalaga, G. Boyra, M. Santos, Y. Sagarminaga, P. Otheguy, E. Etxebeste, L. Zarauz, I. Artetxe, L. Motos. 2007. Progress in Oceanography 74: 132-148.

Por último, los siguientes artículos forman parte del esfuerzo colectivo desarrollado en los últimos doce años por AZTI, con la colaboración del IEO, UPV/EHU, Ifremer e IPMA, para mejorar el conocimiento sobre la anchoa y el ecosistema pelágico:

- Detecting the presence-absence of bluefin tuna by automated analysis of medium-range sonars on fishing vessels. Uranga, J., Arrizabalaga, H., Boyra, Hernández, C., Goñi, N., Arregi, I., Fernandes, J., Yurramendi, J. and Santiago, J. 2017. PLOS ONE (in press).

- A real-time PCR assay to estimate invertebrate and fish predation on anchovy eggs in the Bay of Biscay. Aitor Albaina, Xabier Irigoien, Unai Aldalur, Unai Cotano, María Santos, Guillermo Boyra and Andore Estonba. 2015 Progress in Oceanography, 131, 82-99.
- Macrozooplankton predation impact on anchovy (Engraulis encrasicolus) eggs mortality at the Bay of Biscay shelf break spawning centre. Aitor Albaina; Xabier Irigoien; Unai Aldalur; Guillermo Boyra; Maria Santos; Andone Estonba. ICES Journal of Marine Science. (2015), 72(5), 1370–1379.
- Large mesopelagic fishes biomass and trophic efficiency in the open ocean. Irigoien, X., Klevjer, T A, Røstad, A., Martinez, U, Boyra, G., Acuña, J. L., Bode, A. Echevarria, F., Gonzalez-Gordillo, J. I., Hernandez-Leon, S., Agusti, S. D., Aksnes, L., Duarte, C. M. and Kaartvedt, S. 2014. Nature Communications 02/2014; 5:3271.
- Buoyancy measurements and vertical distribution of eggs of sardine (Sardina pilchardus) and anchovy (Engraulis encrasicolus). S.H. Coombs, G. Boyra, L.D. Rueda, A. Uriarte, M. Santos, D.V.P. Conway and N.C. Halliday. (2004). Marine Biology 145-5, 959-970.
- Modelling the vertical distribution of eggs of anchovy (Engraulis encrasicolus) and sardine (Sardina pilchardus). G. Boyra, L. Rueda, S. Coombs, S. Sundby, B. Aadlandsvic, M. Santos and A. Uriarte. Fish. Oceanogr., 12:4/5, 381-395, 2003.

Consideraciones idiomáticas

Esta tesis está escrita en castellano e inglés. Se han escrito duplicados en bilingüe el *Resumen extendido* y las *Conclusiones generales*. Por su parte, la *Introducción general* se ha escrito en castellano. Los capítulos centrales, por el contrario, se han mantenido en el inglés original en el que fueron publicados, habiéndose añadido al principio de cada capítulo un breve resumen del mismo en castellano.

Foto: Reunión de coordinación de las campañas JUVESU del Golfo de Vizcaya en el aeropuerto de Santander, en agosto de 1999. Posando junto a la avioneta CASA 212 del INTA que transportaba el LIDAR (Fuente: AZTI).

Chapter 1

Comparison of airborne LIDAR with echosounders: a case study in the coastal Atlantic waters of southern Europe

Comparación de LIDAR aerotransportado y ecosondas: Caso de estudio en las aguas costeras del sudoeste europeo

Para establecer la metodología adecuada para estimar la abundancia de anchoa juvenil, se realizó entre los años 1998 y 1999 una serie de campañas experimentales (JUVESU) comparando la adecuación de la metodología acústico-pesquera (Simmonds and Maclennan, 2005), realizada a bordo de embarcaciones pesqueras y oceanográficas, con el uso de sensores LIDAR aerotransportados (Churnside and Hunter, 1996). La comparación de metodologías se realizó en tres zonas distintas cada año: la costa de Portugal, las rías bajas gallegas y el Golfo de Vizcaya, empleando para ello una avioneta dotada de un LIDAR pesquero que sobrevolaba consecutivamente las tres áreas que estaban muestreándose simultáneamente con embarcaciones oceanográficas y pesqueras. Se seleccionaron las áreas de máxima superposición espacio-temporal entre muestreo LIDAR y acústico, y en ellas se realizaron comparaciones de mapeos espaciales y regresiones lineales. Además, se realizaron estudios de autocorrelación espacial de los registros LIDAR y acústicos para establecer el diseño de muestreo óptimo en términos de distancia inter-radial y área potencial de muestreo. La extensión vertical de anchoa juvenil encontrada se empleó para considerar posibles métodos de pesca para identificación de especies y obtención de muestras para análisis biológicos.

1.1 Abstract

The feasibility of using airborne LIDAR (Light Detection and Ranging) was studied to assess the early juvenile fractions of the main pelagic fish species that occur in the coastal Atlantic waters of southern Europe (*i.e.*, anchovy, sardine, mackerel, and horse mackerel). Field comparisons with more established acoustic methods were undertaken in the summers of 1998 and 1999 during the recruitment period of sardine and anchovy in the selected areas and in the presence of a variety of oceanographic and environmental conditions. Backscattered energy as well as the typology of the targets collected by both devices was compared. The distribution of energy and observed typologies were generally similar for both techniques, with moderate numerical correlation between sensors, proving the potential of LIDAR for assessment of three of the targeted species of juveniles, namely anchovy, sardine, and mackerel. However, differences in received backscattering energy were found, especially in the presence of certain plankton structures (more visible for LIDAR) and isolated thick schools. Experimental *ad hoc* optical reflectivity measurements of fish and plankton are proposed to discriminate these two types of targets. In addition, an improvement on LIDAR implementation and data processing is suggested to achieve fish abundance estimates.

1.2 Introduction

One of the most important components of fishery management is the assessment of the strength of the year classes before they enter the fishery. Good larval survival produces strong year classes (Smith, 1985, Houde, 1996). It seems, therefore, that the strength of the recruitment of many species is already established five or six months after spawning, once they are already at juvenile stages. This has been demonstrated for many populations all over the world, including California rockfishes (Ralston & Howard, 1995), walleye pollock (Bailey & Spring, 1992), and several pelagic populations like herring (Leblanck et al., 1998), northern anchovy (Smith, 1985), etc. Hence, when assessment of those early juveniles can be done at that phase, the estimates can be used to predict, at least in relative terms, the strength of the future recruitment to the fisheries. Targeting juveniles for the assessment of recruitment is of special interest for the fisheries of short-lived species, like sardines and anchovies, because of the short time between spawning and the exploitation of subsequent emerging recruits. In fact in some areas, these types of fisheries are managed through Total Allowable Catches (TACs) based on the estimates of juveniles from direct surveys, as in the anchovy fishery of South Africa (Butterworth and Bergh, 1993, Hampton, 1992) or Icelandic capelin, where immature 1- and 2-year-old classes are targeted (Anon, 2000a).

Acoustic methods have traditionally been applied to obtain recruitment estimates (Dragesund and Olsen, 1965). However, the assessment of early juveniles may be difficult, since many juveniles display epipelagic phases, where they remain in the upper layers of the water column. Also, they are often found in coastal areas or, in some cases or phases, even in shallow waters (Mays, 1974, Boyd et al., 1997, Leblanck et al., 1998, Alshuth S., 1988, Villamor et al., 1997, Locwood, 1988, Dias et al., 1988, 1989, Anon, 1998). This behaviour would set juveniles outside the vessel range and/or the effective operating range of an acoustic transducer (MacLennan & Simmonds, 1992). Besides, acoustics may underestimate schools if they are actively avoiding the ship (Freon & Misund, 1999). All these potential problems suggest a need for improved acoustic methods and/or other complementary techniques for the detection of juveniles.

In the 1990s, research began into the development of aerial LIDAR surveys for detecting fish schools (Hunter and Churnside, 1995, Gauldie et al., 1996), based on some earlier feasibility studies (Fredriksson, et al., 1978, Squire and Krumboltz, 1981). LIDAR was tested as a technique to detect tuna in the Pacific (Oliver et al., 1994) and to detect pelagic species like sardines (Churnside et al., 1997), capelin (Brown et al., 2002), mullet (Churnside et al., 2003), and even zooplankton (Churnside and Thorne, 2005). It seems likely that it could be a useful tool to effectively map the distribution of schools of juveniles close to surface, because it is capable of detecting schools from the surface to a depth of about 30 – 40 m, which is a depth range typical of juveniles. In addition, it can be operated from a small inexpensive airplane, so shallow coastal waters could be easily surveyed from the air. The processing of the LIDAR signal to obtain quantities proportional to the number of fish within the depth resolution has been demonstrated, although the conversion into biomass requires species identification and experimental knowledge of fish reflectivity and size (Churnside and McGillivary, 1991, Krekova et al., 1994, Churnside and Hunter, 1996, Churnside et al., 1997). Thus, aerial surveys seem to be a promising technique for juvenile assessment, and the LIDAR system could be an effective component of such a technique.

In the Atlantic waters of the Iberian Peninsula and in the Bay of Biscay, sardine and anchovy are the most important pelagic fish species and support important fisheries in Portugal, Spain, and France (Anon, 2000a, 2000b; Carrera and Porteiro 2003, Uriarte et al., 1996). Off the Iberian Peninsula, the recruitment of sardine at age 0 mainly occurs in the northern and central part of Portugal from summer to winter (Anon, 1982, Pestana 1989, Dias et al., 1988, 1989, 1993, Porteiro et al., 1986, 1993). In the Bay of Biscay, the major nursery areas for anchovy are located in the southern part of the Bay (Prouzet et al., 1994, Uriarte et al., 1996).

Acoustic surveys to estimate sardine recruitment at age 1 are routinely conducted in spring around the Atlantic waters of the Iberian Peninsula. Besides, an acoustic survey is conducted in November off Portugal to estimate its recruitment at age 0 (Dias et al., 1996, Porteiro et al., 1996). For anchovy, both acoustic and egg surveys are undertaken in spring, estimating the strength of the year classes at age 1 (Massé, 1996, Santiago and Sanz, 1992, Uriarte et al., 1999).

However a systematic study of juveniles at age 0 of anchovy and sardine in the south of Europe had never been performed, since most of the acoustic surveys take place during springtime when most of the fish are already spawners (Carrera et al., 1996, Masse et al., 1992, Masse, 1996, Porteiro et al., 1993, Scalabrin and Masse, 1993). Juvenile shoals of both fish species show an epipelagic distribution and, in the case of sardine, one that is close to the coast (Soares, 1995, Cort et al., 1976, Martín, 1989), which, in turn, could make it difficult to achieve a precise estimation of the fish biomass using echo-sounding methods.

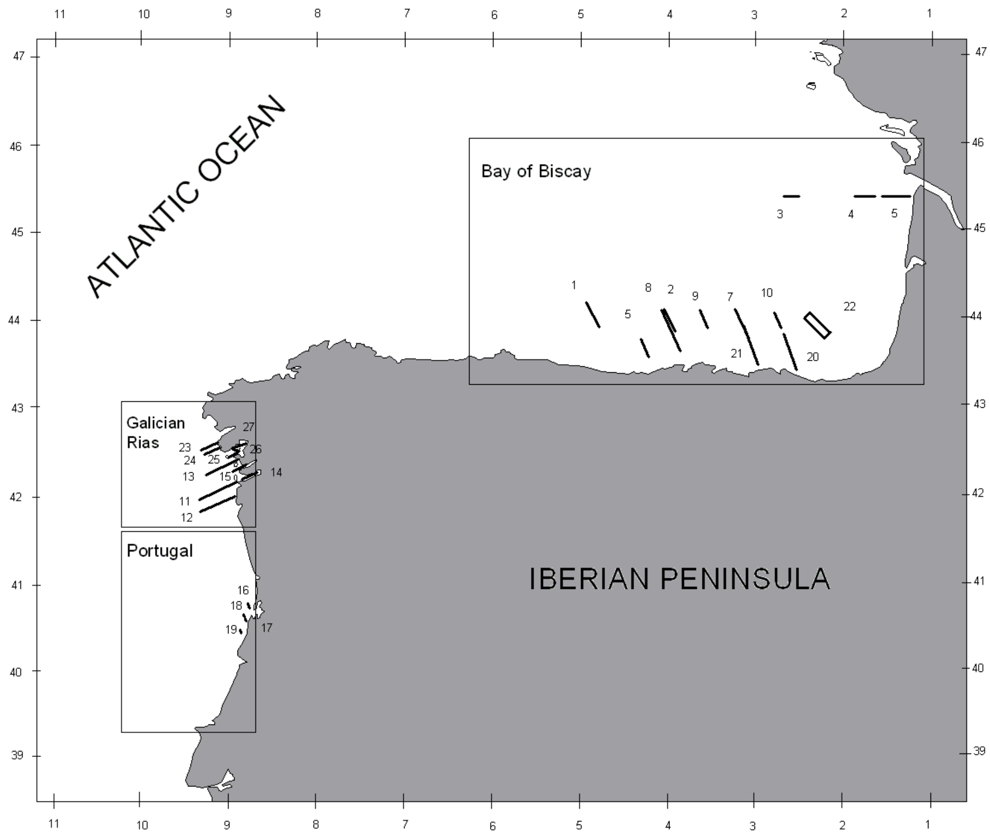

Figure 1-1. Survey areas and position of the HAGCs.

In this context, in order to improve surveying methods for the estimation of recruitment for these pelagic resources, a research project called Experimental Surveys for the Assessment of Juveniles (JUVESU-FAIR CT 97-3374) was developed. The major goal of this project was to evaluate the possibilities and problems for directly surveying the spatial distribution and relative abundance of early juveniles of sardine and anchovy using airborne systems and comparing them with the usual ship-borne acoustic systems. The experimental surveys were made in 1998 and 1999 in western Iberian Peninsula waters and in the southern part of the Bay of Biscay (Figure 1-1). These areas present remarkable oceanographic differences and contain nurseries of several pelagic species of major interest for various European fisheries (mainly ardine and anchovy and secondarily mackerel and horse mackerel).

This paper describes the results of the analysis of the relative performance of the LIDAR and acoustic systems for the detection of juveniles of the main pelagic species arising from the experimental surveys performed in the summers of 1998 and 1999. In addition, direct analysis between sensors was made in discrete areas with particularly homogenous distribution of juvenile school type. Finally, we also discuss the potential of LIDAR technology for future assessment of the main juveniles in the study areas.

1.3 Material and methods

Two experimental surveys were performed, in August – September 1998 and 1999, to test the performance of LIDAR and acoustic systems in detecting fish, primarily juveniles (Table 1-1). These study areas, shown in Figure 1-1, were the southeastern Bay of Biscay (43º N-46º N, 1º W-5º W), the Galician Rias and the shelf in the northwest of the Iberian Peninsula (41.8º N-43º N, 8.7º W-9.4º W), and the north-central shelf off Portugal (39.5º N-41.8º N, 8.6º W-10.2º W). These were selected because juveniles of anchovy, sardine, mackerel, and horse mackerel were likely to occur here based on previous knowledge about their distributions.

Fish distribution mapping and species identification were done by acoustic and fishing surveys, coupled with airborne LIDAR surveys. Ship-borne acoustic coverage of each area was carried out with various research vessels equipped with echo sounders. Fishing to provide ground truth (McClatchie *et al.*, 2000) was performed by the acoustic survey vessels (pelagic and bottom trawl) and by rented commercial vessels (purse seines).

Table 1-1. Main characteristics of the cruises.

AREA	DATES	ACOUSTICS SETTINGS	LIDAR SETTINGS
		1998	
Bay of Biscay	04/09/98-18/09/1998	R/V Gwen Drez, acoustics and pelagic trawl F/B: Beti Euskalherria, purse seine hauls OSSIAN1500 (38 kHz, single beam, hull) Echogram: Digital Post-processing: Movies + Calibration Copper Sphere	Aircraft: CASA 212-200 Transmiter: Laser CFR200 doubled Nd:YAG Wavelength 532nm Pulse length 12 ns
Galicia	20/08/98-28/08/1998	R/V: José María Navaz, acoustics F/B M. Presas, purse seine hauls Simrad EY500 (38 kHz, single, towed body) Echogram: digital Post-processing: Echoview Calibration Copper Sphere	P. energy 100 Mj P. repetition rate 30 Hz Night: 65 mrad. Receiver: Detector R6915U PMT Aperture diam. 17 cm. Field of view: 17-65 mrad
Portugal	26/08/98-03/09/1998	R/V: José María Navaz, acoustics R/V Noruega, pelagic and bottom trawl Simrad EY500 (38 kHz, single, towed body) Echogram: digital Post-processing: Echoview Calibration Copper Sphere	(day and night) Op. bandwidth 10nm. Sample rate 1GHz Digitiser STR81G
		1999	
Bay of Biscay	01/09/99-19/09/1999	R/V Gwen Drez, acoustics and pelagic trawl F/B: Divino Jesús de Praga, purse seiner OSSIAN1500 (38 kHz, single, hull) Echogram: Digital Post-processing: Movies + Calibration Copper Sphere	Aircraft: CASA 212 Transmitter: Laser CFR200 doubled Nd:YAG Wavelength 532nm Pulse length 12 ns
Galicia	25/08/99-03/09/1999	R/V: José María Navaz, acoustics F/B Praia de Portonovo, purse seiner Simrad EY500 (38 kHz, single, hull) Echogram: digital Post-processing: Echoview Calibration Copper Sphere	P. energy 100 mj P. repetition rate 20 Hz Beam div Day: 17 mrad. Night: 65 mrad. Receiver: Detector R6915U PMT Aperture diam. 17 cm.
Portugal	24/08/98-30/08/1998	R/V Capricornio, acoustics and pelagic trawl R/V Mestre Costeiro, bottom trawl Simrad EK500 (38 kHz, split beam, hull) Echogram: digital Post-processing: Movies+ Calibration Copper Sphere	Field of view: 17-65 mrad (day and night) Op. bandwidth 10nm. E. bandwidth 300 MHz Sample rate 1GHz Digitiser STR81G

The acoustic surveys were conducted in two phases. The first was an extensive coverage of the target area, whereas the second was an intensive coverage of a selected portion of the area. The intensive legs were located in those areas of high juvenile abundance, where repeated passes were done at different periods of the day. The main goal of this second phase was to characterize the aggregation patterns of the pelagic fish and their changes during the day. To facilitate the comparison of the results, common transect lines were designed for the ship and aircraft cruises for all areas.

An Elementary Distance Sampling Unit (EDSU) was set at 1 nautical mile and the track was covered at a speed of 7 – 10 knots. The extensive area was covered only during daytime. For the analysis presented here, the extensive data and both day and evening data from the intensive were used. For the backscattering comparisons only the extensive data were used. Data from either the extensive or intensive coverages were used to scrutiny the datagram and to perform the echo-trace analyses.

The LIDAR system is the NOAA radiometric LIDAR described by Churnside *et al.* (2001). Survey tracks for the flights were the same as those performed by the different research vessels. In this case the survey speed was around 140 knots and the mean altitude was around 300 m. With such conditions, during daytime, the swath width was set to 5 m at the sea surface. Depth penetration varied from area to area and from year to year, depending on the water clarity, light level, and laser power, but was generally around 25 – 30 m.

1.3.1 Data Analysis

The primary LIDAR data-processing method applied to the entire extensive coverage was denoted as "school processing". Here, the clear water part of the signal was removed from each shot, so that only schooling, or plankton structures aggregated to it, resulted in positive value returns. The clear-water signal at each depth was approximated as the median of the values from all shots over segments of about 1 nautical mile in horizontal extent. Unfortunately, in this process, extensive juvenile layers were rejected. Therefore, for the analysis of this paper, another method, denoted "echo-integration" for its similarity to the acoustic processing method, was developed (see Figure 1-2 for an illustration of each). On the other hand, acoustic data were echo-integrated with a –60 dB threshold for 5 m depth layers from the transducer depth (*i.e.* 3 – 5 m depth) to the bottom.

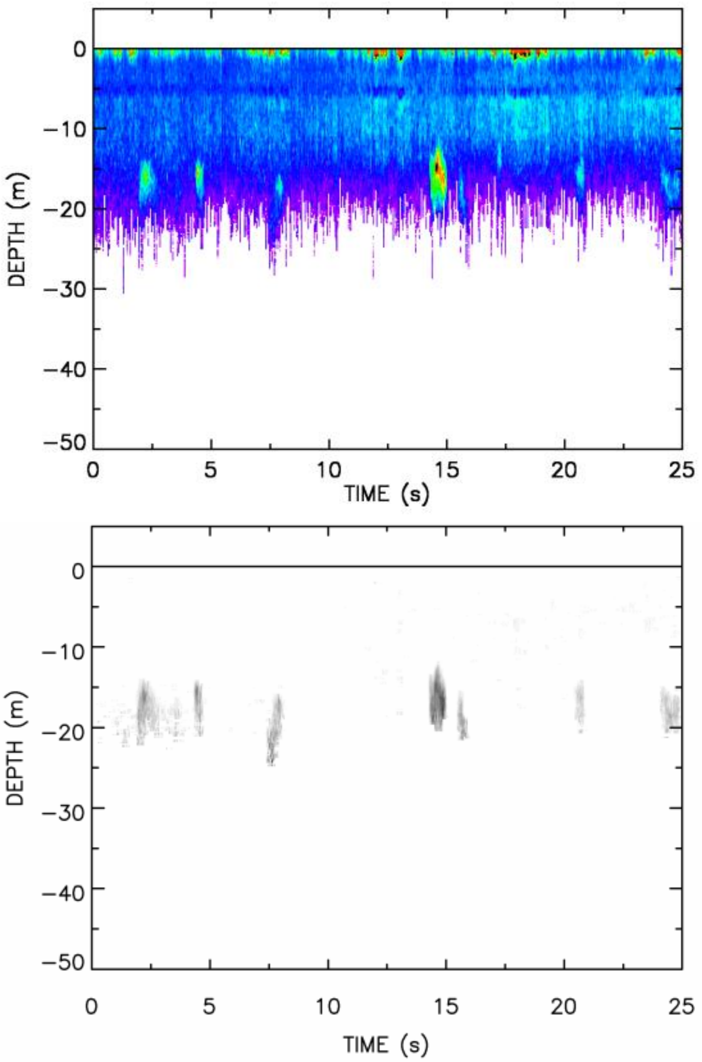

Figure 1-2. Comparison of the results of school processing (top panel) and echo-integration processing (bottom panel) for a period of 25 seconds (about 1 nm) on the Galician shelf (around 42ºN and 9º10'W) on the morning of 31/8/99. Several large and dense schools can be seen below a diffuse plankton layer in a zone where acoustics made no detections.

No conversion of acoustic or LIDAR energy into biomass was attempted, and the signals were treated in units of energy as energy or by their physical features. Thus, in addition to backscattered energies, acoustic and LIDAR typologies (*i.e.* echo traces) were processed by extracting several school size and shape descriptors for further analysis.

In order to evaluate the performance of the LIDAR in the studied area, a series of comparisons was done. For this purpose, it was assumed that the echo sounders provided a better (and known) backscattered energy/fish biomass conversion relationship along the areas. Fish avoidance was assumed to produce little disturbance (Fernandes *et al.*, 2000), and only diving responses would be expected from the fish (Blaxter *et al.*, 1981; Schwarz and Greer, 1984).

The first comparison analyzed the results for the entire extensive coverage of the three areas surveyed, assuming a stationary distribution and either a single species or a uniform mixture of species. Under this assumption, one would expect to find the same overall mean relative value in the back-scattering energy in a given area obtained from both devices. The whole depth range of penetration of the LIDAR was used, whereas for the acoustic data, only the first 30 m were used to correspond to the mean LIDAR depth penetration. Each data set was log-transformed and then put in relative units by weighting each observation by its maximum. For each data set, the spatial distribution was studied by means of geostatistic tools (Matheron, 1971; Petitgas 1991, 1993). This analysis was done using Estimation Variance Analysis (EVA) (Petitgas and Prampart, 1993) and SURFER v7.0 (Golden Software) packages. According to the results and the experimental variograms obtained in the previous analysis, contour maps were constructed. These were done by kriging using variogram models fit to the data for each map and the same map grid for both acoustic and LIDAR data. For each area, krige contours for both devices were compared. Wilcoxon paired-sample tests were performed on results obtained after the kriging process.

The second comparison was done on a more local scale, allowing for nonstationary conditions where the echo-trace type and, in some cases, backscattering energy could change with time. For this analysis, some simultaneity of coverage is required, as similar targets are expected to be detected by the two devices, and direct comparison of their respective detecting capabilities can be made. From the surveys performed in each area, segments of transects were chosen for comparison according to two criteria. The acoustic targets along the segment all had to be of the same type, and the aircraft and ship had to cover the transect at the same time of day (either daytime, night-time or evening) within two days of each other. These segments were called Homogeneous Areas for Geographic Comparison (HAGC). Figure 1-1 presents the location of selected HAGCs.

Both LIDAR processing methods were compared with the acoustic results for the HAGCs. The quantitative and ordinal (Pearson and Spearman) correlations between the average acoustic echo-integrated and LIDAR energies across HAGCs were calculated. LIDAR and acoustic energies were normalized by the average value for each area and year and were logarithmically transformed. That is, for every HAGC *i*, the energy E_i was substituted by the result of the following expression:

$$\log E_i - \log < E >_{area,year} ,$$

where $<E>_{area,\ year}$ corresponds to the average value of the energy from a given sensor obtained for the corresponding year and area (Bay of Biscay, Galician, or Portuguese surveys). Correlations were made for these transformed energies. Also, acoustic echo traces were classified according to their shape in four categories (schools, pelagic and bottom layers, and scattered echo traces).

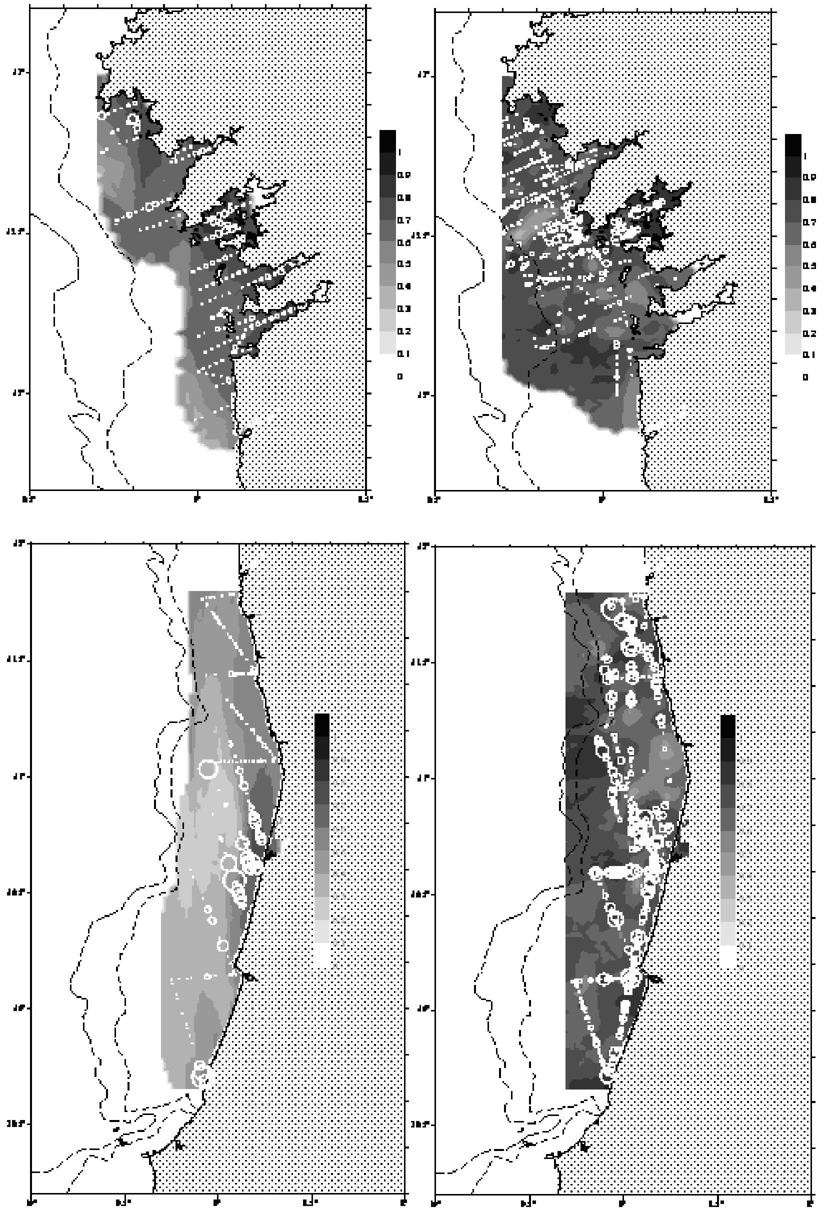

Figure 1-3. Contour maps made by kriging on log transformed variables together with the raw backscattering energies represented as circles scaled using the Square Root method for 1998 data. Top panels: Galicia. Bottom panels: Portugal. Left: acoustics. Right: LIDAR.

1.4 Results

1.4.1 General results and kriging maps Data Analysis

Several technical and meteorological problems during the two years of campaigns caused cancellation of part of the planned surveys. Strong storms prevented sufficient acoustic data for the 1998 Bay of Biscay extensive coverage, and the delay produced by the aircraft replacement in 1999 prevented aerial coverage over the Portuguese area. As a consequence, no general comparative maps could be produced for these two surveys.

In Portugal in 1998, most of the fish schools were near shore (Figure 1-3). The main species were juvenile and adult sardine, as well as juvenile mackerel, chub mackerel (*Scomber japonicus*), and horse mackerel. No clear spatial separation of juvenile and adult sardine was observed. The area of higher proportion of juveniles was found close to the shore from near Aveiro to Figueira da Foz, and this area was selected for the intensive survey. Both sensors agreed with the general distribution in the coastal area (see some sample echograms in Figure 1-4), despite the detection of some plankton layers by LIDAR that were not visible in the acoustic echograms using the -60 dB threshold. Offshore, LIDAR provided consistently higher estimates, but did not observe some large schools detected by acoustics.

In Galicia in 1998, most of the fish were near the coast, especially within or at the mouth of the Rias, as was pointed out by both sensors (Figure 1-3 and Figure 1-5). Juvenile sardine was the most abundant fish species, but in low abundance from an historical perspective. In 1999, sardine abundance was even lower and more restricted to coastal waters (Figure 1-6). Outside the bays, the main species (although scarce) was mackerel. No fish were found in surface waters near the 200 isobath. During this year, LIDAR tended to attribute more energy in the outer part of the surveyed area than acoustics. Examples of these LIDAR detections not seen by acoustics are shown in Figure 1-2. In addition, some differences arose in the inner part of the covered area, which corresponded to a few dense schools detected only by the LIDAR.

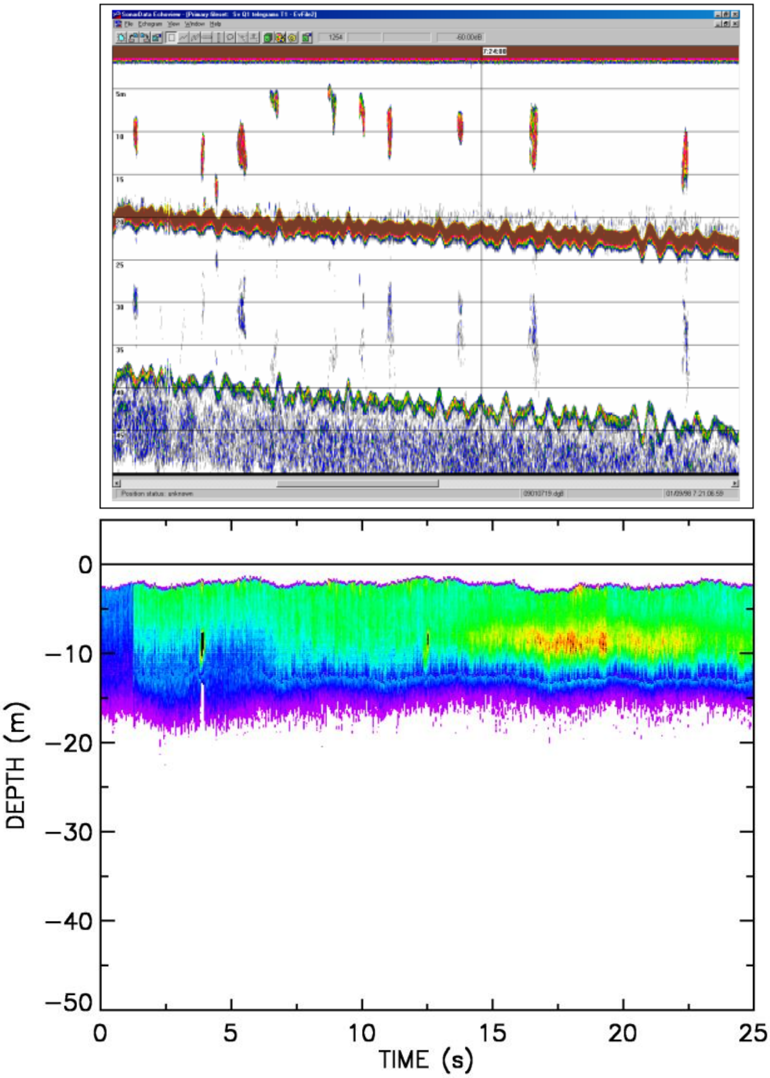

Figure 1-4. A fragment of HAGC 17. Top panel: Echogram of a Portuguese shallow area (1 nm) with many dense fish schools in the middle of the water column of both juvenile and adult sardine at about 40º34'N and -8º50'W covered in the morning of 01/09/98. Bottom panel: LIDARgram of about 1nm over a close area in the morning of the next day, showing neat schools and thick layers of fishes and/or plankton.

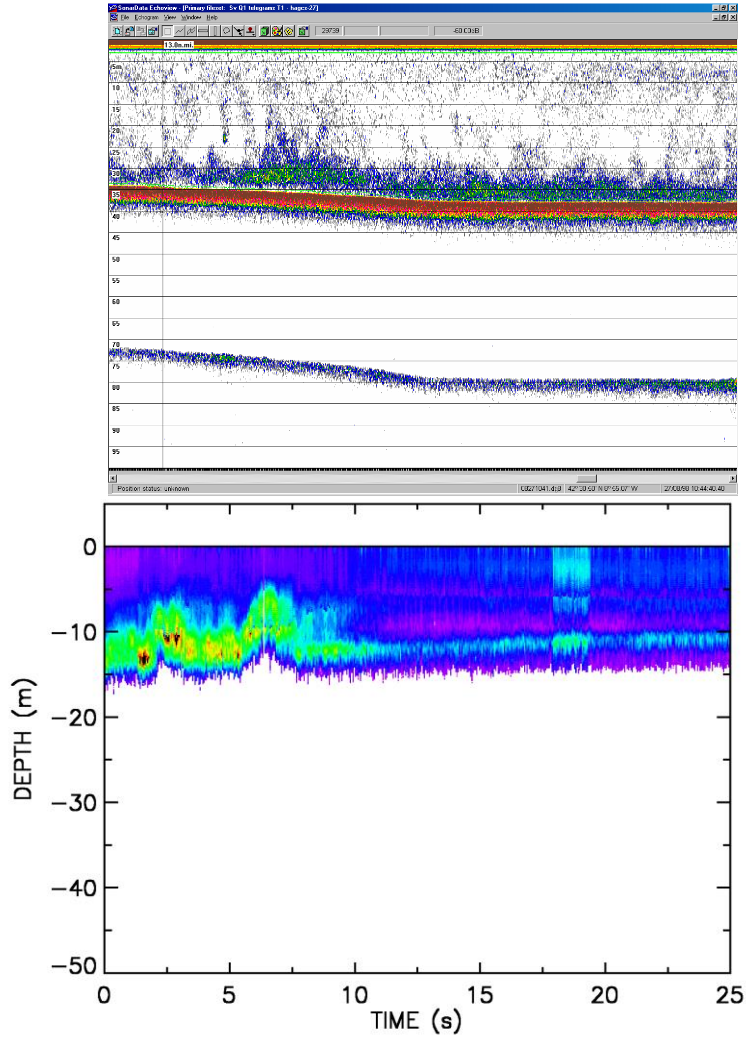

Figure 1-5. A fragment of HAGC 27. Top panel: Echogram of a transect line over the central part of Galician Ría de Arousa (1/2 nm) with thick plankton layer close to the sea floor. Bottom panel: LIDARgram of about 1 nm over the inner part of the Ría de Arousa covered in the morning of the same day, showing fish and/or plankton aggregations over the bottom.

In the Bay of Biscay in 1999, almost all of the fish caught were anchovy juveniles found off the continental shelf. The comparison of the maps produced by each sensor did not show clear patterns like those observed in the western Iberian Atlantic, except for some differences near the beginning or end of the tracks

(Figure 1-6). LIDAR estimates were higher in the surrounding areas, whereas acoustics gave higher estimation in the central part of the surveyed area. In any case the differences were generally small. In the Garonne area, for the single track analysed, juveniles occupied the midwestern part of the shelf in weak densities, whereas in the coastal zone, more relevant concentrations of adults of different species were found. The major differences observed between both devices in this track are related to two gaps encountered along the acoustic track that were not seen in the LIDAR data. Sample echograms can be seen in Figure 1-7.

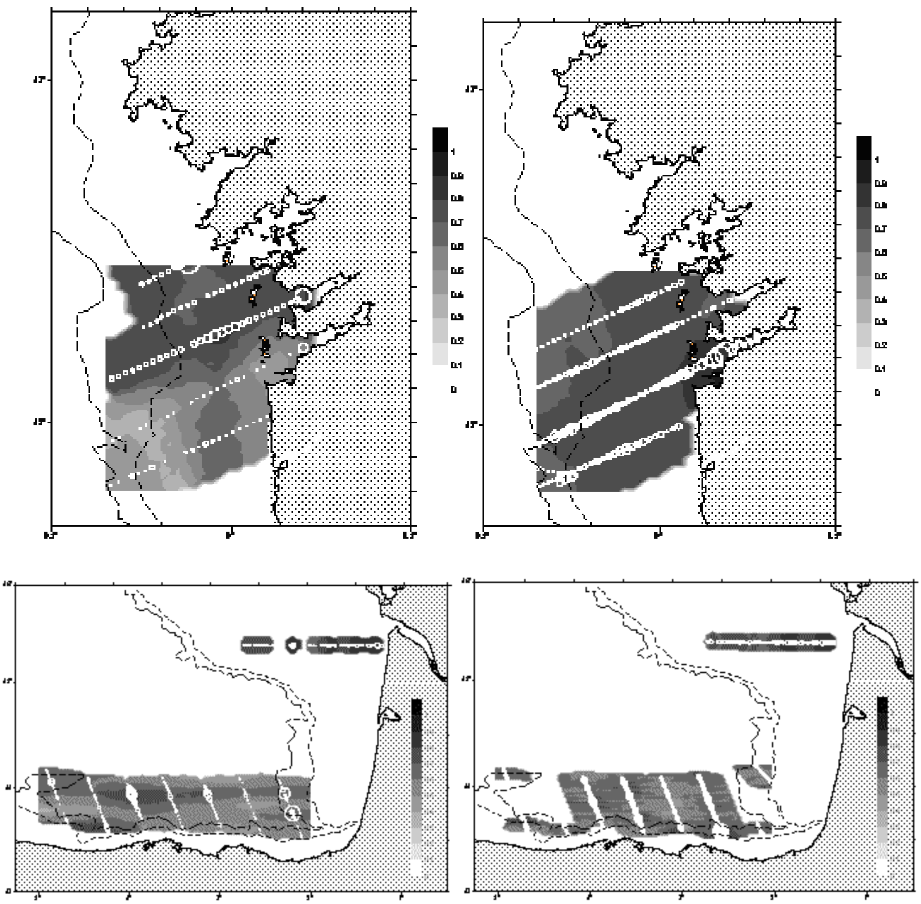

Figure 1-6. Contour maps made by kriging on log transformed variables together with the raw backscattering energies represented as circles scaled using the Square Root method for 1999 data. Top panels: Galicia. Bottom panels: Bay of Biscay. Left: acoustics. Right: LIDAR.

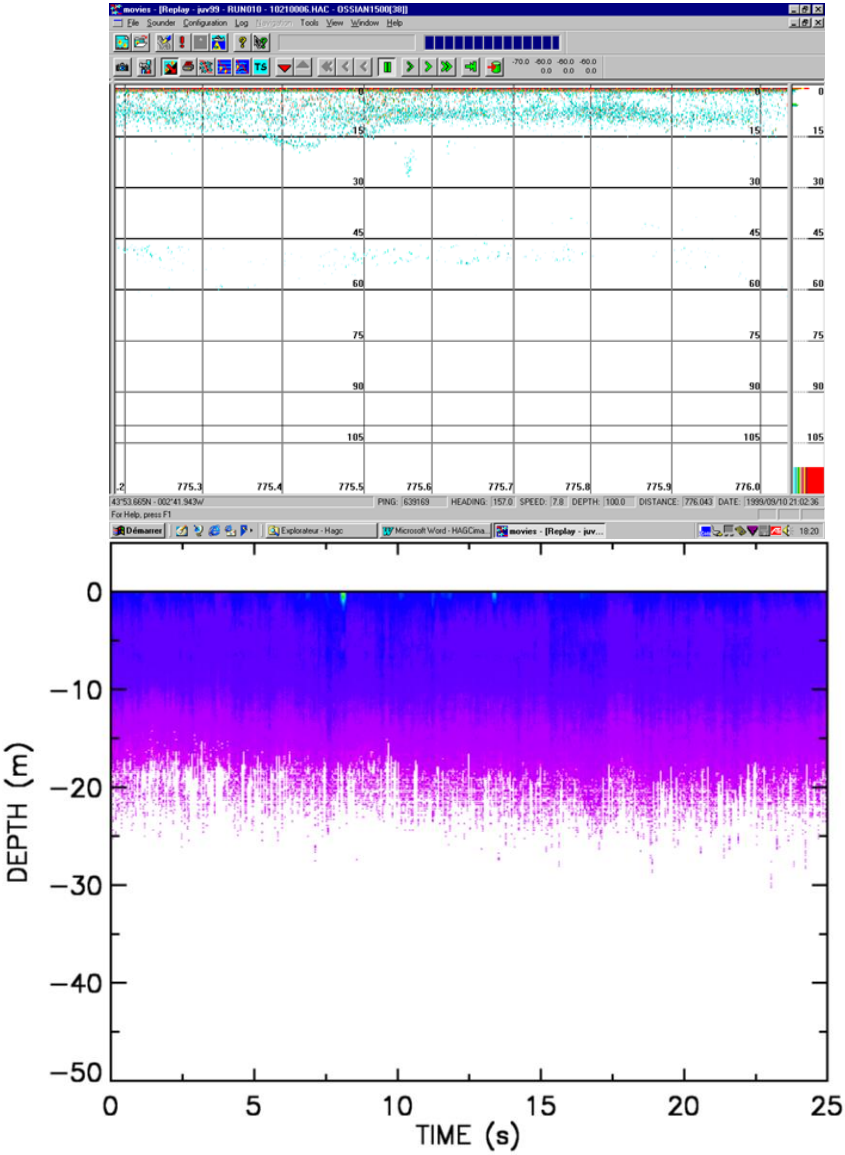

Figure 1-7. A fragment of HAGC 10. Top panel: Nighttime echogram of almost 1 nm over offshore waters of the southern part of the Bay of Biscay, showing scattered anchovy juveniles close to the surface. Bottom panel: LIDARgram of about 1nm, showing a homogeneous layer 0-12 m depth.

Table 1-2. Main statistics of the stationary comparison for each device and area.

			Acoustic		Lidar	
Year	**Area**	**Statistics**	**Raw**	**Transformed**	**Raw**	**Transformed**
1998	*Portugal*	*No*	305		561	
		Sum	238910.55	132.22	8.5651	405.26
		Max	24047.00	1.00	0.2309	1.00
		Min	1.01	0.19	0.0000	0.16
		Mean	783.31	0.43	0.0153	0.72
		s.d.	2734.42	0.22	0.0268	0.14
		Median	12.00	0.39	0.0056	0.75
		Geomean	21.51	0.38	0.0040	0.71
1998	*Galicia*	*No*	169		489	
		Sum	81102.20	114.83	7.5681	353.27
		Max	6326.51	1.00	0.3500	1.00
		Min	0.40	0.13	0.0000	0.15
		Mean	479.89	0.68	0.0155	0.72
		s.d.	770.96	0.15	0.0281	0.12
		Median	215.00	0.69	0.0080	0.75
		Geomean	182.95	0.66	0.0053	0.71
1999	*Galicia*	*No*	159		358	
		Sum	36900.77	105.55	14.1459	252.74
		Max	4636.02	1.00	0.9897	1.00
		Min	0.09	0.17	0.0000	0.22
		Mean	232.08	0.66	0.0395	0.71
		s.d.	575.03	0.17	0.0840	0.10
		Median	118.08	0.72	0.0186	0.71
		Geomean	57.72	0.63	0.0171	0.70
1999	*Bay of Biscay*	*No*	206		548	
	Inner Part	*Sum*	5017284.00	122.47	4.3345	363.08
		Max	871882.00	1.00	0.0943	1.00
		Min	30.00	0.25	0.0002	0.32
		Mean	24355.75	0.59	0.0079	0.66
		s.d.	80790.11	0.14	0.0111	0.12
		Median	2946.50	0.58	0.0039	0.65
		Geomean	3401.99	0.34	0.0043	0.65
1999	*Bay of Biscay*	*No*	46		56	
	Garonne	*Sum*	304210.00	36.28	0.2550	42.76
		Max	41002.00	1.00	0.0124	1.00
		Min	486.00	0.58	0.0010	0.48
		Mean	6613.26	0.79	0.0046	0.76
		s.d.	8156.88	0.08	0.0025	0.11
		Median	4386.50	0.79	0.0036	0.75
		Geomean	4341.73	0.78	0.0040	0.76

1.4.2 Stationary comparison

Summary statistics for each data set (area-year) are shown in Table 1-2. Raw data were in general skewed, with some high values that had a large contribution in both arithmetic mean (called mean in Table 1-2) and standard deviation. The log-transformation, together with a weighting equal to the maximum of each data set, resulted in an improvement on the quality of the data and permitted a direct device comparison. Whereas some parts of the western areas presented almost no targets (i.e. neither fish nor thick plankton layers) in the uppermost layers, no empty EDSU were seen in the Bay of Biscay. Besides, the relation between the maxima and the minima of the transformed data for each device in a particular area and year are similar and suggest a similar general performance of both devices.

Table 1-3. Fitted experimental variograms for each data set.

Year	Device	Area	Nugget	Model	Sill	Range	%nugget/model	Var est
1998	Echosounder	Portugal	0.01	Spherical	0.039	6	7%	0.00046
		Galicia	0.005	Spherical	0.015	7	10%	0.0004
	LIDAR	Portugal	0.012	Spherical	0.007	3.5	40%	0.000074
		Galicia	0.012	Spherical	0.006	3	33%	0.0000076
1999	Echosounder	Galicia	0.01	Spherical	0.0175	7	34%	0.000054
		Inner part	0.005	Spherical	0.016	6.5	1%	0.003
		Garonne	0.002	Spherical	0.002	6.5	72%	0.00012
	LIDAR	Galicia	0.004	Spherical	0.002	7	10%	0.000054
		Inner part	0.007	Spherical	0.005	11	1%	0.00118
		Garonne	0.008	Spherical	0.002	6.5	85%	0.00017

There was spatial autocorrelation for each device, area, and year, as shown in Table 1-3. However, acoustic data showed a consistent spatial structure and the ranges were similar, around 7 nautical miles. Conversely, LIDAR data were patchier (i.e. higher nugget effect). In the 1998 surveys, covariogram ranges for LIDAR were lower than those of the acoustics (restricted to 3 nautical miles). In 1999, LIDAR ranges increased and approached or surpassed those shown in acoustics, being between 6.5 and 11 nautical miles. Empirical variograms were fitted according to the models shown in Table 1-3. These models were used to construct kriging surfaces over the same grid (Figure 1-3 and Figure 1-6).

Table 1-4. General description of the HAGC characteristics including echo-trace type, time of day, date of the acoustic survey, date of the corresponding LIDAR survey, length of HAGC (nautical miles), and the fraction of the echo-sounder returns within the estimated depth coverage of the LIDAR.

HAGC	Type	Period	Date Acoustic	Date LIDAR	Length	Area	LIDAR Fraction
1	Pel. Lay.	Day	9/6/99	9/7/99	17	B. Biscay	0.53
2	Scat.	Eve.	9/8/99	9/7, 9/9	25	B. Biscay	1.0
3	Small	Day	9/16/99	9/16/99	6	B. Biscay	0.99
4	Scat.	Day	9/16/99	9/16/99	10	B. Biscay	0.59
5	Small	Day	9/16/99	9/16/99	13	B. Biscay	0.49
6	Pel. Lay.	Day	9/8/99	9/7/99	9	B. Biscay	0.67
7	Pel. Lay.	Eve.	9/9/99	9/9/99	21	B. Biscay	1.0
8	Large	Day	9/5/99	9/7/99	14	B. Biscay	1.0
9	Small	Day	9/9/99	9/8/99	8	B. Biscay	1.0
10	Scat.	Eve.	9/10/99	9/9/99	8	B. Biscay	0.98
11	Nothing	Day	8/31/99	8/31/99	39	Galicia	0.22
12	Nothing	Day	8/31/99	8/31/99	26	Galicia	0.03
13	Nothing	Day	9/2/99	9/2/99	22	Galicia	0.06
14	Small	Eve.	9/1/98	8/31/98	10	Galicia	0.41
16	Large	Day	9/2/98	9/2/98	3	Portugal	1.0
17	Large	Day	9/1/98	9/2/98	3	Portugal	1.0
18	Small	Day	9/1/98	9/2/98	3	Portugal	1.0
19	Small	Day	9/3/98	9/2/98	3	Portugal	1.0
20	Scat.	Night	9/9/98	9/9/98	28	B. Biscay	0.73
21	Pel. & Scat	Night	9/9/98	9/9/98	32	B. Biscay	0.79
22	Scat.	Day	9/15/98	9/15/98	73	B. Biscay	0.70
23	Large	Day	8/21/98	8/21/98	10	Galicia	0.53
24	Small	Day	8/21/98	8/21/98	8	Galicia	0.24
25	Small	Day	8/27/98	8/27/98	5	Galicia	0.74
27	Pel. Lay.	Day	8/27/98	8/27/98	6	Galicia	0.61

Wilcoxon signed-rank tests performed on the kriged values showed significant differences. In Galician and Portuguese waters, LIDAR values were higher than those recorded by the echo sounders ($Z = 10.7$, p-value $= 0$; $Z = 35.6$, p-value $= 0$; $Z = 15.9$, p-value $= 0$ for data from Galicia in 1998, Portugal in 1998 and Galicia in 1999, respectively). The same situation occurred in the inner part of the Bay of Biscay ($Z=12.5$, p-value$=0$). All this suggests that LIDAR was detecting more targets than acoustics. Conversely, in the Garonne area, echo-sounder records were higher than those of the LIDAR ($Z = 2.40$, p-value $= 0.0081$).

1.4.3 Non-stationary comparison

Echo traces from both devices were compared over 22 HAGCs across years and areas (see Table 1-4 for the main characteristics of each HAGC). The comparison of energy-transformed values for all HAGCs together produced moderate levels of positive correlation between sensors (Table 1-5, Figure 1-8), which were significant for the case of school processing.

Detailed analyses are shown by typologies. The LIDAR echo-integration method improves slightly the comparison of acoustic and LIDAR for HAGCs of scattered fishes, but generally worsens the comparison for other typologies. This is particularly noticeable for the few HAGCs with large-school detections, which can even result in negative correlations. Combining all typologies together except large schools gave significant (at $\alpha = 5\%$) or almost significant correlations (with $p < 0.1$) with both LIDAR signal-processing methods. Comparing years, the 1998 HAGCs seemed to show better agreement for the two sensors than did the 1999 HAGCs. Among geographical zones, Galician waters (and all the western areas together) obtained the best fit between sensors, while for the Bay of Biscay correlations were not significant.

We considered discarding likely outlier values from HAGC comparisons. Three likely outliers or abnormal values were identified that corresponded to HAGC numbers 2, 8, and 17. The first two were contradictory measurements of the transect P5 in the Bay of Biscay during the 1999 surveys in a short period of time. The third was from Portugal during the 1998 surveys and is the highest outlier in the scatter plot of Figure 1-8.

Table 1-5. Spearman and Pearson Correlation between acoustic and LIDAR energies among HAGCs according to several aggregation criteria of target typologies (log energy values scaled to the mean per year and area). Results are given for the two types of LIDAR energy processing.

Criteria	N	R_S	R_P	P	R^2	R_S	R_P	p	R^2
Total	22	0.47	0.55	0.01	0.30	0.24	0.35	0.11	0.12
By Type									
Small	7	0.96	0.90	0.01	0.81	0.46	0.42	0.35	0.17
Large	3	0.5	0.53	0.65	0.28	-0.50	-0.63	0.57	0.40
Pel. Lay.	4	1.0	0.93	0.07	0.86	0.0	0.02	0.98	0.0
Scat.	5	0.20	0.50	0.39	0.25	0.50	0.77	0.13	0.59
Small + Pel. Lay. + Scat.	16	0.54	0.57	0.02	0.32	0.41	0.44	0.09	0.20
By Time									
Day	17	0.37	0.44	0.08	0.19	0.15	0.31	0.23	0.09
Eve.	5	0.60	0.72	0.17	0.52	0.20	0.58	0.31	0.33
By Year									
1998	10	0.61	0.68	0.03	0.46	0.39	0.68	0.03	0.46
1999	12	0.19	0.45	0.14	0.21	0.14	0.25	0.44	0.06
By Area									
B of B	11	0.28	0.36	0.28	0.13	0.18	0.12	0.73	0.01
Gal.	8	0.74	0.77	0.02	0.60	0.48	0.65	0.08	0.42
Port.	3	0.50	0.93	0.23	0.87	-1.0	-0.78	1.43	0.60
Gal. + Port.	11	0.74	0.74	0.01	0.54	0.31	0.60	0.05	0.36
By Type in	1998								
Small	3	1.0	0.88	0.31	0.78	0.50	0.99	0.11	0.97
Large	3	0.5	0.53	0.65	0.28	-0.5	-0.63	0.57	0.40
Pel. Lay. + Scat.	4	1.0	0.90	0.10	0.81	0.80	0.76	0.24	0.58
By Type in	1999								
Small	4	1.0	0.98	0.02	0.95	0.60	0.51	0.49	0.26
Pel. Lay. + Scat.	5	0.20	0.15	0.81	0.02	-0.10	-0.11	0.86	0.01

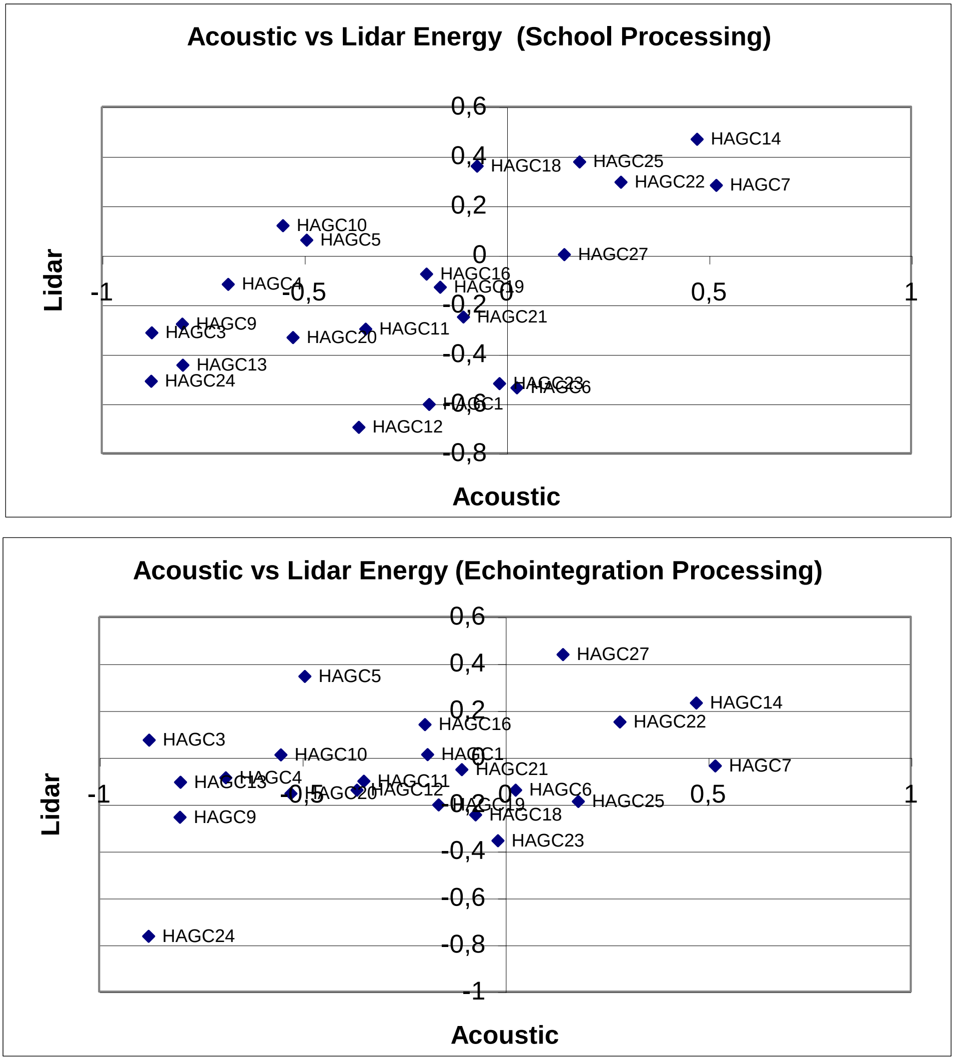

Figure 1-8. Scatter plots of acoustic energy and LIDAR energies (school and echo integration LIDAR energies) for the different HAGCs.

The results from HACG 2 and HACG 8 illustrate the effects that temporal variability can have on an intercomparison, since the HACGs were in the same area. Acoustic surveys were made on September 5 and 8, producing values of 3.23 and 0.66, respectively. LIDAR surveys were made on September 7 and 9, producing values of 0.44 and 2.86, respectively. The first day of survey with each instrument was used to produce the HACG 8 data (for large-school structures), and the second survey with each instrument was used to produce the HACG 2 data (for scattered fish). That is, 3.23 was compared with 0.44 and 0.66 with 2.86. But, both the acoustic and LIDAR survey results are changing very rapidly over these five days, with high values on September 5 and 9 and low values on September 7 and 8. This rapid change suggests that these data should not be used to compare acoustic and LIDAR data, and may put in doubt the suitability of making such comparisons with data taken on different days.

HACG 17 is the largest visual outlier of the school processing (Figure 1-8) and corresponds to a large-school detection in the acoustic data. It does not appear as an outlier in the total echo-integration processing. This HAGC is a three-mile line starting from shore which was covered in consecutive days by each sensor device. The first mile of the LIDAR data was contaminated by bottom return, and was not included in the data set. Thus, the LIDAR return from this segment does not correspond exactly with the same segment of acoustics in position or date, and, depending on the actual distribution of schools in the transect line, this may result in some difference. In addition, the large difference in the results of the two LIDAR processing methods suggests that there might be some part of the LIDAR data that is not properly processed in the echo-integration processing. We have considered removing this HAGC from the analysis to see how that changes the result.

Removing these three points from the data set improved the correlation to 0.65 (in linear scale) or to 0.55 (in log scale). Removal of any other additional points barely increased the correlations. The complete analysis omitting those three potential outliers is shown in Table 1-5 and in the plots on the right side of Figure 1-8. The primary difference introduced by the omission of those outliers appears in the correlation of the large-school acoustic detections, which (though based now on only 3 points) becomes positive in the school processing for LIDAR (not negative as before). In general, all the analysis of the school processing for LIDAR is improved: the 1998 set of HAGCs become statistically significant, and the diurnal correlation among HAGC values is also improved.

The last column in Table 1-4 summarizes the fraction of fish stocks in the upper 30 m of the water column for each region. In Portugal, the situation was ideal for the LIDAR; the HAGCs corresponded to the shallow waters of the radials of the intensive campaign, and almost all of the schools were in the upper 30 m. Conditions in the Bay of Biscay were quite good also, with high percentages of schools inside the nominal LIDAR range, although the actual LIDAR penetration depth turned out to be less than 30 m in most areas. The worst cases were in Galicia, especially in 1999. These HAGCs were mostly in inshore waters with fish very close to the bottom, which made separation of the fish signal and the bottom signal difficult (Figure 1-8).

1.5 Discussion

The stationary comparisons based on the smoothed contour maps of backscattering transformed energies have shown that there exists a general consistency between both sensors, thus evincing the ability of LIDAR to detect and map the distribution of the targeted fish species. However, LIDAR (a noisier sensor according to the range and sill values obtained in the variograms presented in Table 1-3) produced more detections than acoustics (Figure 1-3 and Figure 1-6). This may be due in many cases to differences in the relative target strengths (TS) of various species for each sensor.

In Galician waters in 1999, the offshore detections made by LIDAR that were not seen by acoustics (Figure 1-2) may consist of schools of *Polybius spp.*, a pelagic crab common in the area that would have a high optical reflectivity, but small acoustic target strength at 38 kHz. Other thick plankton layers, seen in some parts of the Bay of Biscay in 1999, also scatter light more effectively than sound. Similarly, fish without swim bladders do not scatter sound as effectively as fish with swim bladders, while differences in optical scattering between fish species do not depend on whether or not the fish has a swim bladder. This could explain the detections made in southern Galicia (off the Ría de Vigo) by LIDAR in 1999, where the echo sounder detected very little. In this area, concentrations of juvenile mackerel, which do not have a swim bladder, were detected by both acoustics and fishing stations, but producing very low echo-integration values, compared, for example, with sardine. LIDAR, on the other hand, would produce similar backscattering energies for these two fish species.

LIDAR has a smaller target-strength difference than acoustics between plankton and fish, and between fish with and without a swim bladder. This leads to noisier data that make it more difficult to set a signal-threshold level to discriminate plankton from fish than in acoustics, and further complicates attempts to obtain a conversion from energy to fish biomass. As a consequence, it is clear that complementary fishing surveys for species identification of LIDAR detections are necessary. In addition, it is necessary to study light reflectivity properties of the fish and plankton targets, including the effects of school patchiness in the global signal return if we are interested in making LIDAR biomass estimations. Nevertheless, in any case, it is advisable to choose surveying periods in which the fish schools are not mixed with plankton layers or other non-targeted scatterers.

1.5.1 Non-stationary comparisons

The varying performance of LIDAR under different conditions of fish aggregation structure, plankton–layer intensity, and water turbidity (due to suspended matter and phytoplankton) have made it difficult to establish a single satisfactory processing method for the different times of the day, areas, and species. Two types of LIDAR signal processing have been essayed during the current study; both gave interesting results under some conditions, but further refinement will be required. The reflection that LIDAR obtains from a school of fish must be processed to obtain quantities proportional to the number of fish within the depth resolution. This issue has been considered (Krekova et al., 1994, Churnside and Hunter, 1996, Churnside et al., 1997), although the conversion into biomass requires species identification and experimental knowledge of fish reflectivity and size.

Direct HAGC analyses were performed to further understand the energy and visual-shape properties of particular target types. If we check the correlations annually, the results show better relationships for the set of HAGCs analyzed in 1998, likely due to more different types of aggregations and better LIDAR performance in 1998. The latter was caused by the need to operate at lower power in 1999.

By typologies, the analysis was limited by the number of observations, which made it more difficult to obtain significant quantitative conclusions. However, the detections made by both sensors of small schools, scattered fish and pelagic layers were significantly correlated. It is not clear why echo-integration processing of LIDAR signals worked well for scattered fish, but was not as good as school processing for diffuse layers of fishes and plankton.

LIDAR school processing looks for schooling structures and should provide good performance for schooling typologies, especially large ones that are easier to detect. Contrary to this expectation, the correlation apparently failed for these large-school structures. This failure may be explained by the inherent variability in detecting few large hits. Sometimes, one single school can produce half or even more of the acoustic energy in the HAGC, so a single missed school can change the whole HAGC. These schools can easily move between the time they are detected by the echo sounder and the time of the LIDAR pass, even when both are done on the same day.

1.5.2 Comparability of the different surveys

There were several factors that may have affected the results of this analysis. First, the delay between the coverage of the two sensors was often greater than one day (even in the HACG analysis). Given the high mobility of fish schools, this may have prevented the sensors from detecting the same targets in some cases. One particularly noticeable example of the inter-daily variability is demonstrated by HAGCs 2 and 8 in the Bay of Biscay, as described earlier. Of course, it would have been better to use only segments that were covered on the same day by both instruments, but there were not enough of these to make a good comparison.

Other sources of variability in the comparison include differences in equipment, weather, environment, fish behavior, and in the fundamental scattering properties of sound and light. In the case of the equipment, all of the echo sounders operated at 38 kHz, but there were significant operational differences in ship characteristics, mounting configurations, beam geometries, and processing software. Notably, the different noise characteristic of the various ships may have produced different levels of vessel avoidance in the near surface water of interest here.

Also, coastal and bottom topography and oceanography features are very different throughout this region, which can affect LIDAR performance and operations. Along the Iberian Atlantic coasts, upwelling events are common in summer and contribute to the presence of fog which diminishes the LIDAR capability. The Galician region has a narrow continental shelf, with depths less than 50 m close to the coast, a rough bottom, and narrow fjord-like Rías that occupy a large portion of the coast. The waters inside the Rías as those very close to shore in Galicia and Portuguese waters are very productive and turbid, which often limited LIDAR water penetration to the upper 15 meters. Low-altitude aircraft operations within the Rías can be limited by safety considerations, especially at night. On the other hand, the Bay of Biscay has a narrow (South, Spain) or wide (North, France) continental shelf with a stable water column. Here, waters are neither as productive nor as turbid, so LIDAR penetration is optimal, reaching about 25 m (on average) during day time in the offshore waters where the juveniles occurred, and even reaching deeper during night time (about 35 m).

Finally, some of the differences between LIDAR and echo sounder results may be caused by differences in the relative target strengths of various species. This seems, for example, to be a likely explanation for the differences offshore of Galicia, as discussed previously. In general, exact comparison of the energy received by each sensor is difficult, because of the relative differences in acoustic target strength between fish and plankton, which are not the same as the differences in optical reflectivity. Hence, experimental research on the reflectivity properties of the fish and plankton targets should be performed as a basic step in the implementation of LIDAR as a routine surveying system of fish resources.

1.5.3 Applicability of LIDAR to survey juveniles of pelagic species

Juveniles of anchovy, sardine, and mackerel exhibit several common aggregation patterns and behavior that make them potentially suitable for the application of LIDAR. All of them are found in the upper layers of the water column, and, to a great extent, within the LIDAR range. Also, they concentrate in schools during daytime and disperse during the night in pelagic layers, hardly distinguishable from plankton, thus making daytime the appropriate diel period for surveys.

There are also some common drawbacks for the direct application of LIDAR for sardine and mackerel juveniles that need to be taken into account. Both species of juveniles share the coastal Iberian Atlantic waters, mixed in different proportions with respect to each other, as well as with respect to other species (either adults or juveniles). This requires that a LIDAR survey being combined with an acoustic and fishing survey to assure the identification of the different species in the area. Also, the area of this study presents several environmental features (described in the previous subsection) that tend to reduce LIDAR capabilities compared with more oceanic waters. Finally, LIDAR recorded significant detections of schools in the offshore part of the area, where acoustics did not. This is likely because of patches or layers of plankton.

Anchovy juveniles are widely distributed throughout the upper layers of the Bay of Biscay. For this species, the medium-sized and largest schools of anchovy were detected by LIDAR, but small schools were hard to discriminate from the normal empty signal return or from plankton layers. Therefore, although LIDAR surveys during daytime should, in principle, be able to detect of these juveniles (particularly given the wide extension covered), the relatively low correlation of the

HAGCs analysis in the Bay of Biscay indicates a need for further study to reliably discriminate between juvenile fish schools and aggregations of plankton.

Thus, for these potentially suitable species, LIDAR surveys could complement a minimal acoustic cruise that would provide identification and a biological sampling survey that would provide average acoustic strength and biomass of schools. From this point of view, it seems that LIDAR surveys could improve the accuracy of a reduced acoustic survey by expanding the number and length of surveyed tracks and by assuring spatial coverage of all the potential distribution of these juveniles. Such a survey design would speed up the time of the survey and reduce the total cost.

Juvenile horse mackerel, at least in the Galician waters, occurred close to rough terrain with no noticeable day/night changes. These areas were difficult to survey with aircraft, little data were acquired, and no general conclusions could be made about the suitability for LIDAR surveying for this species.

1.6 Conclusions

The positive correlation between LIDAR and echo sounders, along with the visual correspondence observed in the kriged maps, prove that LIDAR is able to detect and map the aggregations of the pelagic species targeted in the present work. Of the four species of juveniles studied, anchovy, sardine, and mackerel were shown to be suitable for LIDAR application, although, for sardine and mackerel, several practical difficulties of aerial surveying have been found in some of the areas studied. For horse mackerel, little can be said about LIDAR applicability from this study.

Several difficulties related to LIDAR performance need to be considered. Firstly, and most importantly, it provides poor discrimination between fish and plankton. Secondly, little information is available on optical target-strength values for the different fish and plankton species present in the area. Finally, none of the data processing evaluated in this work have proved yet to be ready for the detection of all possible aggregations of fish juveniles. Consequently, the following improvements are recommended so that airborne LIDAR can provide abundance estimates:

1. Measure LIDAR target strengths for the fish and plankton of the region.
2. Design mixed aircraft/ship surveys that take advantage of the strengths of each platform.
3. Improve LIDAR signal processing to better distinguish between different targets.

1.7 Acknowledgements

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1.8 Publication data

Type	Peer-reviewed article
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Journal	ICES Journal of Marine Science
Year	2005
Volume	53
Pages	1735-1750


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Foto: Cerquero Mater Bi en JUVENA 2005 (Fuente: propia).

Chapter 2

Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance as an indicator of the next year's recruitment and spatial distribution patterns

Campañas acústicas de anchoa juvenil en el Golfo de Vizcaya: Abundancia como indicador del reclutamiento entrante y patrones de distribución espacial

A partir del año 2003 se puso en marcha la campaña JUVENA para estimar abundancia y distribución espacial de anchoa juvenil en el Golfo de Vizcaya. Esta campaña descartaba la metodología LIDAR para centrarse en la metodología acústico-pesquera, empleando ecosondas científicas calibradas para caracterizar la distribución espacial de biomasa y pescas para la identificación de especies. Este capítulo presenta la metodología desarrollada en la campaña JUVENA, así como los resultados obtenidos de (i) distribución espacial de anchoa juvenil en la época de estudio; (ii) serie temporal de estimas de biomasa de anchoa juvenil y (iii) chequeo de la eficiencia del índice abundancia juvenil como anticipador del reclutamiento.

2.1 Abstract

A series of acoustic surveys (JUVENA) began in 2003 targeting juvenile anchovy (*Engraulis encrasicolus*) in the Bay of Biscay. A specific methodology was designed for mapping and estimating juvenile abundance annually, four months after the spawning season. After eight years of the survey, a consistent picture of the spatial pattern of the juvenile anchovy has emerged. Juveniles show a vertical and horizontal distribution pattern that depends on size. The younger individuals are found isolated from other species in waters closer to the surface mainly off the shelf within the mid-southern region of the bay. The largest juveniles are usually found deeper and closer to the shore in the company of adult anchovy and other pelagic species. In these eight years, the survey has covered a wide range of juvenile abundances, and the estimates show a significant positive relationship between the juvenile biomasses and the 1-year-old recruits of the following year. This demonstrates that the JUVENA index provides an early indication of the strength of next year's recruitment to the fishery and can therefore be used to improve the management advice for the fishery of this short-lived species.

2.1 Introduction

The management of short-lived fish species such as small pelagics is conditioned by the annual recruitment to the population. For example, in the Bay of Biscay, age 1 anchovy (*Engraulis encrasicolus*) usually contribute about 75% of the total stock biomass (Uriarte et al. 1996; ICES, 2010). In addition, recruitment in marine fish in general (Leggett and Deblois, 1994) and pelagic species in particular (Kawasaki, 1992) varies greatly and is influenced by environmental conditions (Borja et al., 2008; Fernandes et al., 2010), which limits the potential use of stock-recruitment relationships. It is therefore difficult to manage short-lived species based on annual advice due to the unknown increase in abundance that will represent the strength of next year's recruitment.

This problem has long been recognized (Hjort, 1914; Allain et al. 2001), and different approaches other than classical stock-recruitment relationships have been considered in order to improve information on the incoming recruitment. Some possible approaches are: (i) statistical relationships between environmental variables and recruitment; (ii) mechanistic models of early-stage survival; and (iii) direct surveys of early stages (Painting et al. 1998). There is a vast amount of literature on environment-recruitment relationships. Several attempts have been made to predict recruitment based on environmental variables for the Bay of Biscay anchovy population (Allain et al., 2001; Borja et al., 2008); however, none of them obtained sufficient precision to improve management advice effectively (de Oliveira et al., 2005; ICES 2009). More robust data mining approaches have recently been developed (Fernandes et al., 2010), but they still need to be fully validated. Mechanistic models based on transport and survival (Allain et al., 2007) are potentially useful, but there is still little information on the factors that determine mortality and this limits how the model outputs can be applied.

The third possibility is to assess the abundance of an earlier stage as a proxy of the recruitment strength (Dragesund and Olsen, 1965; Larkin, 1976; Walters, 1989). As there is no significant correlation between egg and/or larval abundances and recruitment on small pelagic species (Peterman et al., 1988) due to the high variability in mortality rates during early life stages, they cannot be used as a recruitment proxy. However, it is generally accepted that the recruitment strength is mainly determined by the mortality at the pre-juvenile stages (Leggett and Deblois, 1994), and can therefore be measured at later stages (Bradford, 1992). Attempts to determine the incoming recruitment strength based on later stages, such as post-larvae or juveniles, have proven successful (Axenrot and Hansson, 2003; Dragesund and Olsen, 1965; Hourston, 1958; Koeller et al., 1986; Schweigert et al., 2009) and have been incorporated into some fisheries management policies, such as those for South African anchovy (Barange et al. 2009, De Oliveira and Butterworth 2004).

In the Bay of Biscay, a succession of low recruitments since 2001 and the consequent closure of the fishery from 2005 to 2009 highlighted the need for an early indication of recruitment strength in order to improve management (Barange et al. 2009). With this purpose in mind, an acoustic survey (JUVENA) for estimating the abundance of juvenile anchovy in early autumn was set up following methodologies derived from the European project JUVESU (Uriarte 2002; Carrera et al., 2006). The idea was to test the hypothesis that juvenile abundance estimates can provide a reliable indicator of the abundance of recruits that will enter the adult stock the following year. This requires that the most variable mortality rates occur at earlier life stages being the recruitment strength determined at the juvenile stage at the end of the summer.

There are some methodological challenges involved in sampling juvenile anchovy in the Bay of Biscay in early autumn. Anchovy have a vertical distribution that is very close to the surface (Uriarte et al., 2001), and a considerable part of the population is found at 7.5-15 m depth, which is above the initial depth of the typical acoustic sampling range. In relation to the horizontal distribution, they can occupy a huge potential area that can extend from shallow coastal to off-shelf waters, and from the northern Spanish coast (43.5º N) to the western French coast up to 47ºN (Uriarte et al, 2001, Martin, 1989), which implies a great deal of sampling effort. The bulk of the juvenile population is found in the outer waters or off the shelf (in the typical fishing grounds for the tuna live bait fishery in autumn, Martín, 1989, Lezama-Ochoa et al., 2010), isolated from adults and other pelagic species. They are thus easily identifiable, but are occasionally found in the company of gelatinous plankton (Uriarte et al., 2001). This distribution of juveniles has been suggested to correspond to the passive drift of eggs and larvae and early juveniles towards the southwest offshore waters as a result of the predominant north-eastern summer winds. At the end of summer the juveniles reach a size that makes them capable of migrating back towards nursery areas near the coast (Uriarte et al. 2001, Irigioien et al. 2008). However, some authors have questioned the capacity of this off-shelf part of the juvenile population to survive the winter and hence to contribute to the recruitment of 1-year-old fish during the following year (Petitgas et al., 2004). In general, it can be said that before the JUVENA survey series was launched the juvenile stage of Bay of Biscay anchovy was little studied and their ecology and spatial dynamics were poorly understood.

The objective of this paper is to present the methodology developed in the JUVENA survey series to assess the juvenile anchovy in the Bay of Biscay; show the abundances and spatial distribution patterns of this life stage obtained after eight years of surveys (from 2003 to 2010); and finally, determine the relationship between the juvenile and recruitment indices to evaluate the potential of JUVENA as a predictive tool for anchovy recruitment.

2.3 Material and methods

2.3.1 Sampling strategy

The JUVENA surveys were carried out annually from 2003 to 2010 between September and October in the Bay of Biscay (Table 2-1). In these months the juveniles have grown enough to be visible to the echosounders (allowing the tuna fishing fleet to target them as live bait) and normally occupy large outer and off shelf areas in front of the northern Spanish and west French coasts (Uriarte *et al.*, 2001; Cort *et al.*, 1976; Martin, 1976). Acoustic sampling was performed during the day because at this time of year juveniles usually aggregate in schools in the upper layers of the water column during the day, and can be distinguished from plankton structures (Uriarte *et al.*, 2001, Cort *et al.*, 1976). The sampling was carried out following a regular grid formed by transects arranged perpendicular to the coast (Figure 2-1), spaced at 17.5 nmi (from 2003 to 2005) or 15 nmi (2006 onwards) to ensure their independence (Carrera *et al.*, 2006). Sampling started in the northern Spanish coast, going from west to east, and then moved to the north to cover the waters in front of the French coast of the Bay of Biscay. It is important to conduct the survey in the precise temporal window that extends from mid-August to mid-October, which is not too early, so juveniles can be detected and caught, and not too late, so they have not yet abandoned the offshore grounds.

The survey covered the entire expected spatial distribution of juvenile anchovy in these months of the year, from offshore areas well beyond the continental shelf to very coastal waters, because the spatial process of anchovy juvenile recruitment occurs from offshore areas towards the coast during autumn (Uriarte *et al.*, 2001). This exploration area can vary from year to year and is potentially large. Consequently, considerable effort was made to achieve the broadest possible coverage of the area by using an adaptive sampling strategy. In this strategy, the boundaries of the sampling area were defined according to the findings of each survey and the parallel information obtained from the commercial fishing fleet, which uses juvenile anchovy as live bait for tuna fishing.

Table 2-1. Summary of sampling effort

Year	Start of the survey	End of the survey	Number of vessels	Effective survey time (days)	Fishing operations	Anchovy-positive fishing operations	Inter-transect distance (nmi)	Sampled area (nmi^2)	Positive area (nmi^2)
2003	18/09	14/10	1	20	47	36	17.5	16,829	3,476
2004	19/09	19/10	1	18	21	9	17.5	12,736	1,907
2005	12/09	07/10	2	20	47	45	17.5	25,176	7,790
2006	13/09	14/10	2	42	80	52	15	27,125	7,063
2007	04/09	30/09	2	37	70	40	15	23,116	5,677
2008	26/08	25/09	2	33	85	46	15	23,325	6,895
2009	26/08	25/09	2	39	67	42	15	34,585	12,984
2010	1/09	30/09	2	40	79	60	15	40,500	21,110

Along the Spanish and French coastlines, the minimum limits of the sampling area were set at 5º W and 46º N respectively. According to previous information on juvenile distribution, this area was expected to contain the vast majority of the juvenile anchovy abundance (Uriarte *et al.* 2001; Carrera *et al* 2006, Cort *et al.* 1976). For practical reasons, a maximum surveying area was set within the limits 6º W and 48º N. Between these limits, the actual along-coastline boundaries were set each year at the points where there was a clear decrease in abundance or, if possible, a transect in which juvenile anchovy was not detected. The length of the transects extended from about the 20 m to at least the 1000 m isobaths, and, according to the adaptive scheme of the survey, if the detections continued they were enlarged offshore to 4 nmi beyond the last detection of an anchovy school. In addition, the information from the commercial live bait tuna fishery collected before and during each survey was taken into account when decisions about the sampling strategy were made during the surveys. As a result of this sampling scheme, the years with a larger abundance of anchovy required a larger sampling coverage.

In the period from 2003 to 2004, the area was sampled with a single commercial purse seiner subcontracted for the survey and equipped with scientific echo sounders. In 2005 a second purse seiner was added to the survey to provide extra fishing operations, and in 2006 a pelagic trawler with complete acoustic equipment, the R/V Emma Bardán, replaced the second purse seiner (see Table 2-2 for vessel characteristics and equipment employed in each survey).

2.3.2 Data acquisition

The acoustic equipment included Simrad EK60 split beam echo sounders (Kongsberg Simrad AS, Kongsberg, Norway) of 38 and 120 kHz from 2003 to 2006, plus a 200 kHz transducer from 2007 (Table 2-2). The transducers were installed looking vertically downwards, at about 2.5 m depth, at the end of a tube attached to the side of the vessel in the case of the commercial fishing vessels and on the vessel hull in the case of the research vessel. The transducers were calibrated using standard procedures (Foote, 1987).

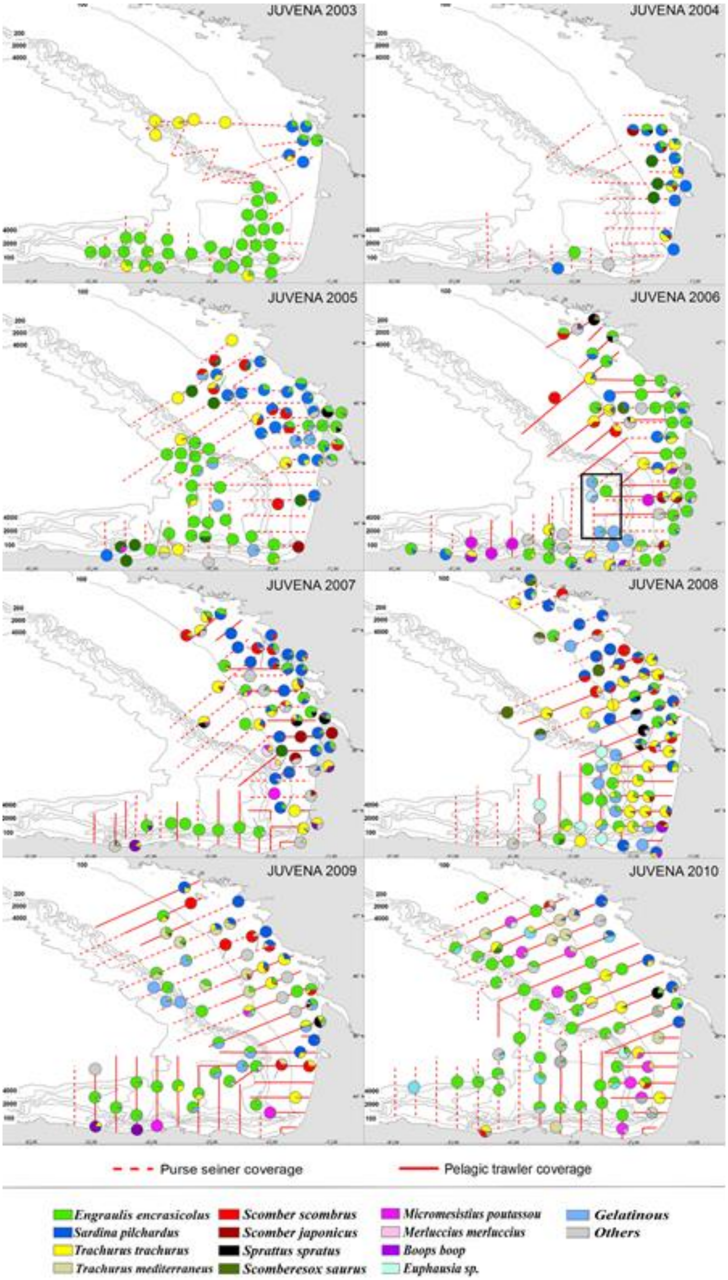


Figure 2-1. Sampling design of JUVENA surveys and species composition of the hauls.

The water column was sampled acoustically to a depth of 200 m. Catches from the fishing hauls and echo trace characteristics were used to identify fish species and determine the population size structure. The fishing stations were decided based on the typology on the detected echoes, trying to identify each change in the detected typologies. Purse seining was used to collect samples up to 2005 and then this was combined with pelagic trawls from 2006 onwards. To improve species identification in the first three surveys when only purse seiners were available, additional night fishing operations were performed by focusing bright light on the water to attract the fish from surrounding waters. In 2006 pelagic trawling was included in the surveys, which made it possible to fish at greater depths than the purse seine range (50 m maximum). The purse seiners generally covered the coastal areas and the waters off the shelf where juveniles occupy the surface waters and are accessible to the purse seine fishing range. The pelagic trawler covered the intermediate shelf regions where it may be necessary to sample at all depth layers. In addition, when deep, anchovy-like aggregations were detected by the purse seiners, the pelagic trawler temporally left its coverage area to carry out additional fishing operations in these areas.

For the years when pelagic trawling was carried out in the surveys (2006 onwards) we have assessed the fraction of juvenile biomass observed deeper than 45 m below the surface. This assessment was restricted to the areas over the shelf because pure aggregations of juveniles off the shelf were all above 45 m depth. This was done in order to determine by how much the limited vertical fishing range of purse seines could have affected the detection and estimates of juvenile biomass in the years 2003-2005, when only this fishing gear was available, and to eventually correct the potential underestimation of the juvenile biomass detected over the shelf in those years.

Table 2-2. Vessels and equipment (*Vessel names: Divino Jesus de Praga (2003), Nuevo Erreñezubi (2004), Mater Bi (2005), Gure Aita Joxe (2005, 2008), Itsas Lagunak (2006, 2007, 2009). **The 200 kHz transducer has been available on board purse seiners since 2007. ***TS of the mean pelagic species. The TS is obtained according to the relationship TS = b20 - 20log(L), where L is the standard length of the fish in cm.

			Vessel 1	**Vessel 2**
Vessel	name		Purse seiners*	Emma Bardán
	Length (m)		30-35	27
	Side (m)		8	7
	Draft (m)		3.5-4	3.5
	Acoustic installation		side perch	hull
Acoustic Equipment	Transducer frequencies (kHz)		38,120, (200)**	38,120,200
	Power (for 38, 120, 200 kHz) (W)		1200, 250, (210)**	1200, 250, 210
	Pulse duration (10^{-6}s)		1024	1024 (except in 2006: 256)
	Ping interval (s)		0.25 - 0.5	
Target Strength (b_{20})* **	*Engraulis encrasicolus* *Sardina pilchardurs* *Sprattus sprattus*	-72.6 dB	Degnbol et al. (1985)	
	Trachurus trachurus *Trachurus mediterraneus* *Scomber japonicas*	-68.7 dB	ICES (2006)	
	Scomber scombrus	-88 dB	Clay and Castonway (1996)	
	Jellyfish (mean TS)	-81.7 dB	Average TS for jellyfish species in Simmonds and Maclennan (2005)	
Fishing gear	Pelagic trawl	nº of doors		2
		vert opening		15
		Mesh size (mm)		4
	Purse seine	Depth	75	
		Perimeter	400	
		Mesh size (mm)	4	

2.3.3 Intercalibration of acoustic data between vessels

Since the 2006 survey, when the acoustic sampling was split between two vessels, intercalibration exercises between the two vessels were routinely carried out each year based on the intercalibration methodology described by Simmonds and MacLennan (2005). The intercalibration process consisted in comparing the echointegration of the bottom echo in areas with a smoothly variable bottom (visible as overlapping transects in Figure 2-1). A minimum distance of 30 nmi was covered simultaneously by the two vessels for these exercises (Figure 2-1). The NASC values (Maclennan *et al.*, 2002) obtained by the layer echointegration of both the water column and bottom echoes obtained by the two vessels were compared to detect recording biases or other potential problems.

2.3.4 Abundance estimates

Echograms were examined visually with the aid of the catch species composition to identify positive anchovy layers. Noise from bubbles, double echoes, and, when necessary, plankton were removed from the echograms. Acoustic data were processed in the positive strata by layer echo integration using an ESDU (Echo integration Sampling Distance Unit) of 0.1 nmi with the Movies+ software (Ifremer, France). Echoes were thresholded to -60 dB and integrated into six depth channels: 7.5-15 m, 15-25 m, 25-35 m, 35-45 m, 45-70 m and 70-120 m (no anchovies were found below 120 m depth).

Generally, only the 38 kHz data were echo integrated using the TS-length relationships agreed in ICES WGACEGG for the main species (ICES, 2006; Table 2-2). Each fishing haul was classified into species. A random sample of each species was measured to determine the length frequency distribution of the different species in 0.5 cm classes for the smaller species (anchovy and sardine) and 1 cm classes for the rest. Complete biological sampling of anchovy was performed to analyse age, size and the size-weight ratio. The hauls were grouped by strata of homogeneous species and size composition. The species and size composition of each homogeneous stratum were obtained by averaging the composition (in numbers) of the individual hauls contained in the stratum weighted to the acoustic density in the vicinity (2 nmi diameter). This species and size composition of each stratum was used to obtain the mixed species echointegrator conversion factor (Simmonds and Maclennan, 2005) for converting the NASC values of each ESDU into numbers of each species. However, although the methodology involved estimating multiple species, the survey strategy was focused strongly on juvenile anchovy and only the positive areas for anchovy were processed. Therefore, only estimates of this species were considered reliable and thus produced.

Anchovy juveniles (age=0) and adults (age ≥ 1) were separated and treated as different species. To separate juveniles from adults, the length frequency distribution of anchovy by haul was multiplied by a corresponding age-length key. The key was determined every year for three broad areas: the pure juvenile area, the mixed juvenile area (with a mix of juveniles and adults), and the Garonne river area (located at the coastal area around 45º40’ N; also a mixed area but here adult anchovy were usually smaller than in the other areas). Finally, the abundance in numbers of juveniles and adults was multiplied by the mean weight to obtain the biomass per age and length class for each ESDU.

2.3.5 Near field correction

Juvenile anchovy showed a near surface distribution during the JUVENA survey period (Uriarte *et al.* 2001). In order to achieve the best possible coverage of the vertical distribution of this species, in this work we started the echointegration at a range of 5 metres from the transducer face (i.e., 7.5 m depth from the sea surface) rather than the 10.5 m (13 m depth) recommended to avoid integrating the near field of the 38 kHz transducer (Simmonds and Maclennan, 2005). Instead of ignoring these first layers, we estimated the bias produced by the near field in the 7.5-15 m echointegration channel and corrected for it in the biomass estimates. The details of this analysis can be found in the *Supplementary information* folder in the ICES JMS web site.

2.3.6 Anchovy spatial distribution

Yearly maps of anchovy NASC values by ESDU along the survey transects were produced. In addition, a synoptic summary was made of the spatial distribution of anchovy juveniles throughout the study period in two different ways: Yearly juvenile biomass values by ESDU were averaged between years over cells in a 30' latitude and longitude grid. In addition, the overall probability of the presence of juvenile anchovy was also provided, calculated as the number of years the anchovy were present divided by the number of years the cell was sampled. The length and depth distributions of juveniles in each cell were also determined as averages over the series. Finally, we determined and plotted the inter-annual horizontal mean centre of gravity (Woillez *et al.*, 2009) of each 2 cm anchovy juvenile size class.

The biomass estimates and the processed data were plotted on maps using Surfer (Golden Software Inc., CO, USA) and ArcView GIS. Matlab (The Mathworks, Inc.) was used to summarize the data from the seven years.

2.3.7 Recruitment predictive capability

In order to estimate the recruitment predictive capability, the annual biomass estimates for anchovy juveniles were compared with the estimates of anchovy recruitment the following year. The recruitment is the biomass of age-1 anchovy in January of the following year, estimated according to the ICES assessment using a Bayesian model with inputs from catches and biomass estimates of two spring surveys: an acoustic one (PELGAS), conducted by Ifremer, and a survey based on DEPM (BIOMAN), conducted by AZTI (ICES, 2011). The biomass estimates were fitted by linear, log-linear and rank regressions between variables using the R software version 2.14.0 (R Development Core Team, 2011).

2.4 Results

2.4.1 Spatial coverage and fishing operations

The sampling coverage over the surveys (Figure 2-1) reflects the adaptive sampling scheme followed and shows the methodological changes made to improve the coverage, particularly since 2005. For example, the northern coverage along the French coast was considerably enlarged. The northern limit changed from 46º N in the first two years to beyond 47º N in the following years. The number of fishing operations increased from 40 in 2003 to over 60 in the years since 2005 (Table 2-1); the small number of fishing operations carried out in 2004 was mainly because few anchovy were detected that year). The incorporation of the pelagic trawler in 2006 improved the fishing flexibility, making it possible to fish near the bottom. This is shown in the fishing maps (Figure 2-1) by the increase in species variability (due to the addition of the close-to-the-bottom species). The potential coverage limitations are discussed in the *Supplementary information* of this article at the ICESJMS web site (Chapter 3 of this PhD).

2.4.2 Spatial occupation patterns of anchovy juveniles

Every year the juvenile anchovy population could be divided into two clearly distinguishable groups. One part of the population consisted in practically pure juvenile anchovy (not mixed with adults) and the other part was mixed with, or in the proximity of, adults. The pure juvenile group was located in the south-western part of the Bay of Biscay, normally off the shelf or in the outer part of it (white strata in Figure 2-2), and the mixed group was located to the north-east in shelf waters of less than 130 m depth. The only exception was in 2006, when the typical off-shelf location of pure juveniles was seen only during the first three days of the survey, then, after two days of rough weather conditions (wind speeds over 11 m/s), the distribution of this pure juvenile group shifted towards shallow coastal waters all along the Spanish and French coasts (up to 45ºN -Figure 2-2).

In each group, juveniles were found in a different species composition context and bathymetrical distribution pattern. In the pure juvenile region, anchovy were generally the only or the largely predominant species (the percentage of anchovy individuals in these strata was always higher than 90%) mixed sometimes with smaller proportions of salp, jellyfish and juvenile horse mackerel (Figure 2-1). In the mixed group, juvenile anchovy was found mixed in variable proportions with adult anchovy (the adult proportion increasing towards the north-east, Figure 2-3) and other pelagic species, mainly sardine, horse mackerel, mackerel and sprat (Figure 2-1).

The trends in density and area of occupation of juvenile anchovy were different for each group (Figure 2-4). In general, the densities were larger for the pure juvenile aggregations than the mixed adult-juvenile aggregations; however, no clear prevalence was observed in the spatial occupation patterns. For the regions with pure juvenile aggregations, the density varied greatly from very low values (less than 5 t per square nautical mile) to values up to ten times higher. For the regions with mixed juvenile-adult aggregations, the densities did not vary much, showing low density values that were about the same as those of the off-shelf aggregations; however, the highest density values were lower.

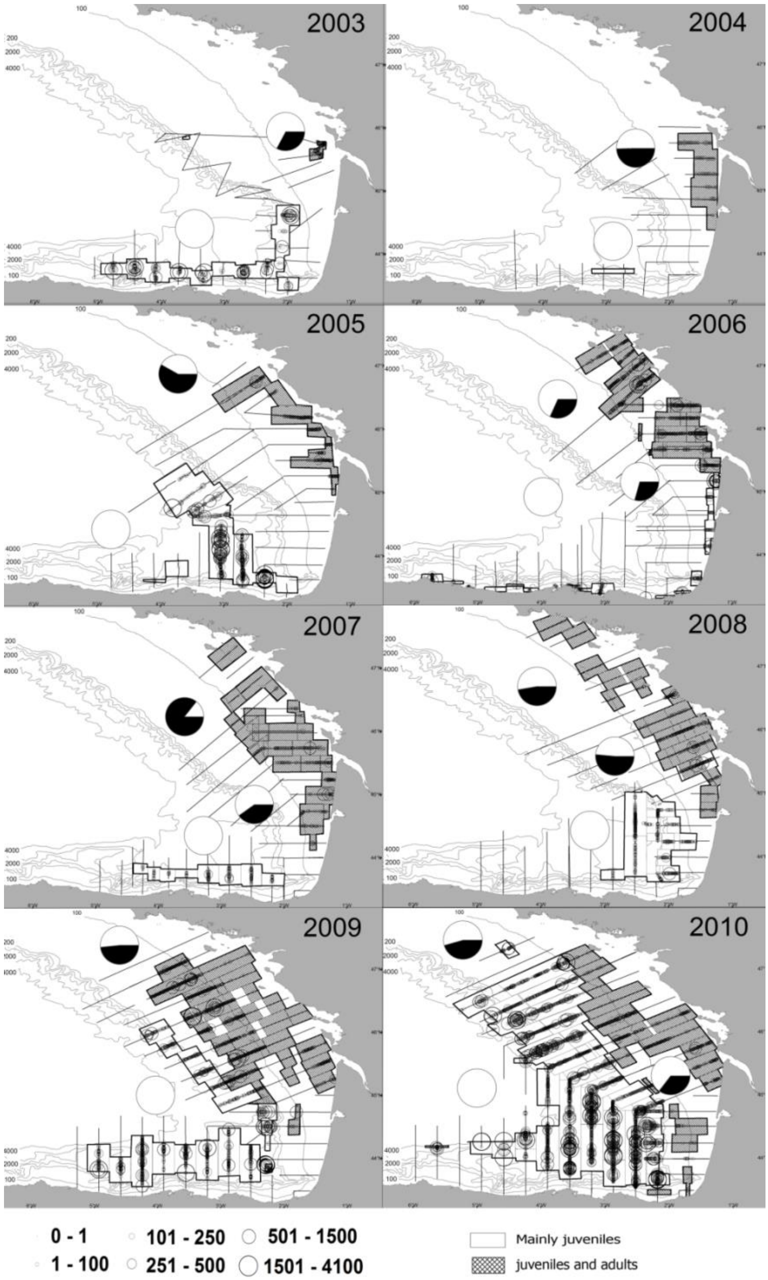


Figure 2-2. Anchovy biomass (bubbles) in kg by elementary distance sampling units of 0.1 nmi (185.2 m) and positive anchovy areas along the surveyed transects. The pie charts represent the mean percentage of juveniles (white) and adults (black) of the fishing hauls in each area.

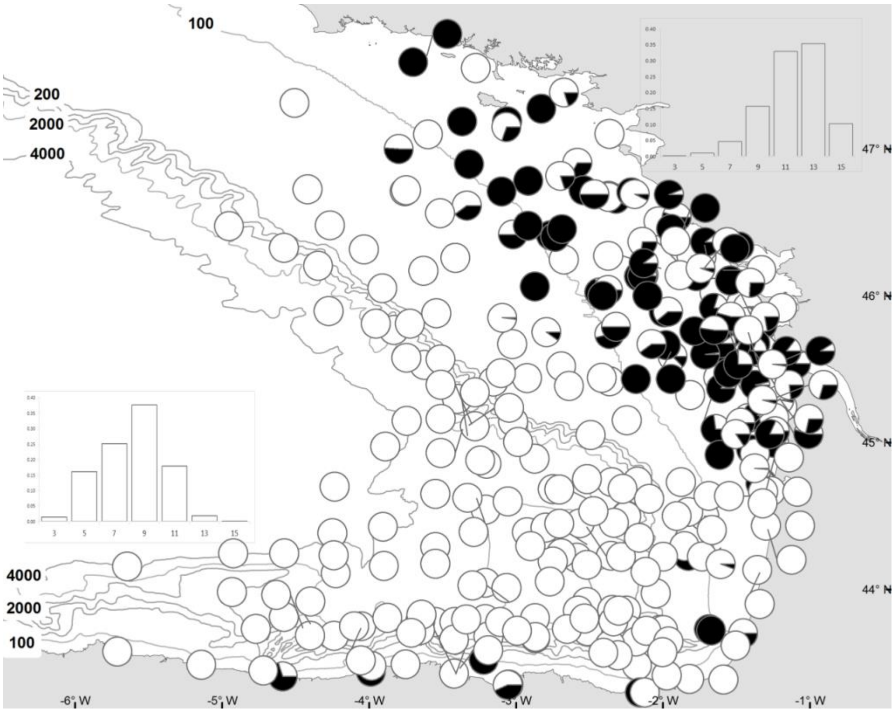


Figure 2-3. Age composition of anchovy for the seven years of the survey. The pie charts represent the mean percentage of juveniles (white) and adults (black) of the fishing hauls at each fishing site. The bars show the length distribution in cm of juvenile anchovy from the pure (left) and mixed (top-right corner) areas.

The areas occupied by juveniles in the first two years of the time-series (Table 2-1) were below 5000 square nautical miles. This then increased and remained rather constant above this value from 2005 to 2008, mainly due to an increase in the area occupied by the mixed juvenile group over the shelf (Figure 2-2, Figure 2-4). In the last two years the occupied areas continually expanded (with no visible gaps) towards the offshore and northern regions, but not towards the west. In 2010, there was a drastic increase in the area of occupation mainly off or at the outer part of the shelf; this is, in the areas occupied by the pure juvenile anchovy group.

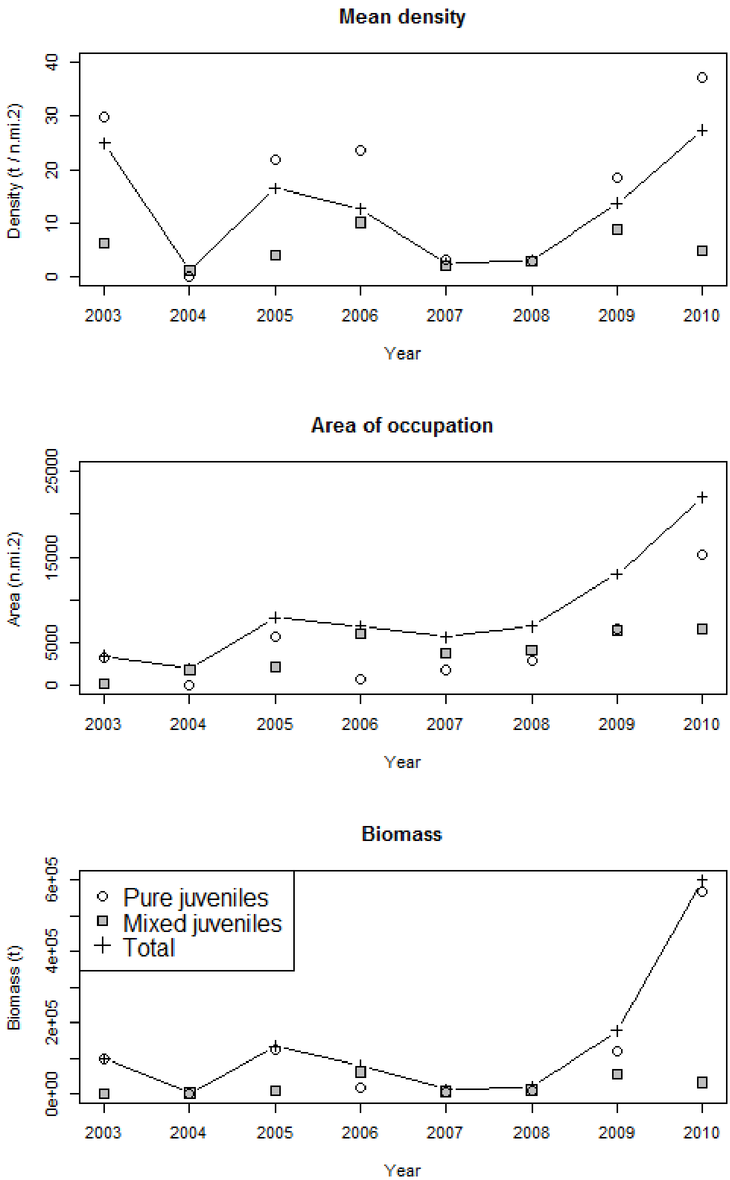


Figure 2-4. Mean density, area of occupation and biomass of juvenile anchovy during the eight annual surveys, differentiating the contribution of the two main groups of juveniles observed: the pure juvenile group located off the shelf or at its outer part and the group of juveniles mixed with adults located at the inner part of the shelf.

For the years that had the highest juvenile biomass estimates, the largest biomass contributions were invariably observed in the pure-juvenile areas (Figure 2-4). This region contained on average 58% of the total biomass. This average increased to 75% when the least abundant years (2004, 2007 and 2008) were excluded, and reached up to 95% of the total biomass in 2010, when the strongest recruitment in the JUVENA series was recorded. The contribution of the mixed-juvenile region to the biomass was quite constant across the series, and in the years with the highest total juvenile abundance the contribution was relatively weak.

A sub-area of the off-shelf region, south of 45º N and around 2-3º W, accounted on average for the highest abundance of juvenile anchovy in the Bay of Biscay (Figure 2-5-top). In the southern part of this area there was a high probability that juvenile anchovy would be present (Figure 2-5-bottom). Another area with a high probability of presence was the Garonne plume (French coast between 45º and 46º N); however, in this area, the mean abundances were much lower.

The minimum sampling area established for inter-annual comparison, i.e., the area sampled in the years 2003 and 2004 (which was restricted to the south of 46º N, Figure 2-2), accounted on average for 86% of the juvenile biomass found in the JUVENA series (Figure 2-6-top). When 2003 and 2004 were excluded from this average (so that only the years with good northern coverage were included; see Figure 2-1 and Table 2-1), the percentage of juvenile biomass to the north of 46º N was 16%, with a maximum percentage (in year 2006) of 40% of the total juvenile biomass. In practical terms, this implies that in the years when the northern regions were not sufficiently covered at the beginning of the series (2003 and 2004), on average about 14% of the juvenile biomass was probably missed.

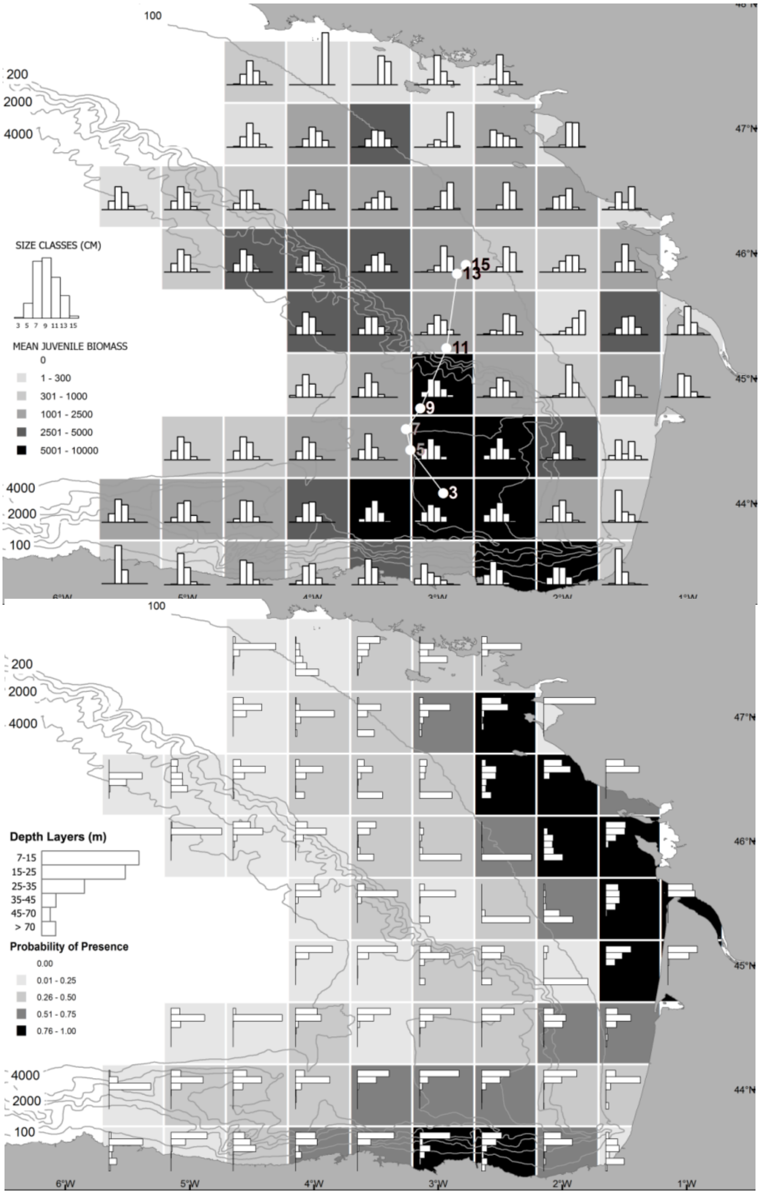
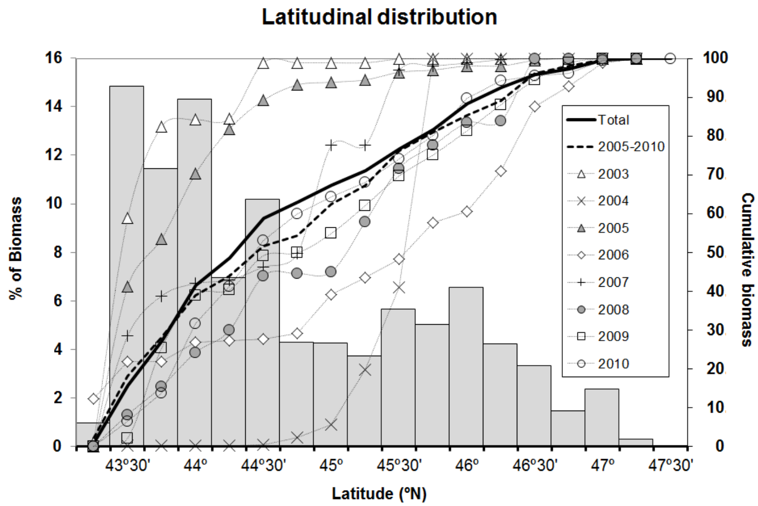


Figure 2-5. Top: The grey level represents the total aggregated biomass of juvenile anchovy in geographic 30 nmi side squares; the vertical bars show the size distribution inside each square; and the connected white dots, the location of the center of mass of each size class. Bottom: Overall horizontal probability of the presence of juvenile anchovy in 30 nmi side geographic squares; the horizontal bars represent the vertical distribution of juvenile anchovy in each square. The figure is intended to provide a kind of overall "3D map" of the juvenile anchovy distribution.



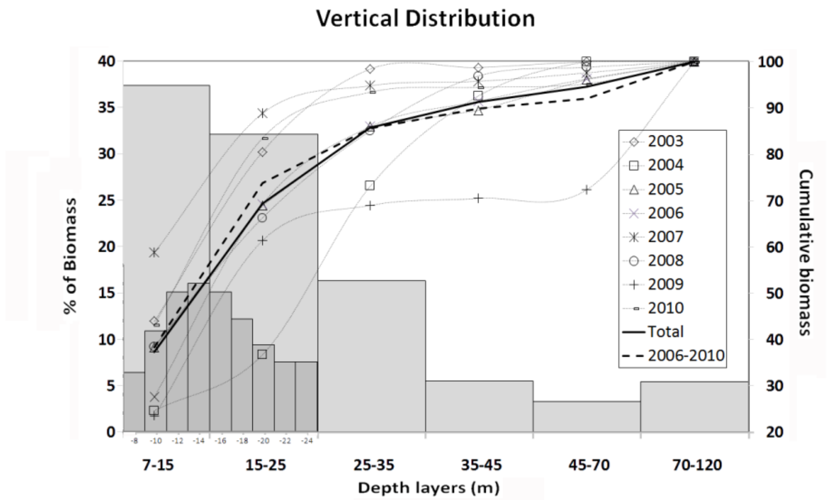


Figure 2-6. Top. Percentage (grey bars) and cumulative (lines) biomass of juvenile anchovy against latitude. The dashed line shows the results for 2005 to 2009, when there was a larger coverage of the northern shelf region than in 2003 and 2004. Bottom: Percentage (light grey bars) and cumulative (lines) vertical distribution of juvenile anchovy biomass according to the integration layers used in the project. The dashed line shows the contribution of 2006 to 2009, in which the pelagic trawler was available. The dark grey bars represent a higher-resolution vertical distribution of the first two depth layers, showing that the biomass does not increase continuously to the surface, but has a maximum at 14 m depth.

In terms of the size-age composition of the anchovy (Figure 2-3, Figure 2-5-top), the offshore or pure-juvenile group was generally composed mainly by the smallest juveniles with a mean size of about 9 cm. In the inshore areas, the mean size of the juveniles was about 12 cm, whereas the mean size of the adults observed throughout these surveys was 13.5 cm. The size distribution was in agreement with the age distribution pattern (Figure 2-3). The horizontal distribution of the center of masses in each size class (Figure 2-5-top) displayed a clear gradient towards the north in combination with another offshore-inshore gradient. This shows that juveniles probably moved from the south-western off-shelf areas to the north-eastern inshore areas.

2.4.3 Vertical distribution of anchovy juveniles

Anchovy juveniles showed different vertical distribution patterns according to the horizontal distribution and bathymetry. The pure juvenile anchovy aggregations, which mainly occupied off-shelf waters, were located in the first 45 m of the water column (Figure 2-5-bottom). As the juveniles came closer to the shore they started to sink deeper until eventually they resembled the typical adult anchovy aggregations about 10-20 meters above the seafloor (Massé, 1996). In the shallow coastal areas they were observed in various typologies occupying all the layers in the water column (Figure 2-5-bottom). On average, throughout the series, about 92% of juvenile anchovy biomass was located above 45 m depth (Figure 2-6), i.e., within the purse seine range. When only the surveys carried out since 2006 (from this date a pelagic trawler allowed the entire water column to be sampled) were considered, the percentage only decreased to 88%.

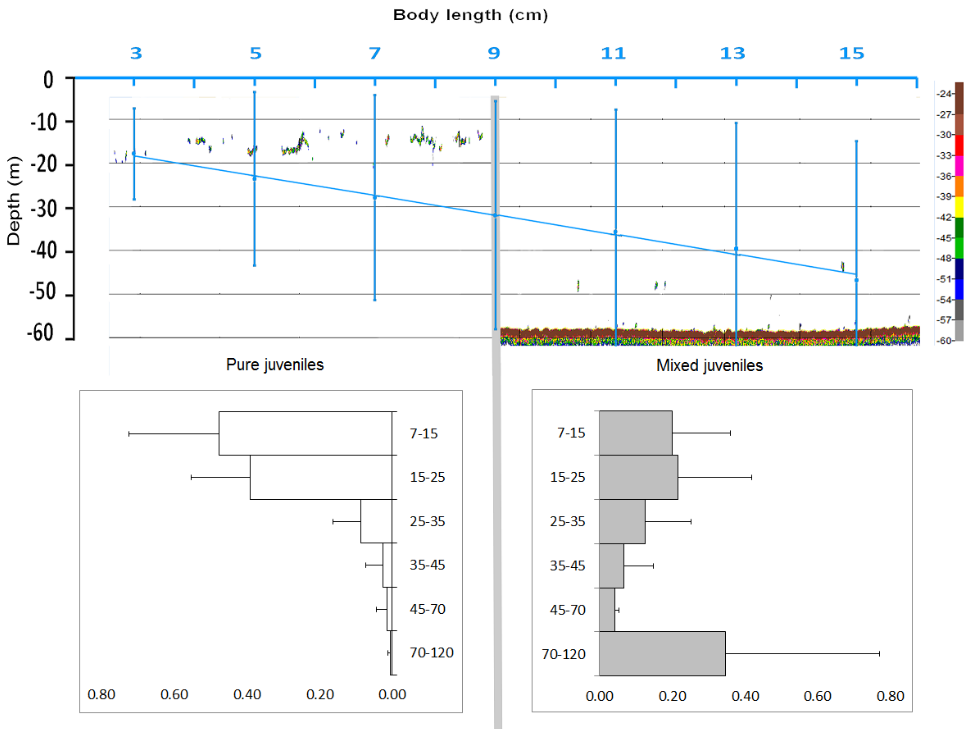


Figure 2-7. Top: Sample echograms of anchovy juveniles at -60 dB threshold. On the left, close-to-surface pure juvenile aggregations, and on the right juveniles mixed with adults in the typical adult-like near-bottom schools. The horizontal extent of each echogram is about 1 nmi. Overlapped to the echograms blue dots with vertical error bars represent the mean depth of anchovy juvenile length classes and associated confidence intervals at 99% confidence levels. The mean depth increased linearly with body length, being the fitted linear regression: depth (m) =-11.14 – 2.27*length (cm); R2=0.99. Bottom: Mean vertical distribution of acoustic density of juvenile anchovy obtained for years 2006-2010 for the two different groups observed.

Another interesting pattern that was observed concerned the mean depth of the different length classes of juvenile anchovy (Figure 2-7). The mean depth of juveniles gradually and consistently increased according to their body length at a rate of almost 2.5 m per growing centimeter. The mean length of juveniles in the echointegrated depth layers also showed a consistent and continuous pattern, with the mean lengths increasing from less than 9 cm at the first depth layer to about 11.5 cm at the deepest layer.

2.4.4 Anchovy biomass estimates and recruitment prediction

A wide range of acoustic estimates of juvenile anchovy biomass was assessed over the JUVENA series (Figure 2-4). The estimates showed differences of more than two orders of magnitude between the lowest value in 2004 and the highest value obtained in 2010.

The series of juvenile anchovy biomass estimates showed a good parallelism to the independent estimates of anchovy biomass at age-1 recruitment at the beginning of the following year (Figure 2-8). Both quantitative linear (Pearson) and non-parametric rank (Spearman) correlations showed highly significant values (the coefficients of determination were 0.93 and 0.86 respectively, with probabilities of being random below 0.0001 and 0.001 respectively). These significant relationships were not dependent on the extreme values of the series: Both correlation results (at an alpha of 1%) continued to be significant even when the highest or lowest juvenile index from the JUVENA series was excluded from the analysis. Several quantitative linear or log linear models can be fitted to series of recruitment based on the juvenile abundance indexes from JUVENA. The best fitting was achieved by the log-linear model, i.e., a potential model in linear scale, with coefficient of determination of 0.95 and p-value=5e-5 (Figure 2-8).

Concerning the main observed groups, the biomass of the pure juvenile group was significantly correlated with recruitment, explaining 87% of the recruitment variability, while the biomass of the mixed juvenile and adult group showed no significant relationship and explained less than 20% of the recruitment variability.

The main error sources involving the estimation of juvenile anchovy biomass along the temporal series of JUVENA surveys were analysed to check their impact in the recruitment prediction capacity. Applying the corrections derived from the potential sources of bias, either one by one or all at the same time, did not affect the significance of the relationships between the JUVENA index and the next year's recruitment, which remained highly significant in all cases. Refer to Chapter 3 for further details.

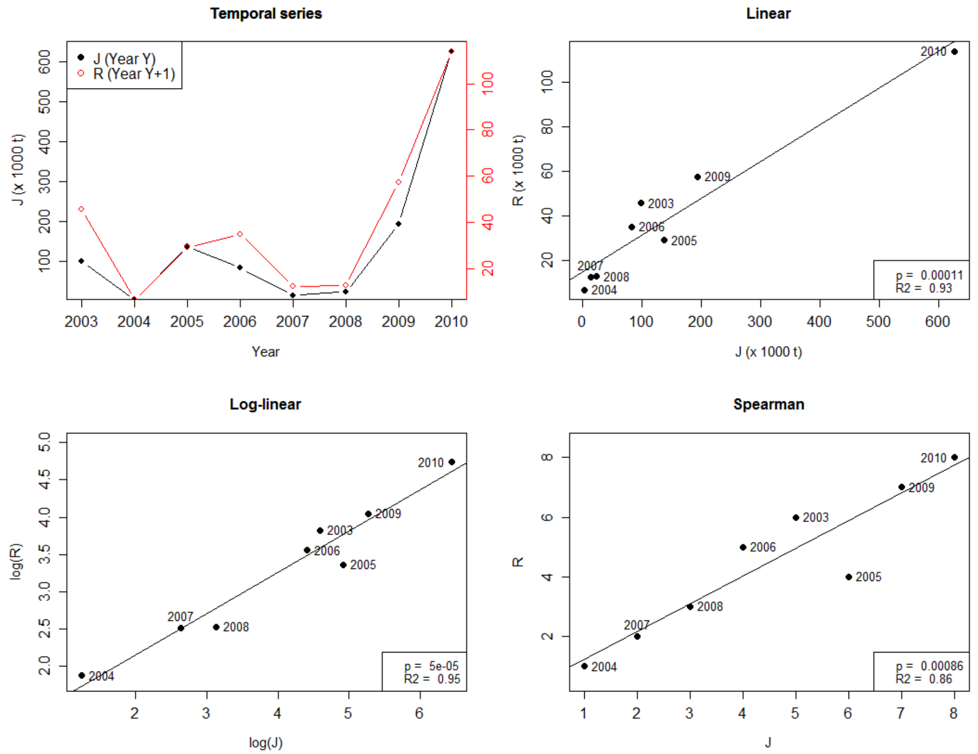


Figure 2-8. Temporal series of juvenile (J) against recruitment (R) indices and fitting of different regression models between them: linear, log-linear and Spearman (rank regression between the variables).

2.5 Discussion

2.5.1 Spatial occupation patterns

The spatial distribution of juvenile anchovy in the Bay of Biscay shows clear differences between the two main groups in this particular season (Figure 2-2). The pure juvenile group, isolated from adult anchovy (Figure 2-3) and from most of the other small pelagic species (Figure 2-1), occupies the first 45 m of the water column in the daytime (Figure 2-7) and is distributed off or in the outer part of the shelf.

The mixed juvenile group is found on the inner shelf mixed in variable proportions with adults and other species, it is more deeply distributed and starting to show the typically adult nycthemeral behaviour (Figure 2-7). The pure juvenile group also contains most of the juvenile biomass in abundant years (Figure 2-4). In addition, Bachiller *et al.* (2013) recently found that the pure juvenile group has better feeding conditions than the mixed group in spite of occupying an area with a lower prey abundance. These authors suggest that this *a priori* worse situation may be compensated by the lower predation risk (which allow them to concentrate activity on feeding) and higher visibility caused by the lower water turbidity. This is the case in the slope waters of the Bay of Biscay (Irigoien *et al.*, 2007), which provide better feeding conditions for a selective hunter species like juvenile anchovy (Van der Lingen *et al.*, 2006).

The pure juvenile group seems to have spatial dynamics in which both the mean density and the area change with population abundance; therefore, the combination of a high mean density and a high occupation area can produce huge abundances, as occurred in 2010. In contrast, in the mixed region, the density of juvenile anchovy was rather constant, and the biomass changes were mainly related to the range of the occupied area (Figure 2-2). According to these trends the two groups correspond to different spatial dynamics models (Petitgas, 1998): a constant density model for the mixed juvenile group, and a varying density and area model for the pure juvenile group. In both cases the biomass depends on the range of the occupied area, which highlights the importance of correctly defining its boundaries to obtain a correct estimate of the biomass level. This type of spatial dynamics of expansion of the occupied area according with the abundance was shown for the adult anchovy stock by Uriarte *et al.* (1996) and by Somarakis *et al* (2004). Other pelagics do also show similar spatial dynamics, as Japanese sardine (Zenitani and Yamada 2000).

The occupation of the off-shelf waters by pure juvenile anchovy is consistent throughout the series and agrees with previous works on juvenile anchovy in the Bay of Biscay (Carrera *et al.*, 2006; Lezama-Ochoa et al., 2010; Uriarte *et al.*, 1996; Uriarte *et al.*, 2001). Uriarte *et al.* (2001) described a large juvenile abundance in the French outer-shelf waters (as in 2009 and 2010) in the 1999 JUVESU survey, which was followed by strong recruitment in 2000 (ICES, 2010).

The off-shelf distribution of the bulk of the juveniles is the result of a south-west drift of eggs and larvae from the usual spawning grounds over the shelf as a consequence of the wind regimes and currents in late spring and summer in the Bay of Biscay (Borja *et al.*, 1996, 2009, Cotano *et al.*, 2008, Allain *et al.* 2001, Uriarte *et al.* 2001, Irigoien *et al.*, 2008). An autumn migration pattern of juveniles towards the shelf as they grow and develop sufficient swimming abilities is necessary in order for them to return to the spawning grounds and thus complete their life cycle (Cort *et al.* 1976; Irigoien *et al* 2008; Uriarte *et al.* 2001). This autumn migration of juveniles also matches the spatial distribution patterns of juvenile anchovy according to size observed in the JUVENA survey. Small juveniles (from 3 to 11 cm in length) show a gradual shift from the areas off the shelf in the central Bay of Biscay (Figure 2-4) in a north-northeast direction towards the French shelf; while the largest juveniles and the bulk of the adults are already found on the French shelf. These migration patterns are in agreement with the patterns observed by Aldanondo *et al.* (2010), who used otolith chemistry to show that anchovies born in low salinity waters drift to higher salinity waters and return back after the development of their swimming skills. Curiously, these size distribution patterns are almost opposite to the patterns of adult anchovy during the spawning season (Motos et al., 1996; Petitgas et al., 2011), in which the small adults (mainly the age 1 recruits) are located on the inner continental shelf, whereas the largest ones (mainly age 2 and older) occupy the outer shelf and slope waters.

Concerning the vertical distribution, the presence of a local abundance maximum in deep waters only for the mixed group (Figure 2-5-bottom and Figure 2-7) suggests that part of the juveniles of this group already perform the daily vertical migrations characteristic of the adults. This is in agreement with previous reports on Bay of Biscay juvenile anchovy (Carrera *et al.*, 2006; Petitgas *et al.*, 2004; Uriarte *et al.*, 2001). It is still unclear whether the eventual change to this behaviour is mediated by adults (Petitgas *et al.*, 2004, Petitgas 2007). Although some of our observations (particularly the capture of near-bottom pure juvenile schools in the northern shelf areas) do not support this idea at small scale, the persistent lack of near bottom juveniles in areas empty of adults (as the whole north coast of Spain) tends to support it at larger regional scales.

2.5.2 Recruitment forecasting capability

The main aim of this work was to test whether the abundance of juveniles in autumn constitutes a reliable indicator of the strength of recruitment to the adult stock each year in the Bay of Biscay. The hypothesis has been confirmed by the significant positive correlations between the biomass estimates of juveniles and the next year's age-1 recruits (Figure 2-8). This relationship is not too dependent on any particular point of the series, neither the maximum nor the minimum.

Of course, the positive correlation between juvenile abundance and subsequent recruitment at age-1 ought to be presumed because they are successive estimates of the abundance of the same cohort. It should be noted, however, that obtaining a good relationship between the juvenile and age-1 anchovy abundance estimates first requires that the surveying and acoustic estimation methodology are correctly implemented in order to determine the juvenile biomass, and second that the inter-annual variability in the survival rates between these two stages of the same cohort are low during late autumn and winter. High variability in survival rates could have corrupted the expected correlation between juveniles and subsequent recruits. Therefore, the confirmation of this good relationship indicates that the JUVENA series has produced a reliable index of juvenile abundance (provided that the ICES assessment is correct, at least in relative terms), and also that the year-class strength of anchovy in the Bay of Biscay is already determined by the end of the summer, when the mean age of the juveniles is usually between 2 and 4 months (Aldanondo *et al.*, 2010). This means that, for Bay of Biscay anchovy, as for other species (Leggett and Deblois, 1994), the high variability in the year-class strength is generated from the varying survival rates during the earliest life stages of its life cycle (eggs and larvae). Our results are in agreement with previous reports of a correlation between juvenile abundance and year-class strength found for other species and populations (Axenrot and Hansson, 2003; Gudmundsdottir *et al.*, 2007; Hourston, 1958; Koeller *et al.*, 1986; Schweigert *et al.*, 2009). Furthermore, in some cases the year-class strength has also been reported to relate to earlier pre-recruit abundances, such as postlarval abundance (de Barros and Toresen, 1998; Fossum, 1996; Fox, 2001; Oeberst *et al.*, 2009).

The mean rate of juvenile to recruitment estimates across the time-series is 2.7. Although it is tempting to try to use this rate to infer juvenile mortality during winter, there are important methodological differences concerning the way of obtaining the estimates of juvenile biomass and recruitment that prevent us from considering them at the same scale. The juvenile index is based solely on acoustics, while the recruitment index is based on a Bayesian assessment combining three different inputs: acoustics, DEPM and fleet catches, which have some internal unsolved discrepancies (Ibaibarriaga *et al.* 2008; ICES 2012). Moreover, the different vertical distributions, aggregation patterns and gonadal contents between spring (spawning) and autumn (mostly immature juvenile) anchovy are likely to produce different TS-length relationships, which are currently not properly taken into account in the acoustic estimates. Consequently, at the moment the most robust and consistent use of the JUVENA index is to consider it as a relative index, as the mortalities inferred from the rates of the two indices are not reliable. Therefore, the fact that the estimate of juvenile biomass in 2004 was less than the subsequent estimate of recruits in spring 2005 is not considered relevant. First, the extremely low abundance of that year class made the estimate of its abundance in autumn and spring more imprecise than other years, potentially increasing the expected discrepancy between the indices; and secondly, that the 2004 juvenile biomass, the lowest of the series, coincides with the lowest of the recruitment series evidences that the estimate for that year provided highly informative content.

Our results for juvenile anchovy do not fit the entrainment hypothesis (Petitgas *et al.*, 2006; Petitgas *et al.*, 2010) according to which the adults of certain pelagic species transfer the knowledge of the homing migrations necessary for completing the life cycle. In the case of the Bay of Biscay anchovy, it is obvious that the juveniles migrate towards the continental shelf without the aid of the adults, as there are no adults off the shelf (Figure 2-3). In addition, if this hypothesis holds true, then a reduced survival rate of the pure juvenile group will be expected, whereas according to our data it is the pure juvenile group, and not the mixed one, who is significantly correlated with the recruitment. Perhaps the entrainment for the Bay of Biscay anchovy involves transferring behavioural knowledge (the nycthemeral behaviour, as postulated by Petitgas et al., 2004) rather than the migrations routes. Or, alternatively, the entrainment may involve the transference of migration routes but taking place a few months later, in late spring and summer, after the spawning season, when both the recruits and the older adults are known to carry out jointly the trophic migrations towards the North (Uriarte et al., 1996). In any case, the closure of the life cycle of Bay of Biscay anchovy and the differences in life cycle strategy between anchovy and other pelagic species remain unexplained and should be further studied.

In the study period there has been a broad range of recruitment levels, from an extremely low level in 2004, which caused the collapse of the fishery, to one of the highest recruitment levels of the entire recruitment time-series in 2011. The good correlations shown in our results suggest that the JUVENA index can be used to provide an indication of the next year's recruitment at age-1 not only in qualitative terms but also in quantitative ones. However, although linear and log-linear models were shown to be good candidates, the objective of defining the best quantitative modelling was not considered in this paper and has been left to stock assessment modellers to be investigated in the near future when a few more medium and strong year classes become available.

Currently, the information provided by the JUVENA index is not systematically used by ICES for providing management advice. However, at the end of 2009, managers used this information to reopen the anchovy fishery with a low TAC (ICES, 2010). Different methods for using this information could be adopted such as using the values of the juvenile index to construct recruitment scenarios for short-term projections of the latest stock assessment results (as proposed by

Ibaibarriaga *et al.*, 2010). In any case, we leave it to ICES to decide how the index should be used, while this work is focused on building and testing the index.

In general terms, having an early indication of the recruitment strength would allow the fishing effort to be managed better by minimizing the risk of depleting the population by overfishing (Walter, 1989, De Oliveira and Butterworth, 2004). Schwigert *et al.* (2009) highlighted the importance of this information even in the case of a non-significant relationship. The JUVENA index not only provides a significant relationship with recruitment; it also fits conveniently into the existing timetable: In this region, the management of the anchovy fishery is based on direct assessment surveys carried out in spring that provide their advice at the end of the spawning season. By that time a significant part of the annual anchovy fishery has already ended, which logically limits the effectiveness of the management measures. In this case, an early indication of the recruitment level, such as that provided by the JUVENA index, would allow precautionary measures to be applied several months before the next spawning period and the start of the fishery activity. This information would substantially improve the management of the Bay of Biscay anchovy fishery, helping to prevent its collapse as occurred in recent years.

2.6 Supplementary data

The following supplementary material is available at ICES Journal of Marine Science online. A working document entitled "Uncertainties and alternative estimates of the JUVENA index according to its special methodology and assumptions" describes the procedure of assessing the main uncertainties faced in the juvenile anchovy biomass estimation process (it's also the Chapter 3 of this PhD). In addition, a set of echogram images is provided as examples of juvenile anchovy detections during the JUVENA surveys (also in the Appendix of this PhD).

2.7 Funding

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2.8 Acknowledgements

We would like to acknowledge the skippers and crews of the vessels that participated in the survey: FV “Divino Jesú s de Praga”, FV “Nuevo Erreiñezubi”, FV “Mater Bi”, FV “Gure Aita Joxe”, FV “Itsas Lagunak” and RV “Emma Bardán”. We would also like to thank Leire Ibaibarriaga and Sonia Sanchez for their assistance with the statistical analyses.

2.9 Publication data

Type	Peer-reviewed article
Title	Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns.
Authors	Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A.
Journal	ICES Journal of Marine Science
Year	2013
Volume	70
Pages	1354-1358

Foto: Cerquero Gure Aita Joxe, JUVENA 2005 (Fuente: propia)

Chapter 3

Uncertainties and alternative estimates of the JUVENA index according to its special methodology and assumptions

Incertidumbres y estimas alternativas del índice JUVENA según su especial metodología y asunciones

Para estimar las principales fuentes de incertidumbre de la campaña acústica de anchoa juvenil relacionadas con las asunciones varias y especificidades metodológicas. Se analizaron errores sistemáticos y aleatorios, centrándose específicamente en: errores de interpolación del muestreo usando técnicas geoestadísticas, error del campo cercano, intercalibración entre embarcaciones, cobertura horizontal y vertical, identificación de especies y asignación de edad. Los errores obtenidos fueron usados para construir intervalos de confianza de las estimaciones de abundancia de anchoa juvenil. Los resultados de la estimación de incertidumbre fueron publicados como información suplementaria por Boyra et al. (2013).

3.1 Abstract

This document details the assessment of main error sources involving the estimation of juvenile anchovy biomass along the temporal series of JUVENA surveys, to check their impact in the recruitment prediction capacity. In general, the resulting uncertainties have a small impact in the main objective of the survey (providing an early indicator of recruitment) due to (i) the high SNR of the random uncertainties estimated (2.5); (ii) the small difference between alternative estimates compared to the difference between annual biomass levels, (iii) and the highly significant prediction capability of the JUVENA index for all the alternative juvenile biomass estimates (uncorrected or with any of the proposed corrections).

3.2 Introduction

The main sources of uncertainty involving the biomass estimation, especially those related with the various assumptions and methodological issues along the temporal series of JUVENA surveys, were calculated to check their impact in the biomass estimations. Both systematic (bias) and random errors were computed. The former were used to build correction factors and the latter, confidence intervals for the corrected estimates. The aim of the present work is not to achieve a complete review of all the potential sources of error of the survey, but an operational analysis of the incidence of the particular assumptions and methodologies implemented during JUVENA for the main purposes of the project. As such, some of the errors were estimated quantitatively and others were more qualitatively addressed.

3.3 Material and methods

3.3.1 Sampling interpolation

The sampling interpolation error was calculated using geostatistical techniques (Petitgas, 1993). Non-centered covariograms were applied on acoustic density each year to obtain the variance of the biomass estimation (Guiblin et al. 1995, Petitgas and Lafont, 1997) using EVA software (Petitgas and Lafont, 1997). The modelled variograms were fitted by visual inspection. In geostatistical techniques the estimation variance derives from the variogram model (Petitgas, 1993). The coefficient of variation was obtained:

$$cv_{geo} = \frac{\sqrt{\sigma_{geo}}}{\mu}$$

3.3.2 Near field

Two methods were proposed to deal with the presence of juvenile anchovy aggregations inside the near field range of the Simrad EK60 38 kHz transducers (10.5 m, Simmonds and Maclennan, 2005). In the first method, the backscattering from *ranges* less than 11 m were deleted. The second method consisted in measuring and correcting the bias produced when echointegrating fish schools inside the near field (5-11 m *range* from the transducer face, i.e., about 7.5-13 m *depth* from the sea surface), instead of deleting the whole layer. The reason for integrating occasionally the 7.5-13 m depth layer (and thus not following the standard procedure) is that we considered important to retrieve as much information as possible about abundance of juvenile anchovy, a species that largely occupy the first meters of the water column. We also had the intuitive notion that this fact couldn't be introducing much bias in the estimates, because the near field reverberation at 7.5-13 m depth was in fact invisible in the echogram at the -60 dB threshold used for echointegration (and even at the -70 dB threshold that we use for inspection of the echogram). However, in order to clarify whether this intuitive notion was correct, we measured the bias introduced by the near field of the transducer in the echointegrated fish backscatter in these first layers.

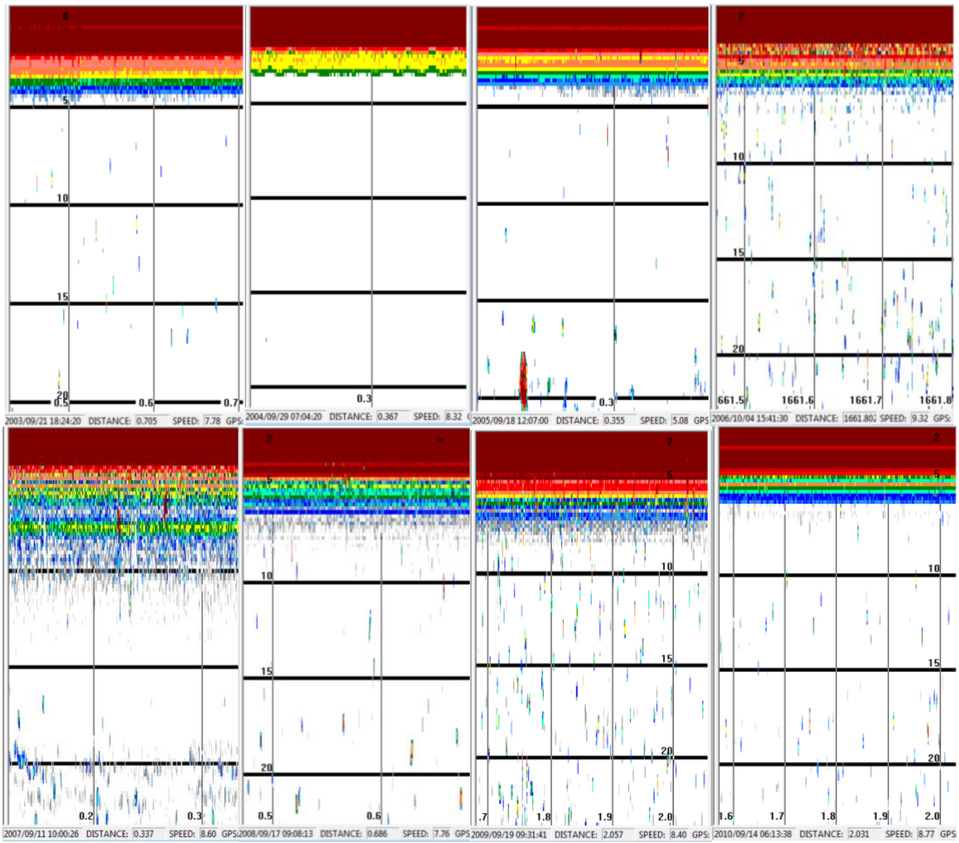

Figure 3-1: Sample echograms of the chosen low plankton areas for the near field characterization. The threshold is set at -80 dB, the same that was used during the visual inspection for the selection of these areas. The process tries to characterize the "rainbow" pattern at the top part of each echogram filtering the overlapping "noise" produced by marine organisms, wave induced bubbles, etc...

To estimate the near field bias, we selected a set of the cleanest possible 38 kHz echograms, this is, with the least presence of plankton at the uppermost layers (7.5-13 m depth). From these relatively free of plankton areas, we picked five acoustic records of about five minutes of duration for each year and vessel. Figure 3-1 shows a sample of these echograms. The idea is to try to characterize the “rainbow” pattern visible at the first layers of these echograms (visible because the echograms are displayed with a threshold of -80 dB), but not accounting the noise produced by the plankton. With this purpose, the backscatter was echo-integrated at -100 dB threshold by single ping in the layer 7.5-13 m. As the records were not completely free of plankton, a filtering procedure was applied to clean it as much as possible. The echo-integrated pings of each file were divided in four groups per minute (about 50 pings per group). Inside each group, the percentile 25 was computed for each depth layer to characterize for each group the purest possible near-field reverberation, free from plankton backscattering. The resulting echo-integration values per layer were further averaged using the mean value for all the records. This estimation of “clean water” backscatter 7.5-13 m depth was used as a proxy of the near field and was subtracted from the fish NASC values of uppermost echointegration channel (7.5-15 m depth). As the filtering procedure could not remove completely the plankton backscatter, some quantity of it was included in the near field estimates, and thus subtracted from the fish backscatter of the first layers. Thus, this correction procedure of the near field is considered to be slightly conservative.

For each method, a Near Field correction factor was derived (F_{NF_remove} and F_{NF_corect} respectively) as the ratio of the near field corrected and uncorrected biomasses.

$$F_{NF\_remove} = \frac{B_{NF\_remove}}{B_{uncorrected}}$$

$$F_{NF\_correct} = \frac{B_{NF\_correct}}{B_{uncorrected}}$$

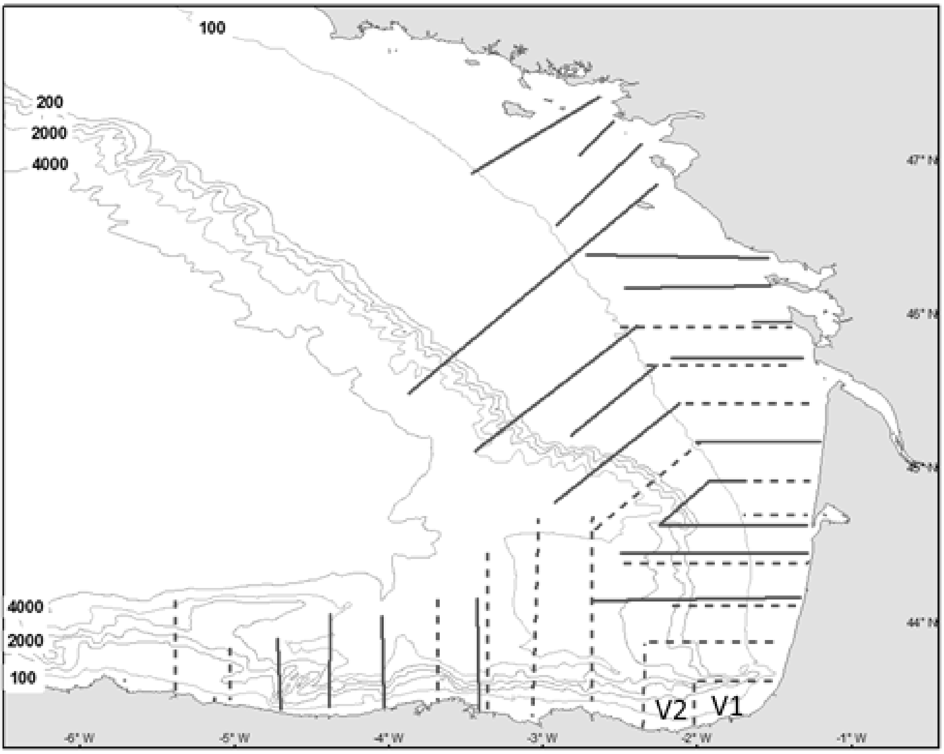

Figure 3-2. Transects covered by the two vessels involved in the JUVENA06 survey (continuous line, R/V Emma Bardan; dashed line, F/V Itsas Lagunak). The common transects were used for the intercalibration exercise between vessels.

3.3.3 TS at 120 kHz in a portion of year 2006

Generally, only the 38 kHz data were echo integrated, using the TS-length relationships agreed in ICES WGACEGG for the main species. The only exception for the use of 38 kHz occurred in 2 of the 32 transects covered in year 2006 (V1 and V2, Figure 3-2) due to the failure of the 38 kHz transducer in the very beginning of the survey, which was replaced by a new one for the rest of the survey. For this small fraction of the sampled area in 2006, the data from the 120 kHz channel were echo integrated, and an ad hoc calculated TS value for this frequency was used to estimate abundance.

Table 3-1. Values of TS of anchovy (in dB) obtained from bibliography , according to the TS- length relationship: TS = a log(L) - b. Consulted bibliography: 1, Zhao (pers. com.); 2, Machias et al. (2000); 3, Gutierrez and MacLennan (1998).

Species	*b* (dB)	a	Location	Frequency (kHz)	Source
Engraulis japonicus	71.5	20	Japan	120	1
Engraulis encrasicolus	79.46	19.26	Mediterranean	120	2
Engraulis ringens	76.2	20	Perú	120	3

Different alternative procedures were explored to obtain an appropriate TS value for the target species at 120 kHz. The TS values for anchovy reported in bibliography covered a range of almost 8 dB (Table 3-1), making it difficult to make a choice. Therefore, the TS values of the main target species at this frequency were obtained by an optimization process, trying to maximize the internal consistency of the JUVENA abundance estimates. To obtain an operational TS value for 120 kHz, the anchovy juvenile abundance in an area with similar species composition to V1 and V2 was estimated using the 120 kHz frequency. The chosen TS value for 120 kHz was the one that provided the closest abundance in the area to the 38 kHz one. An iterative process was followed, in which the optimum TS values at 120 kHz were those that produced a biomass estimate as close as possible to the biomass obtained with the 38 kHz echosounder in the same transects. The optimization was applied to a selection of strata that presented pure offshelf juvenile anchovy and well configured and calibrated data sets for both 38 and 120 kHz. The values were initialized according to: TS120=TS38-3dB. Then, an iterative process was applied, aiming to minimize the following objective function:

$$\sum_{strata} (\log(Biomass_{38}) - \log(Biomass_{120}))^2$$

The logarithms were used to give similar weights to the contribution of all the strata independently of their abundance levels. The correction factor F_{120} was calculated as the ratio of the biomass at 38 and 120 kHz. The correction factor and error attributed to the whole biomass estimate in year 2006 produced by use of the

120 kHz in a portion of the area was calculated as the product of the percentage of the total biomass represented by those transects times the mean error obtained by using the ad hoc TS value in the analysis.

$$F_{Tot} = \frac{F_{120} \cdot B_{120}}{B_{38} + B_{120}}$$

$$cv_{Tot} = \frac{cv_{120} \cdot B_{120}}{B_{38} + B_{120}}$$

3.3.4 Intercalibration of acoustic data between vessels

Since the 2006 survey, when the acoustic sampling was split between two vessels, intercalibration exercises between the two vessels were routinely carried out each year based on the intercalibration methodology described by Simmonds and MacLennan, (2005). The data were collected by two vessels advancing side to side, about 100 m apart. The intercalibration process consisted in comparing the echointegration of the bottom echo in areas of smoothly variable bottom.

A minimum distance of 30 n.mi. was covered simultaneously by the two vessels for these exercises. The ratio of NASC ((Maclennan *et al.*, 2002)) values per ESDU between vessels was calculated. Initially, layer echointegration of both water column and bottom echo obtained by the two vessels were compared, but preliminary results indicated that, while both target types provided similar ratios, the bottom echo provided a much smaller variability than the water column. Therefore, the bottom echo was chosen as the reference target and the rest of the analysis is based on bottom echo NASC values. The intercalibration factor F_{int} was estimated as the median of the NASC ratios, R_i.

$$F_{int} = Median(R_i)$$

The median was chosen as a robust alternative to the average, given the high number of outliers of the data (because the transducers were not pointing at exactly the same targets).

As a robust standard deviation, the Median Absolute Deviation (MAD, Hoaglin et al., 1983) was calculated, based upon the deviation of individual data points to the median of the population:

$$MAD_{int} = (Median\{|Ri - F_{int}|\}) \times 1.4826$$

The value 1.4826 is a constant factor that adjusts the resulting robust value to the equivalent of a normal population distribution. Thus, for a normally distributed population, the SD and the MAD should be equal. In accordance to this, a robust CV was calculated as:

$$CV_{int} = MAD_{int} / F_{int}$$

Finally, the correction factor and error attributed to the whole biomass estimate caused by intercalibration was calculated as the product of the percentage of the total biomass sampled by EB times the mean error obtained by using the ad hoc TS value in the analysis.

$$F_{\text{int}}^{Tot} = \frac{F_{\text{int}} \cdot B_{EB}}{B_{EB} + B_{AZTI}}$$

$$cv_{\text{int}}^{Tot} = \frac{cv_{\text{int}} \cdot B_{EB}}{B_{EB} + B_{AZTI}}$$

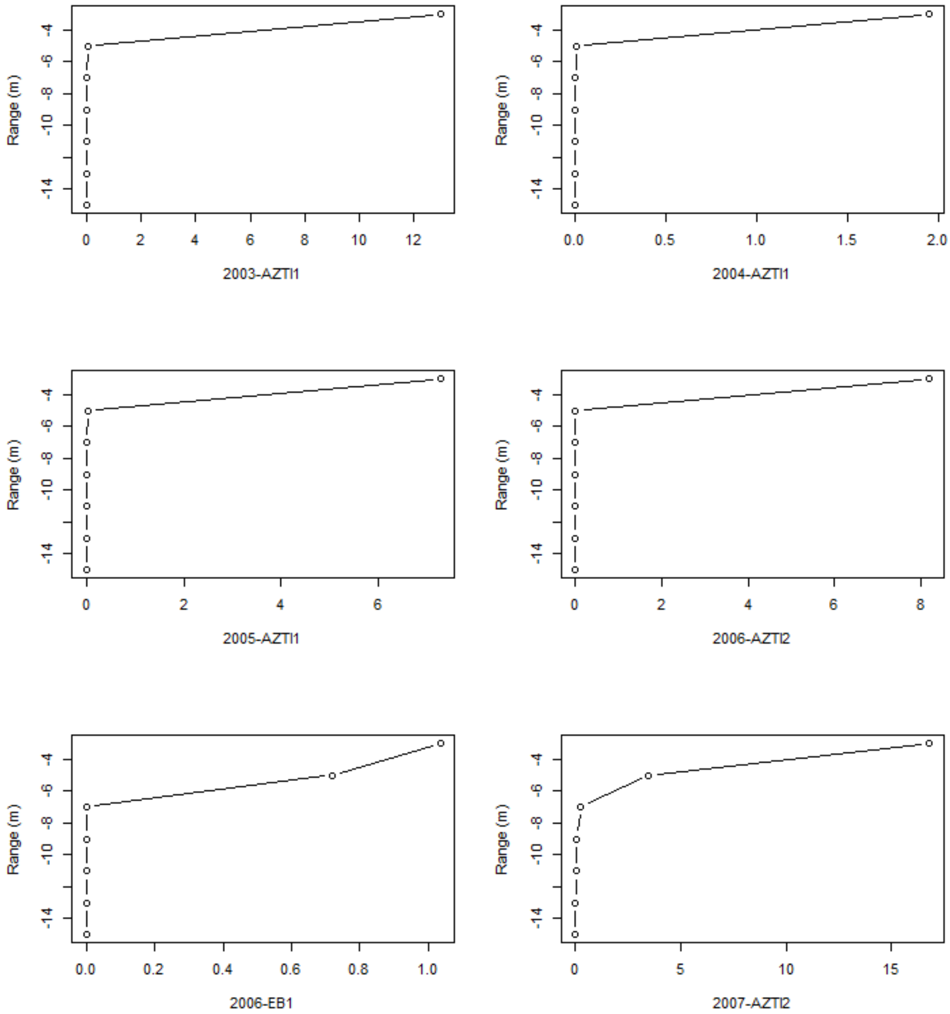

Figure 3-3. Echointegration of the near field (range 3-15 m) in layers of 2 m for each year and vessel for the period 2003-2007. The sum of layers 5-11 m was used as estimation the near field correction.

3.3.5 Horizontal (> 46ºN) coverage in years 2003-2004

In years 2003 and 2004 there was a comparatively reduced sampling effort compared to the rest of the years of the series, especially in the Northern area (Figure 2-1). In 2003 and 2004 the coverage reached the latitude 46ºN while for the rest of the years it reached around (and even beyond) 47ºN. The potential underestimation bias caused by the limits of the coverage of the northern area in these two years was addressed through analysis of the latitudinal spatial pattern observed across the rest of the years (2005-2010). The bias and uncertainties were estimated as the mean biomass found to the North of 46ºN in these years and its associated variability.

3.3.6 Vertical (>45m depth) coverage in years 2003-2005

The lack of a pelagic trawler in the first years of the survey caused a potential underestimation biomass of juvenile anchovy near the bottom. In order to estimate this bias, the mean biomass proportion of juvenile anchovy outside the purse seine range (about 45 m) was calculated in the years where the pelagic trawler was available. As the vertical distribution patterns are different for the two parts of the juvenile population (Figure 3-3 and Figure 3-4), the correction was applied independently for pure and mixed juveniles.

3.3.7 Vertical (<7.5m depth) coverage

The extremely near surface distribution of juvenile anchovy may potentially cause and underestimation in the very first meters of the water column. The potential underestimation was addressed by echointegration of the 7.5-25 m depth layers at 2m depth resolution of the full temporal JVUENA series.

3.3.8 Species identification error

The potential species identification error associated with estimation of the abundance of juvenile anchovy was not assessed quantitatively in this work. The aim of the conducted preliminary analysis is to show that the species identification error is not an issue (compared to the typical multispecies acoustic surveys) rather than trying to give a detailed assessment of such error. The qualitative justification is based on the application of a proper methodology, the proportions of anchovy to the rest of fishing species in the fishing hauls and the generally straightforward and easy process of splitting the acoustic backscattering between anchovy juveniles and plankton due to different typology of juvenile anchovy and plankton aggregations and the higher acoustic density of anchovy schools.

Species identification in JUVENA surveys was based on the information collected in the hauls. First, hauls were grouped by strata of homogeneous species and size composition. The species and size composition of each homogeneous stratum was obtained by averaging the composition (in numbers) of the individual hauls contained in the stratum weighted to the acoustic density in the vicinity (2 n.mi. diameter). This species and size composition of each stratum was used to obtain the mixed species echointegrator conversion factor (Simmonds and Maclennan, 2005) for converting the NASC values of each ESDU into numbers of each species. Regarding planktonic species, in the scarce strata where it was detectable in the echograms at -60 dB threshold, one of the following procedures was applied: (i) remove the plankton from the echogram (manually or increasing 1-3 dB the threshold) and ignore it in the multispecies echointegration factor (typical procedure for salp); or (ii) leave it in the echogram and include it in the multiespecific echointegration factor (typical procedure for jellyfish).

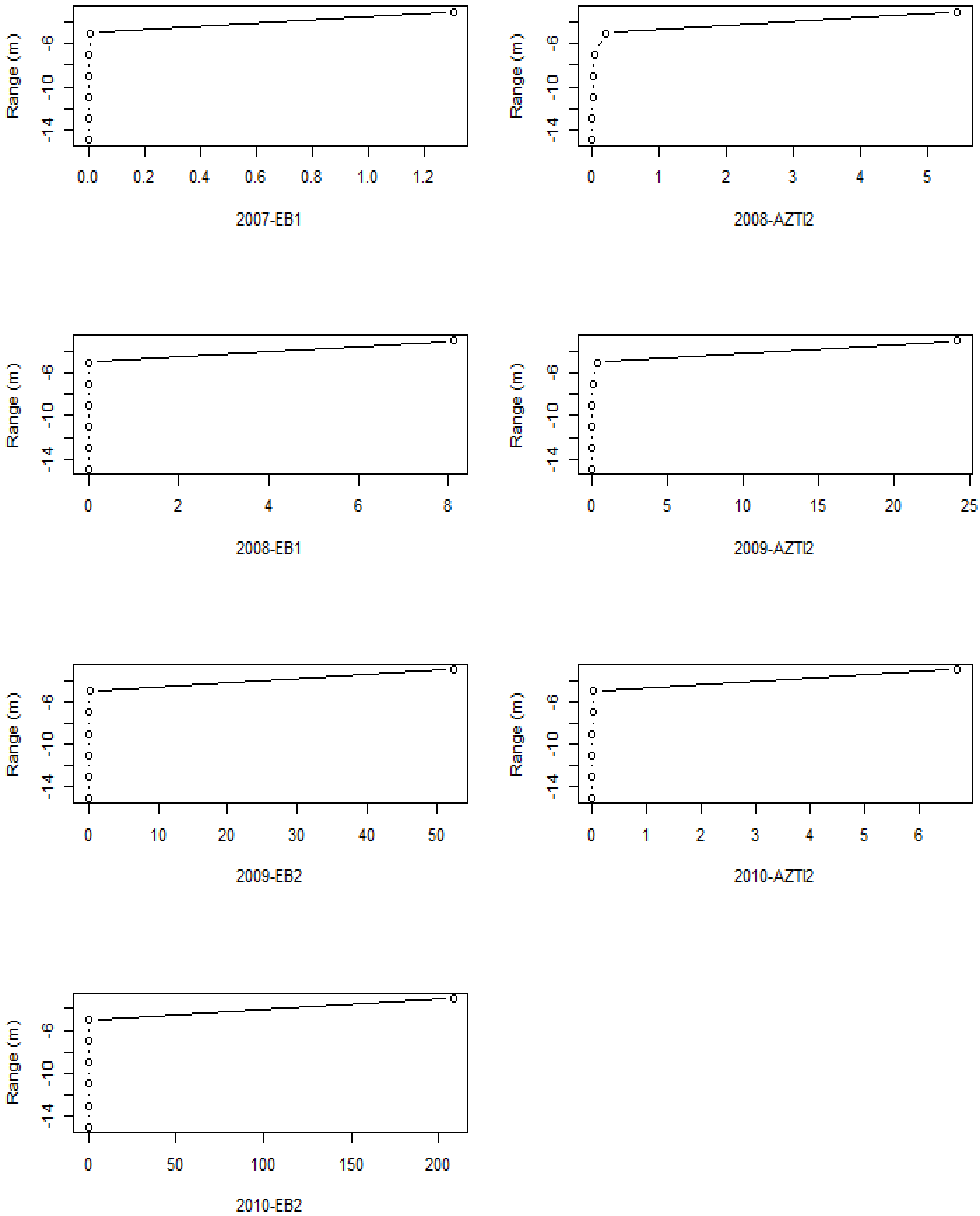

Figure 3-4. Echointegration of the near field (range 3-15 m) in layers of 2 m for each year and vessel for the period 2007-2010. The sum of layers 5-11 m was used as estimation the near field correction.

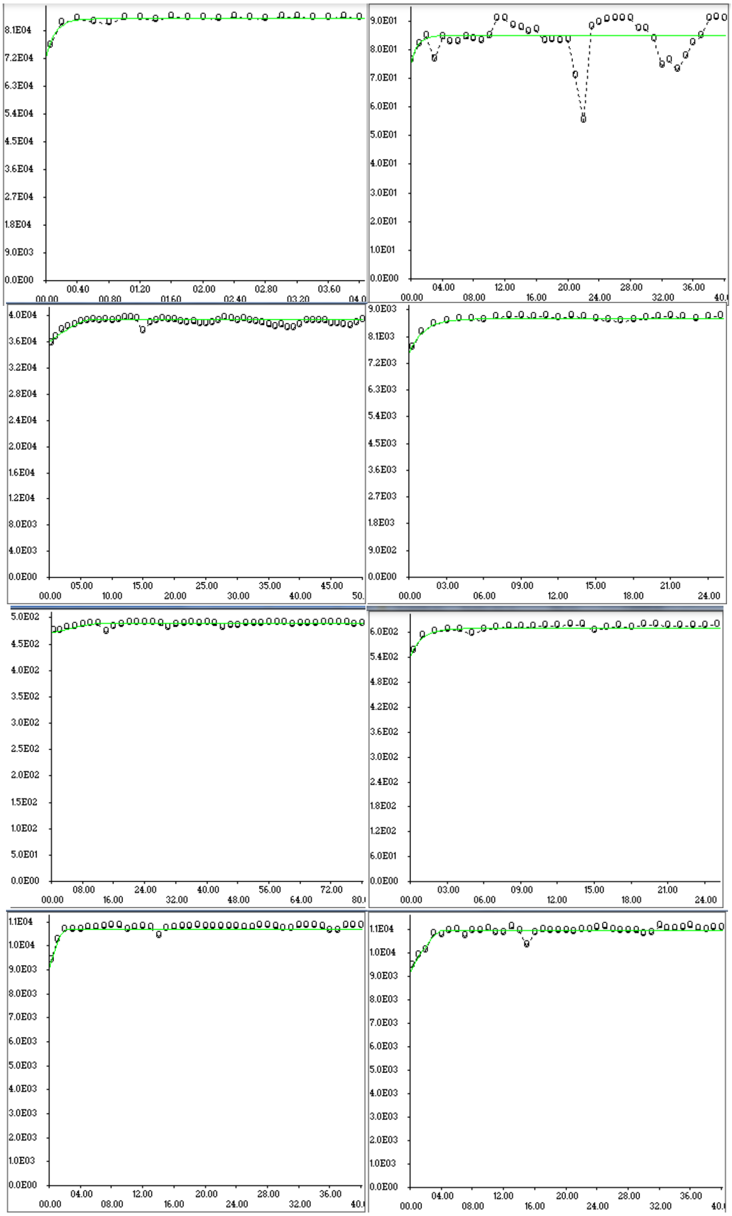

Figure 3-5. Covariograms of density of juvenile anchovy showing the spatial autocorrelation and the geostatistically obtained estimation variance of the annual biomass estimations. From top-left to bottom-right, years 2003 to 2010 are presented.

3.3.9 Ageing error

Finally, the variance associated to ageing process and partitioning of acoustic echoes into species was qualitatively assessed according to the results of previous otolith reading workshops. The otoliths exchanges revealed that the percentage of confusions between 0 group and older fishes was minor. The percentage of agreement between readers for the 0 groups was 100% in the 2009 and 2006 age reading workshops (ICES, 2010 and Uriarte *et al.*, 2007) and 97% in the 2001 age reading workshops (Uriarte *et al.*, 2002). This level of agreement is attributed to the relative simplicity of distinguishing juveniles (age 0) for adults (age >0) based on the presence of the annual ring, that has been recently confirmed by the application to the daily growth reading procedures. Therefore, even for the mixed areas the percentage of confusion should not be large. As the age composition was different for the two group of juveniles (mixed and pure, Figure 2-3), the errors were estimated independently for each. The ageing bias was considered zero and the random error was assumed to be zero in the pure juvenile area (due to the absence of adults practically in this area, Figure 2-3) and the bias was assumed zero and the random error 5% in the mixed area. The mean annual error was obtained as the average between areas weighted to the biomass per area.

3.3.10 Combination of errors

The combination of the correction factors and random errors lead to an updated juvenile anchovy biomass estimation with error bars. This is the biomass estimation that is now presented in the paper. From this, a signal to noise ratio (SNR) was calculated as the inverse of the average of the annual coefficients of variation (Schroeder, 1999).

The effect of these corrections was measured by computing the regression of the R index against the J index while incorporating each of the corrections both individually and all at the same time.

Table 3-2. Near field induced bias (in percentage) estimated per year and vessel-transducer for the 2003-2010 JUVENA temporal series. AZTI 1 and 2 are the purse seiners rented by AZTI, the number changes because of the change of transducer in year 2006. EB stands for Emma Bardan, the number changes because of the change of transducer after year 2008. The correction factor is obtained from these biases as: F= 1 + (bias/100).

Year	AZTI1	AZTI2	EB1	EB2
2003	0.05			
2004	0.01			
2005	0.04			
2006		0.04	0.76	
2007		3.86	0.01	
2008		0.27	0.06	
2009		0.34		0.16
2010		0.06		0.36

3.4 Results

3.4.1 Sampling interpolation

The spatial interpolation error obtained from the computed non-centered covariograms (Figure 3-5) showed cv values from about 17 % during the first three years, that decreased (to around 13%) with the reduction of the inter transect distance since year 2006 and further decreased with the expansion of the area of occupation of juveniles since 2009 (9.5%) and 2010 (7%).

3.4.2 Near field

The estimation of the near field showed the expected pattern (given the appearance of the near field in the echograms, Figure 3-1): low values, rapidly decreasing with range (Figure 3-3 and Figure 3-4). The NASC values at ranges higher than 5 m were smaller than 1 m2/nmi2 except for the year 2007, when they reached values of about 4 m2/nmi2, still a small percentage of even the weakest anchovy aggregations. The sum of the echointegration of the 5-11 m *range* (i.e., around the 7.5-13 m *depth*) layers provided an estimation of the near field bias for Method 2 (Figure 3-6, Table 3-2).

These are the corrections to be applied on each school found inside the near field. The application of these biases on the ESDUs that were integrating juvenile schools in the near field resulted in an average correction of less than 0.05% of the total biomass each year (with an annual maximum of 0.2 %, Table 3-3, Figure 3-7). On contrast, the application of the Method 1 (complete removal of backscattering from 5-11 m range) caused on average a loss of 20 % in the total annual biomasses (Table 3-3, Figure 3-7). Therefore, we would be ignoring almost 20% of the biomass if we were removing this layer for a really small (around 0.05 %) bias.

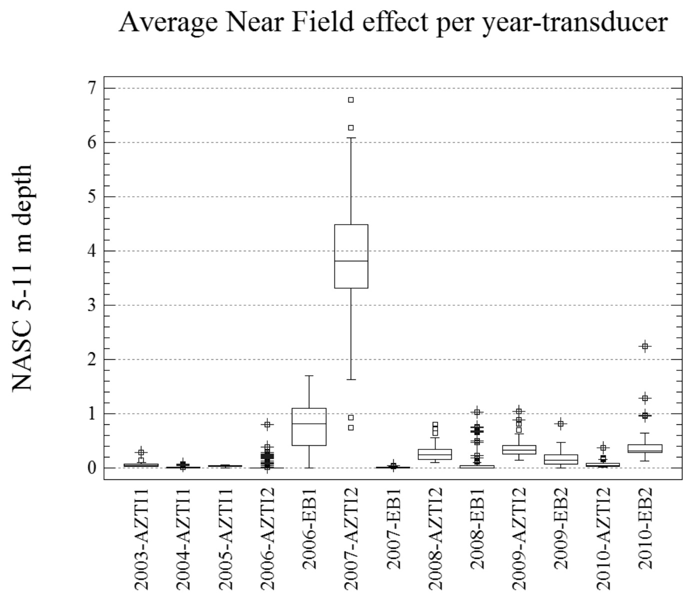

Figure 3-6. Near field bias estimated by year and vessel-transducer. For each year, and vessel this value was subtracted from the NASC of those ESDUs that included fish backscattering in the 7.5-15 m depth echointegration channel.

Table 3-3. Comparison of juvenile anchovy biomass obtained using the two different methods for dealing with the nearfield.

Year	Original estimates (December 2010)	Nearfield-corrected estimates (depth>7.5m)	Nearfield-removed estimates (depth>13m)	Final estimates (after applying all the corrections)
	(t)	(t)	(t)	(t)
2003	98,602	98,595	67,941	99,023
2004	2,499	2,499	2,137	3,471
2005	134,131	134,127	102,353	137,315
2006	78,299	78,298	70,255	82,277
2007	13,763	13,737	8,372	13,946
2008	20,879	20,877	17,027	22,946
2009	177,885	177,837	168,634	193,493
2010	599,990	599,821	528,250	626,196

3.4.3 TS at 120 kHz in a portion of year 2006

The optimization process provided an operative value of the 120 kHz TS of -74.1 dB for the 2006 data (Table 3-4). The error of the optimization process was 38%, which resulted in an error of about 2% of the total annual biomass that year.

3.4.4 Intercalibration of acoustic data between vessels

The results of the intercalibration exercises are presented in Table 3-5. In 2006, the intercalibration exercise showed a mean subestimation of 44.75% (25.6% cv) of one of the vessels respect to the other vessel. This result was caused by both the erroneous configuration of the 38 kHz transducer (pulse length of 256 µs, which is not enough to ensure a sufficient number of wavelengths for the 38 kHz transducer) and the effect of the bubble attenuation due to the small draft of the new vessel, the R/V Emma Bardán. An average factor of 1.81 was applied to correct the bias to the data acquired by the incorrectly configured vessel. Therefore, the correction, included in our report of the 2006 estimate, resulted in an overall 53% increase of the original biomass estimate.

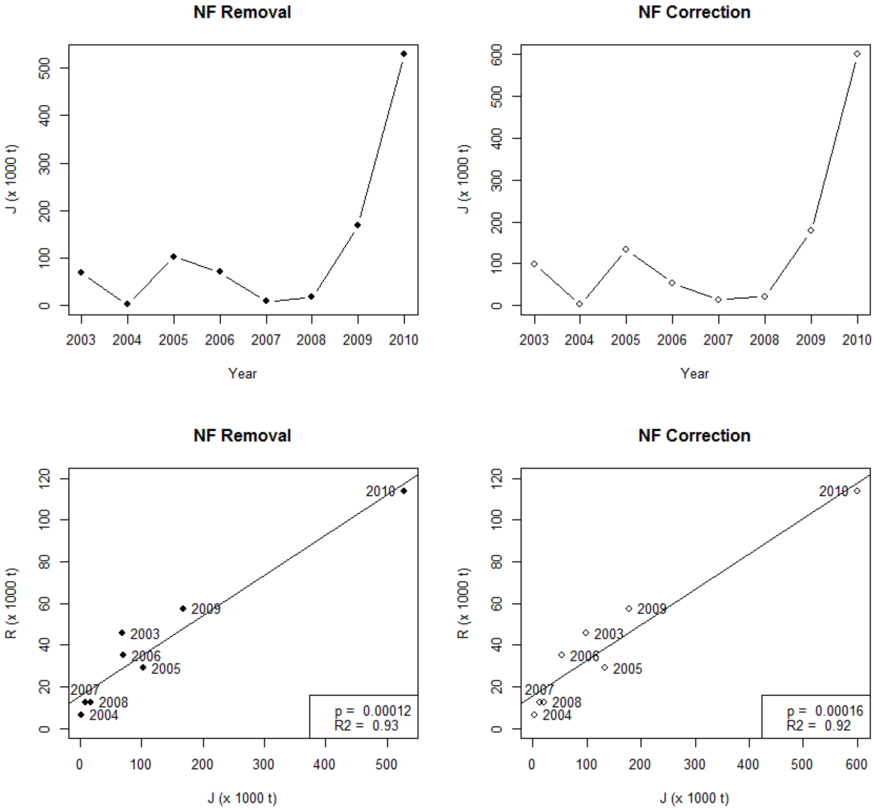

Figure 3-7. Comparison of methods for dealing with integrating part of the near field of the 38 kHz transducer. Top: temporal series of biomasses of juvenile anchovy after near field removal (left) and correction (right). Bottom: scatterplots of juvenile (year=y) against recruits (year=y+1) indices after near field removal (left) and correction (right).

Table 3-4. Selection of strata used in the optimization process for the TS values at 120 kHz. NASC values as well as the biomass estimates at both frequencies are shown for each stratum.

Stratum	Zone	s_A 38	s_A 120	Biom38	Biom120
1	Oceanic	152,51	89,66	1.773	1.976
2	Oceanic	34,65	119,19	1.473	1.688
3	Oceanic	458,57	136,76	5.682	5.847
4	Oceanic	311,23	93,89	423	380
5	Oceanic	274,69	40,54	509	216

For the rest of the years, the pulse length of the R/V Emma Bardán was set to 1024 µs and its speed was reduced (or, when necessary, the sampling suspended) in rough weather conditions to decrease the bubble attenuation caused by the motion of the vessel. The successive comparison between the commercial and oceanographic vessels in subsequent years showed differences in acoustic acquisition of around 10% that caused slightly smaller than 10% biomass corrections.

3.4.5 Horizontal (> 46ºN) coverage in years 2003-2004

The latitudinal distribution of the relative abundance of juveniles from 2005 to 2009 (i.e., the years when the northern coverage was extended, Figure 2-6) shows that the error that can be expected from this limitation is on average about 15%. Nevertheless that error was probably smaller: In 2003 there was a clear decrease in juvenile abundance in the region between 45º and 46º N. This area comprised 1% of the total abundance that year, which suggests that a small amount of juveniles would have been found above the unsampled northern limit. In 2004, the decrease in juvenile abundance towards the north was also supported by an empty transect at the most northern limit of the surveyed area. In addition, the very low juvenile abundance in 2004 was consistent with the recruitment failure that led to the collapse of the fishery the following year (2005). According to these considerations, the horizontal coverage of years 2003 and 2004 was assumed to be sufficiently complete and unbiased, as to be consistent with the rest of the temporal series, and only the contribution of the CV to the global uncertainty of the temporal series was considered; i.e., the horizontal coverage was estimated to cause a zero systematic error (bias) but a non-zero random error contribution.

Table 3-5. Correction factors and uncertainties obtained in the intercalibration exercises (rows 1-4) and propagation of these errors to the annual biomass estimates (rows 5-9). The length of each ESDU is 0.1 n.mi.

	2006	**2007**	**2008**	**2009**	**2010**
F_{int}	1.81114	1.026172	1.100324	1.128546	1.066696
MAD_{int}	0.469725	0.290786	0.2808014	0.3729459	0.4034706
CV_{int}	0.25935323	0.28336965	0.25519883	0.33046584	0.37824329
N_{ESDUs}	295	300	355	468	296
B_{EB}	49571.5227	8712.02613	22689.8169	132614.388	420696.08
B_{AZTI}	26101.0257	4609.22171	255.94469	60437.637	213378.798
B_{Tot}	75672.5484	13321.2478	22945.7616	193052.025	634074.878
F_{int}^{Tot}	1.53136105	1.01711635	1.09920495	1.08830288	1.04425147
CV_{int}^{Tot}	0.16989694	0.18532226	0.25235226	0.22700888	0.2509569

3.4.6 Vertical (> 45 m) coverage in years 2003-2005

The mean estimated biomass at depths higher than 45 m (approximately the range of the purse seine) was on average 11% of the total (Figure 2-6) with a 10% cv. However, as the proportion of juvenile anchovy deeper than 45 m is different in the pure juvenile (Figure 2-7-bottom) and the mixed juvenile's areas, the correction was applied by areas. Therefore, the correction applied to pure juvenile population was assumed zero (with zero uncertainty) and the correction applied to the mixed juvenile area was 39% (cv=44%). The resulting correction factors for the biomass estimates of years 2003-2005 were respectively: 0.4, 39 and 2.4%, with coefficients of variation: 0.5, 43.5 and 2.7 %. The highest correction was applied to year 2004 in which most of the biomass was in the mixed juvenile area.

3.4.7 Vertical (<7.5 m) coverage

The continuous decreasing tendency from 15 to 7.5 m (Figure 2-6-bottom), the fact that apparently no schools were observed beginning to form at 7.5 m (Figure 2-7) and the lack of much space upwards to make schools makes more likely that the decreasing tendency will continue towards the surface Our concern with this issue along the surveys made us stay alert to possible superficial losses of juveniles. Thus we systematically inspected the upper layers of 120 kHz echograms. And the fact is that after nine years, only once, in a single area of particularly shallow distributed strata in 2007 we detected substantial amounts of schools out of the 38 kHz range. The percentage of biomass lost by these “substantial” amounts of out of range schools was less than 0.5% of the total so we finally discarded the correction analysis in this version of the manuscript as non-important. Also, according to the decreasing mean depth of smaller size classes, the out of range juveniles would be of the smallest of the stock and thus less likely to survive. So, although all this doesn’t assure you that the tendency from the surface to the end of the near field remains decreasing, everything tends to indicate that a small effect is expected.

3.4.8 Echogram scrutinizing error

In the strata located in the pure juvenile area, where the bulk of juvenile anchovy is found, the proportion of juvenile anchovy individuals was invariably more than 90% over the rest of the species captured in the pelagic trawling. This includes salps and jellyfish in the strata where these species were included in the assessment (which were scarce, as in most cases the plankton layers were undetectable at -60 dB). Thus, normally, the juvenile schools were the only acoustic targets in the echograms (see the document “Sample echograms.doc”).

Table 3-6. Summary of biases (b) and coefficients of variation (CV) in percentage associated with the potential methodological issues in JUVENA series of surveys. The correction factors are obtained from the biases as: F=1 + (b/100).

	Geost		**Near Field**		**Intercalib**		**Horiz cov.**		**Vert. Cov.**		**120 kHz**		**Ageing**		**Tot**	
Year	**b**	**CV**	**b**	**CV**	**b**	**CV**	**b**	**CV**	**b**	**CV**	**b**	**CV**	**b**	**CV**	**b**	**CV**
2003	0	18	-0.01	0	0	0	0	8	0.44	0.49	0	0	0	0.06	0.43	26.6
2004	0	17	0	0	0	0	0	8	38.9	43.5	0	0	0	4.99	38.9	73.5
2005	0	18	-0.00	0	0	0	0	0	2.38	2.66	0	0	0	0.31	2.38	21
2006	0	13	-0.00	0	53.1	17	0	0	0	0	2	30	0	3.97	55.1	64
2007	0	14	-0.19	0.29	1.71	18.5	0	0	0	0	0	0	0	2.8	1.52	35.6
2008	0	13.5	-0.01	0.01	9.92	25.2	0	0	0	0	0	0	0	2.84	9.91	41.6
2009	0	9.5	-0.03	0.02	8.83	22.7	0	0	0	0	0	0	0	1.61	8.8	33.8
2010	0	7	-0.03	0.03	4.43	25.1	0	0	0	0	0	0	0	0.27	4.4	32.4

In the mixed juvenile strata, the proportion of anchovy was not predominant over the rest of pelagic fish species. Here, the assessment relies more on the multispecies echointegration factor (Simmonds and Maclennan, 2005), which includes a wider variety of species than in the pure juvenile areas, and the uncertainty is believed to be higher than in the pure juvenile area but of a similar range as in the typical multispecies acoustic surveys. Concerning the presence of plankton in the mixed juvenile areas, the case is easier than in the pure juvenile areas because anchovy in this area tends to stay in deep waters, thus vertically separating from the plankton layers.

In general, the main species found in company of juvenile anchovy were salps in the pure juvenile's area and jellyfish (*Pelagia noctiluca*) in the mixed juvenile area. A preliminary analysis of Pairovet, Mik and Bongo hauls from this survey and Bioman (conducted in spring) evidenced a much lower abundance of syphonophores in the Bay of Biscay in autumn than in spring (a difference of two orders of magnitude).

The uncertainty associated with species identification has not been properly calculated, as the present analyses were focused mainly in the special methodologies and assumptions of the JUVENA survey and this error is believed to be, in the worst case, of the same range as in the typical multispecies acoustic survey. In the near future we plan to use frequency response-based algorithms to facilitate automated species identification, especially to separate between juvenile anchovy and plankton layers.

3.4.9 Ageing error

Finally, the mean error associated with the age assignation was 2.1%. This error was higher (up to 5%) in years of higher proportion of mixed juvenile population and lower (less than 1%) in years of higher proportion of pure juveniles.

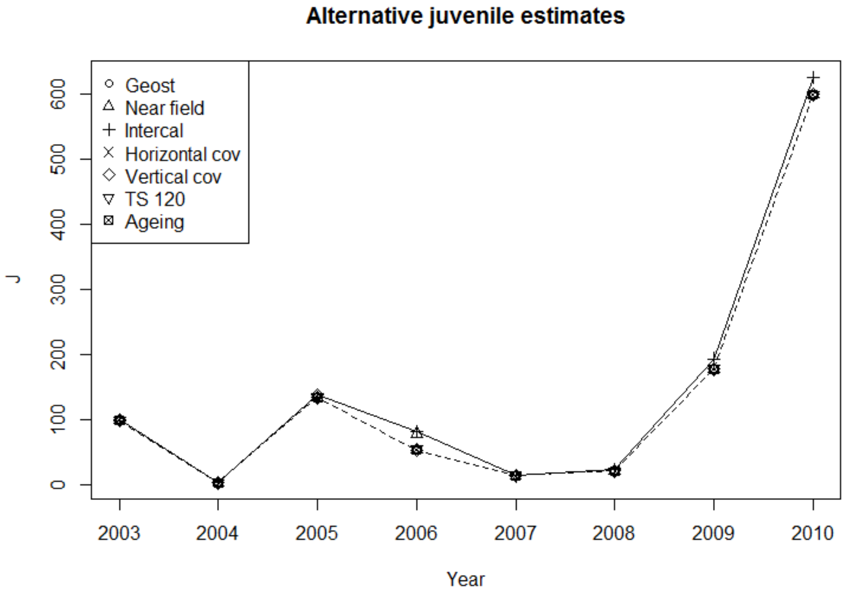

Figure 3-8. Alternative juvenile biomass estimates (in t) according to the estimated correction factors. The continuous line shows the definitive juvenile biomass estimation and the dashed line the uncorrected one. The plot highlights the small difference between the estimates due to the correction factors. The highest increase is found in year 2006 (53%) due to the high intercalibration correction factor.

3.4.10 Combined uncertainty-SNR

The estimated bias and errors are presented in Table 3-6 and the effect of the correction on the biomass estimates is shown in Figure 3-8. The combination of all these error estimates provided a final corrected juvenile anchovy biomass along with uncertainty intervals (Figure 3-9). The computed SNR was 2.57, meaning that, on average, the level of the relevant signal (the magnitude of the juvenile index) is more than twice the level of the uncertainty.

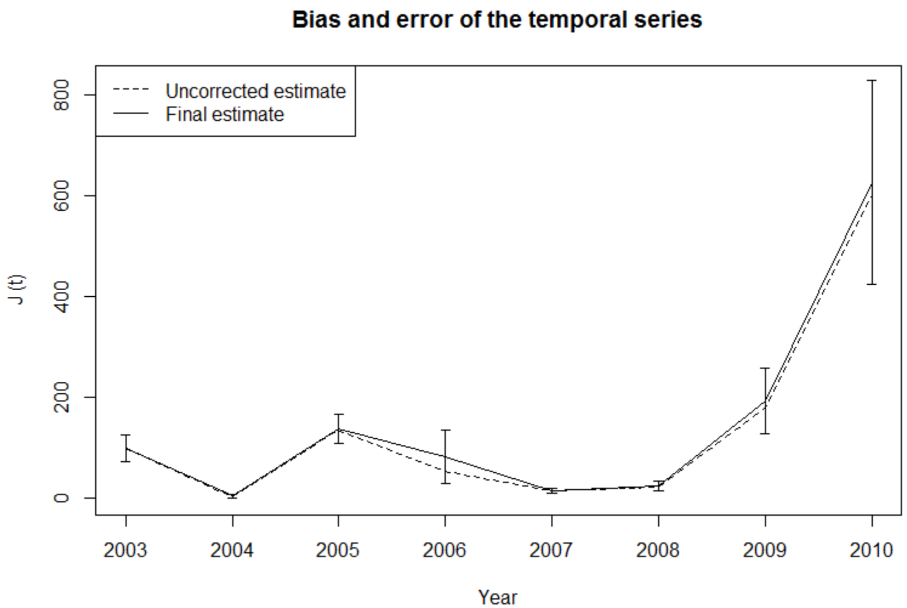

Figure 3-9. Uncorrected versus final juvenile biomass estimates. The difference between the two series shows the cumulative bias correction factors; and the error bars, the cumulative random error. The considered sources of error include geostatistical interpolation error, near field, TS at 120 kHz in 2006, intercalibration, horizontal coverage, vertical coverage and ageing.

The application of all these corrections either one by one (Figure 3-9) or all at the same time (Figure 3-10 and Figure 3-11) produced no incidence in the recruitment prediction capabilities, which reminded unchanged, i.e., highly significant in all the cases and with determination coefficients around 90%.

The various uncertainty calculations developed in this work provided biomass estimates with error bars. However, it must be noted that these error estimations do not cover the full range of sources of uncertainty involving an acoustic biomass estimate, as mainly the uncertainty associated with the particular assumptions and methodologies used in these surveys were quantitatively estimated in this work. Some uncertainties, as TS-related errors, were not considered, and some others (as the ageing errors or the species identification) were rather qualitatively assessed.

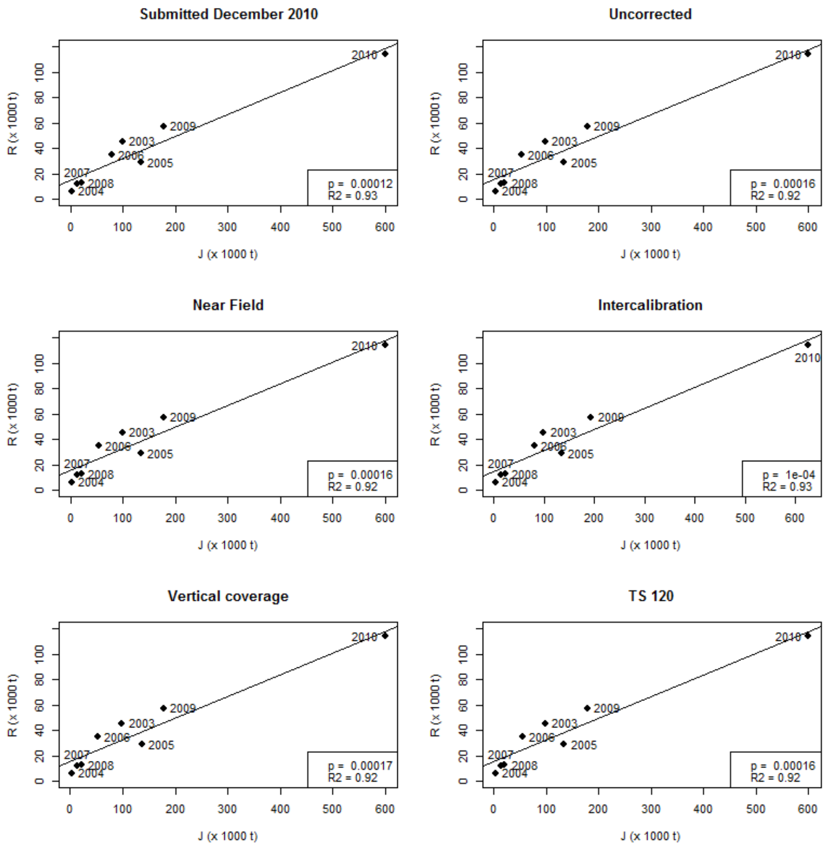

Figure 3-10. Scatterplots of recruitment (R) against juvenile (J) index obtained with of the alternative biomass estimates including the various correction factors independently.

In general, the uncertainties are considered to be substantially lower in the offshore areas than in the inshore ones. This is due to the fact that in the former, the bulk of the population is isolated from other species or anchovy adults, allowing for a less uncertainty in the identification of species and echogram scrutiny. In particular, the ageing error in this region is assumed zero as the percentage of age-0 is practically 100% (Figure 2-2). This tends to support the convenient concept of sampling juveniles in this particular temporal window, when the bulk of the population is still located in the offshore grounds (Figure 2-5-top) allowing more precise biomass estimations.

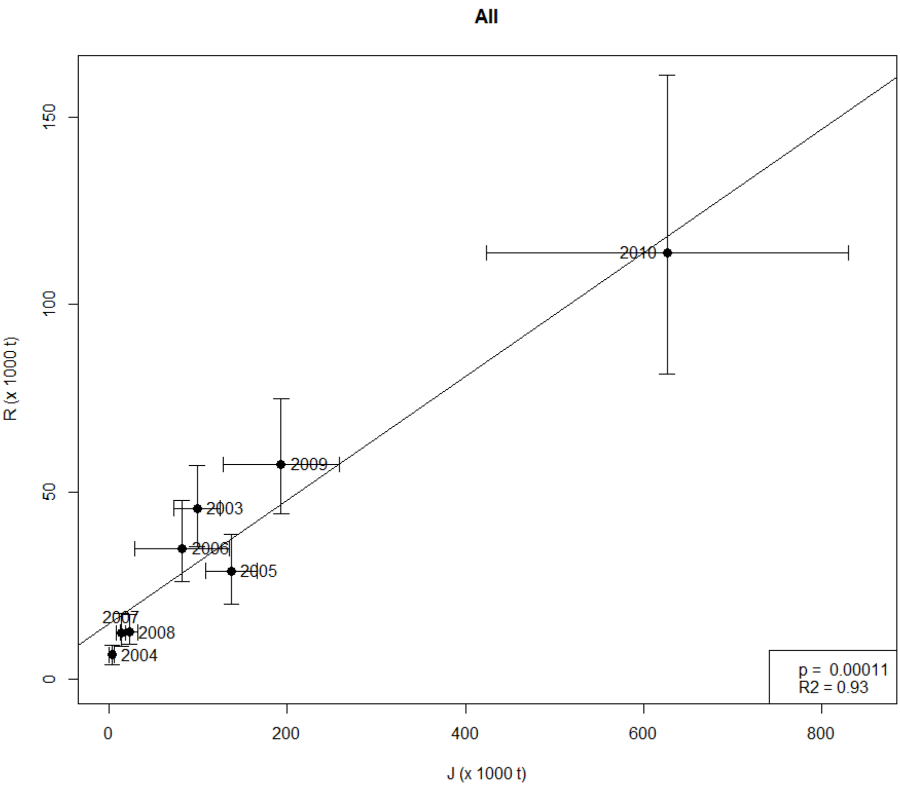

Figure 3-11. Scatterplot of recruitment (R) against juvenile (J) index for the definitive juvenile biomass estimation (including all the correction factors) against recruitment biomass estimations with error bars.

In addition to all these results, the direct relationship between the juvenile index and the indices of abundance of the individual surveys that are used to obtain the BBM index (Bioman, the DEPM survey conducted by AZTI and Pelgas, the acoustic survey conducted by Ifremer) was also checked (Figure 3-12). Both relationships were also positive and highly significant.

3.5 Discussion

3.5.1 Near Field correction

The effect of the application of the near field correction on the annual biomass is so small that the recruitment predictive capability of the near field corrected juvenile index is virtually identical to the uncorrected one ($R2=0.92$, $p=0.00016$; Figure 3-10). This result was not surprising given the invisibility (and hence low value) of the echo-integrated near field at the -60 dB operative threshold. The recruitment predictive capability of the juvenile index after near field removal, despite resulting in a reduction of about 20 % of the biomass each year, doesn't substantially change the relationship between juvenile and recruitment indices (in fact, it improves a little bit, R2 increasing from 0.92 to 0.93). Nevertheless, we preferred to build and index which contains the most complete information, and, given the low value of the bias committed in relation to the signal, the near field corrected estimate is proposed as the best one. Consequently, we opted for correcting the bias (Method 2) rather than removing the whole layer (Method 1), and as such the correction of the near field is included in the definitive biomass estimates of the manuscript.

3.5.2 Spatial coverage

A major challenge for the JUVENA surveys was to achieve good coverage of most (if not all) of the spatial distribution area of juvenile anchovy. Overall, it seems that the horizontal coverage was successfully achieved basically thanks to the innovative survey design: First, the minimum sampling area defined for the survey corresponded to the core of the juvenile distribution because it contained on average about 88% of the juvenile biomass across the whole series of surveys;

furthermore, this area was amply expanded in most of the years since 2006. Second, the adaptive sampling scheme seems to have efficiently defined the boundary limits towards the offshore oceanic waters and towards the north. And third, the epipelagic (Figure 2-6-bottom) and eventually the coastal (Figure 2-1) distribution of juvenile anchovy was taken into account due to the small draft of the chosen vessels (Table 3-2), the close-to-the-surface installation of the transducers and the specific procedure developed to echointegrate part of the near field range.

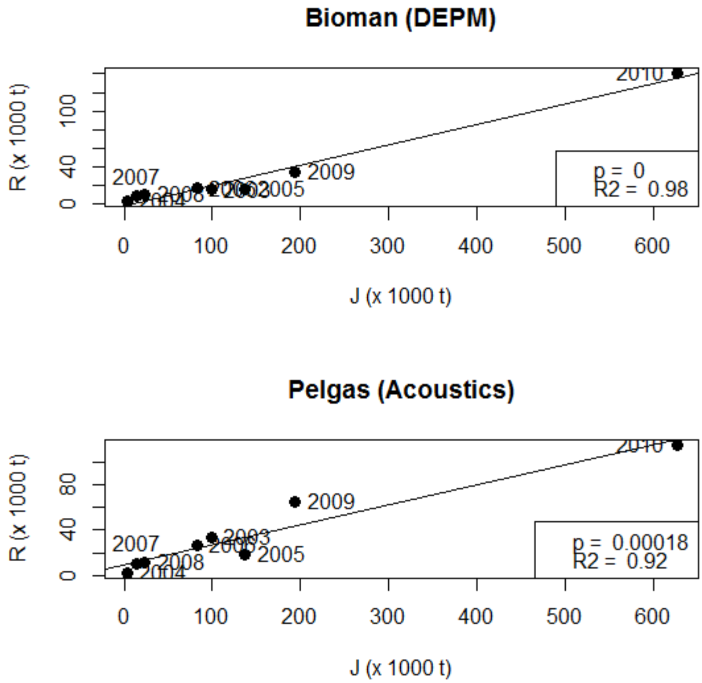

Figure 3-12. Scatterplot of the juvenile index (at year y) against two different direct recruits indices (at year y+1): the index obtained by the DEPM survey "Bioman" (top) and the index obtained from the acoustic survey "Pelgas" (bottom).

Extensive, complete coverage was generally achieved each year, following the planned sampling scheme, and a positive area was consistently defined by the adaptive sampling scheme. This was in agreement with the concurrent information provided by the tuna fishing fleet, which did not detect large amounts of juveniles outside the sampled areas during these surveys.

In the northern area, the coverage was also generally reliable. It fulfilled the requirements of the planned sampling scheme as it recorded clear decreases in abundances or if possible covered a transect in which no anchovy were detected as a way of determining the limit of the juvenile distribution area. Even in the years with reduced northern coverage (2003 and 2004) the potential limitations were not considered important due to the satisfactory application of the adaptive scheme (see below). However, because the limited fishing range in 2003-2005 in this area (due to only using purse seiners) was likely to produce some underestimation of the juvenile biomass detected over the shelf, the estimated juvenile biomasses over the shelf in these years were corrected according to the fraction of biomass over the shelf areas observed at depths greater than 45 m in the years in which the pelagic trawler was available (see below).

In terms of the sampling strategy, it is generally accepted that a systematic strategy is preferable to an adaptive one (Simmonds and Maclennan, 2005) because it avoids potential estimation biases. In our case, the addition of the second vessel in 2005 enlarged the survey coverage (Figure 2-1; Table 2-1), which allowed us to change from an adaptive to a more (although not completely) systematic sampling strategy. Nevertheless, given the huge extension of the potential occupation area of juveniles and the satisfactory performance of the adaptive sampling scheme, we believe that the adopted strategy provides a reasonable compromise between surveying capacity and costs. However, the expansion of the area of occupation in the most abundant years (2009 and 2010) offshore and towards the north is continuous, without gaps from the start of the area to its end in deep oceanic waters (Figure 2-2). This suggests that the chosen adaptive scheme of enlarging transects until several nautical miles after anchovy are no longer detected is an appropriate strategy for efficiently assessing the bulk of the juvenile anchovy in the Bay of Biscay. Finally, the concurrent information collected from the tuna fishing fleet did not reveal any other areas where juveniles concentrate outside those surveyed in these years.

3.5.3 Species identification

Another key methodological issue of the acoustic survey is to correctly identify species. The bulk of juvenile anchovy biomass has been confirmed to be found in isolation from adult anchovy and other pelagic species in the pure juvenile aggregations in the off-shelf grounds (in agreement with Uriarte et al., 2001) except for occasional small numbers of juvenile horse mackerel; this therefore minimizes the uncertainties of fish identification for the acoustic biomass estimates. Anchovy were also occasionally found in the company of gelatinous plankton, but in lower proportions than observed in the previous JUVESU survey (Uriarte et al., 2001). This difference may be caused by the low efficiency of the gear used to fish juvenile anchovy (which had difficulties to fish at the surface) in the previous survey. In the catches of our survey the ratios of captured gelatinous to juvenile anchovy individuals were less than 3% for jellyfish and 5% for salps. The generally small quantities of plankton captured and the lower TS values of jellyfish and salp (Wiebe et al., 2010; Stanton et al., 1994; David et al., 2001; Alvarez-Colombo et al., 2003) resulted in clean juvenile anchovy echograms at -60 dB (Figure 2-7) that were not likely to have significant scrutinization errors. The more problematic resonant scatterers (Mair et al., 2005), such as gas-bearing syphonophores, observed in this region during the plankton bloom in spring surveys have generally disappeared by the late summer season. Therefore, in summary, the general predominance of juvenile anchovy in the off-shelf areas and the high signal-to-noise ratio of the echograms made allocating the acoustic backscatter records to species easier and more accurate than in an ordinary multi-species acoustic survey.

3.5 Conclusions

The potential error sources of the methodology employed were analyzed, and the findings were used to correct the abundance estimates. The most relevant errors examined were the ones related to the intercalibration of vessels, the echointegration of part of the near field and the spatial coverage. In general, the main uncertainties involved in the biomass assessment, especially those related with the various assumptions and methodological issues along the temporal series of JUVENA surveys, have shown to have a small impact in the main objective of the survey (provide an early indicator of recruitment) given:

(i) the high SNR of the random uncertainties estimated (2.5);
(ii) the small difference between alternative estimates compared to the difference between annual biomass levels, and:
(iii) the highly significant prediction capability of the JUVENA index for all the alternative juvenile biomass estimates (uncorrected or with any of the proposed corrections).

The survey thus seems to have achieved sufficient and consistent coverage of the bulk of juvenile anchovy biomass every year. Therefore, the JUVENA index can be considered as a consistent time-series of juvenile anchovy abundance indices in the Bay of Biscay, and has been considered as such by ICES (2012). Nevertheless, we will continue to re-test these relationships each year and to report them to ICES through the appropriate working forums (WGANSA and WGACEGG).

3.6 Publication data

Type	Supplementary material
Article	Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. ICES Journal of Marine Science, 70: 1354–1368.
Title	Uncertainties and alternative estimates of the JUVENA index according to its special methodology and assumptions.
Authors	Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A.
Pages	31 pp.


3ª SS-1-2-05

Foto: Cerquero Itsas Lagunak en JUVENA 2006 (Fuente: propia).

Chapter 4

Update of the temporal series: Juvenile anchovy acoustic surveys JUVENA 2003-2015

Actualización de la serie temporal: Campañas acústicas de anchoa juvenil JUVENA 2003-2015

Este capítulo presenta la actualización del índice de reclutamiento y la evaluación de su capacidad predictiva empleando hasta cinco años más de estimas de juveniles y reclutas, entre los que se contaban el máximo de la serie temporal hasta el momento que certificó la recuperación de la ancho del Golfo de Vizcaya. Se repitieron los análisis de modelos de regresión aplicados en Boyra et al 2103, ampliando el número de años. Se describe y discute asimismo la integración del índice JUVENA en el consejo científico de gestión a partir del año 2014. Por último, se incluye un Addendum (no presente en el artículo original) con la actualización de la serie temporal hasta el año 2016 y detallando el uso de JUVENA en el nuevo sistema de gestión CBBM. Los datos referidos en el Addendum están publicados en los informes al grupo de trabajo ICES WGACEGG correspondientes a los años 2012-2016.

4.1 Abstract

The present work presents the update of the index of recruitment based on the acoustic estimates of juvenile anchovy in the Bay of Biscay provided by the JUVENA survey, after the inclusion of two more years of surveys. The main aim of these surveys was to test whether the abundance of juveniles in autumn constitutes a reliable indicator of the strength of recruitment to the adult stock each year in the Bay of Biscay. The hypothesis has been confirmed by the significant positive correlations between the biomass estimates of juveniles and the next year's age-1 recruits. Boyra et al (2013) showed that there exists a significant correlation between juvenile and recruitment indices, thus supporting the reliability of the JUVENA index to anticipate abundance trends in the Bay of Biscay anchovy. In the present work, after the addition of two more recruitment years, the correlations between juvenile and recruitment are still significant, further supporting the validity of the JUVENA index. Since year 214, the JUVENA index forms part of the new CBBM synthetic abundance index used by ICES to manage the anchovy fishery.

4.2 Introduction

In the Bay of Biscay, the management of anchovy fishery relies on an annual estimation of abundance based on the information provided by the spring acoustic and DEPM surveys plus the annual catches of the fishing fleet (ICES, 2011). This approach has been applied since the late eighties and has become a well-established and robust time series. However, this annual estimation of abundance is provided at the end of the spawning season, when a significant part of the annual anchovy fishery has already ended, thus limiting the potential effectiveness of the management measures.

A succession of low recruitments since 2001, that eventually caused the closure of the fishery from 2005 to 2009, highlighted the need for an early indication of recruitment strength in order to improve management (Barange et al. 2009). With this purpose in mind, an acoustic survey (JUVENA) for estimating the abundance of juvenile anchovy in early autumn was set up following methodologies derived from the European project JUVESU (Uriarte 2002; Carrera et al., 2006). The objective of the survey was to use the juvenile abundance estimate as an indicator of the abundance of recruits that will enter the adult stock the following year.

Table 4-1. Summary of sampling effort

Year	Survey start	Survey end	Nb of vessels	Survey time (days)	Fishing operations	Anchovy-positive hauls	Inter-transect distance (nmi)	Sampled area (nmi^2)	Positive area (nmi^2)
2003	18-sep	14-oct	1	20	47	36	17.5	16,829	3,476
2004	19-sep	19-oct	1	18	21	9	17.5	12,736	1,907
2005	12-sep	07-oct	2	20	47	45	17.5	25,176	7,790
2006	13-sep	14-oct	2	42	80	52	15	27,125	7,063
2007	04-sep	30-sep	2	37	70	40	15	23,116	5,677
2008	26-ago	25-sep	2	33	85	46	15	23,325	6,895
2009	26-ago	25-sep	2	39	67	42	15	34,585	12,984
2010	01-sep	30-sep	2	40	79	60	15	40,500	21,110
2011	01-sep	05-oct	2	40	77	64	15	37,500	21,025
2012	02-sep	05-oct	2	40	67	51	15	31,500	14,271

4.3 Material and methods

The JUVENA surveys were carried out annually from 2003 to 2012 between September and October in the Bay of Biscay (Table 4-1) following an acoustic methodology specifically designed to sample juvenile anchovy (Boyra et al., 2013). Among other particularities, an adaptive sampling strategy was chosen, using a combination of two small vessels (instead of the, more commonly used, single larger vessel) to allow more flexible coverage of the potentially variable and close-to-surface sampling area (see Annex 1.3 and Boyra et al., 2013 for details). Also, the biological sampling and fish species identification was based on commercial purse seining (highly efficient for juvenile anchovy but also highly selective) in the first years of the survey, and incorporated pelagic trawling since year 2006 (see Table 4-2 for vessel characteristics and equipment employed in each survey).

Since the addition of the second vessel, inter-calibration exercises were carried out each year. The inter-calibration process consisted in comparing the echo-integrated acoustic backscattering of the water column and the bottom echo in areas with a smoothly variable seafloor. A minimum distance of 30 nmi was covered simultaneously by the two vessels for these exercises. The NASC values (Maclennan et al., 2002) obtained by the layer echo-integration of both the water column and bottom echoes obtained by the two vessels were compared to detect recording biases or other potential problems.

In general terms only the 38 kHz data were echo integrated using the TS-length relationships agreed in ICES WGACEGG for the main species (ICES, 2006; Table 4 2). Acoustic data were converted to biomass using the information from the hauls and following standard procedures (see Boyra et al. 2013 for details).

Each fishing haul was classified into species. A random sample of each species was measured to determine the length frequency distribution of the different species. Complete biological sampling of anchovy was performed to analyze age, size and the size-weight ratio. The hauls were grouped by strata of homogeneous species and size composition. The species and size composition of each homogeneous stratum were obtained by averaging the composition (in numbers) of the individual hauls contained in the stratum weighted to the acoustic density in the vicinity (2 nmi diameter). This species and size composition of each stratum was used to obtain the mixed species echointegrator conversion factor (Simmonds and Maclennan, 2005) for converting the NASC values of each ESDU into numbers of each species. However, although the methodology involved estimating multiple species, the survey strategy was focused strongly on juvenile anchovy and only the positive areas for anchovy were processed. Therefore, only estimates of this species were considered reliable and thus produced.

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Anchovy juveniles (age=0) and adults (age ≥ 1) were separated and treated as different species. To separate juveniles from adults, the length frequency distribution of anchovy by haul was multiplied by a corresponding age-length key. The key was determined every year for three broad areas: the pure juvenile area, the mixed juvenile area (with a mix of juveniles and adults), and the Garonne river area (located at the coastal area around 45º40' N; also a mixed area but here adult anchovy were usually smaller than in the other areas). Finally, the abundance in numbers of juveniles and adults was multiplied by the mean weight to obtain the biomass per age and length class for each ESDU.

Table 4-2. Vessels and equipment (*Purse seiner names: Divino Jesus de Praga (2003), Nuevo Erreñezubi (2004), Mater Bi (2005), Gure Aita Joxe (2005, 2008), Itsas Lagunak (2006, 2007, 2009, 2010 and 2011); pelagic trawler name: R/V Ramón Margalef (2012). **The 200 kHz transducer has been available on board purse seiners since 2007. ***TS of the mean pelagic species. The TS is obtained according to the relationship TS = b20 - 20log(L), where L is the standard length of the fish in cm.

			Vessel 1	Vessel 2
Vessel	name		Variable vessel*	Emma Bardán
	Length (m)		30-35	27
	Side (m)		8	7
	Draft (m)		3.5-4	3.5
	Acoustic installation		side perch	hull
Acoustic Equipment	Transducer frequencies (kHz)		38,120, (200)**	38,120,200
	Power (for 38, 120, 200 kHz) (W)		1200, 250, (210)**	1200, 250, 210
	Pulse duration (10^{-6}s)		1024	1024 (except in 2006: 256)
	Ping interval (s)		0.25 - 0.5	
Target Strength (b_{20})* **	*Engraulis encrasicolus* *Sardina pilchardurs* *Sprattus sprattus*	-72.6 dB	Degnbol et al. (1985)	
	Trachurus trachurus *Trachurus mediterraneus* *Scomber japonicas*	-68.7 dB	ICES (2006)	
	Scomber scombrus	-88 dB	Clay and Castonway (1996)	
	Jellyfish (mean TS)	-81.7 dB	Average TS for jellyfish species in Simmonds and Maclennan (2005)	
Fishing gear	Pelagic trawl	nº of doors		2
		vert opening		15
		Mesh size (mm)		4
	Purse seine	Depth	75	
		Perimeter	400	
		Mesh size (mm)	4	

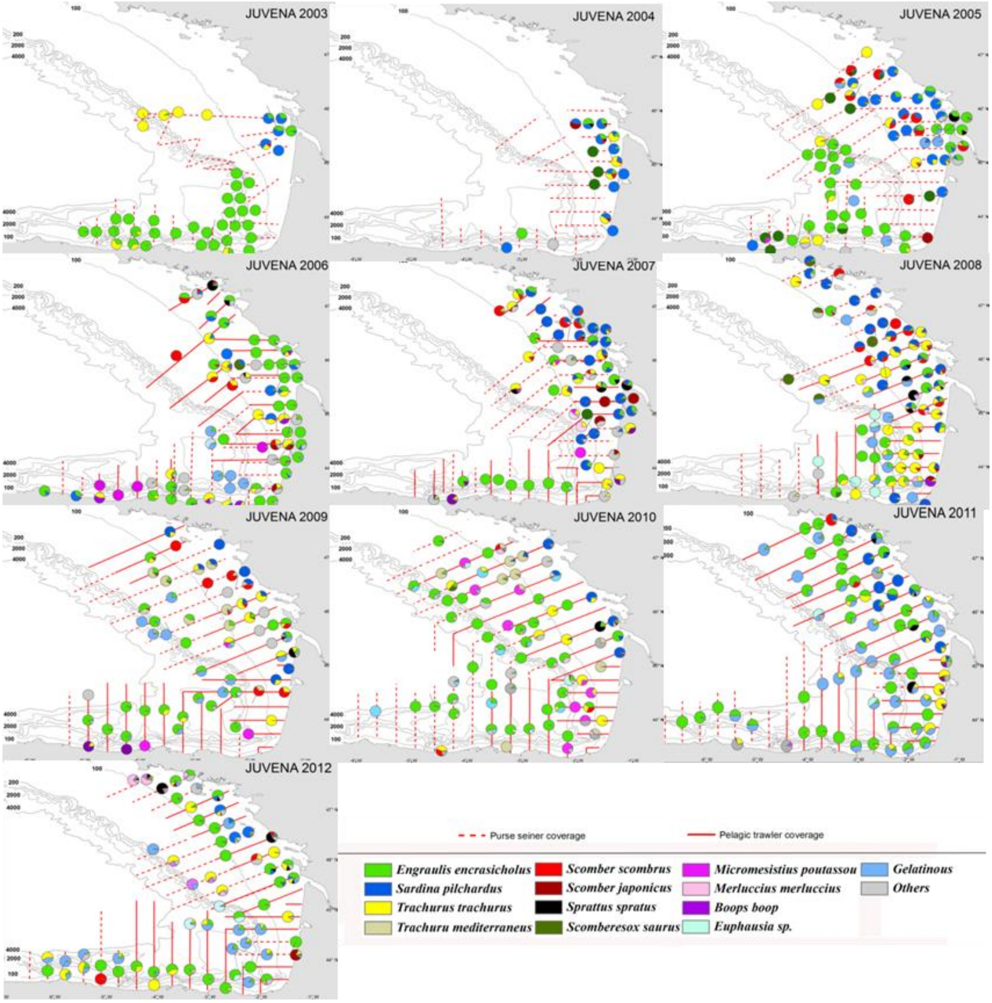


Figure 4-1. Sampling design and species composition of the hauls of JUVENA 2003-20012 surveys.

Juvenile anchovy showed a near-surface distribution during the JUVENA survey period (Uriarte et al. 2001). In order to achieve the best possible coverage of the vertical distribution of this species, in the JUVENA surveys we started the echointegration at a range of 5 metres from the transducer face (i.e., 7.5 m depth from the sea surface) rather than the 10.5 m (13 m depth) recommended to avoid integrating the near field of the 38 kHz transducer (Simmonds and Maclennan, 2005). Instead of ignoring these first layers, we estimated the bias produced by the near field in the 7.5-15 m echointegration channel and corrected for it in the biomass estimates. The details of this analysis are explained in Boyra et al. (2003).

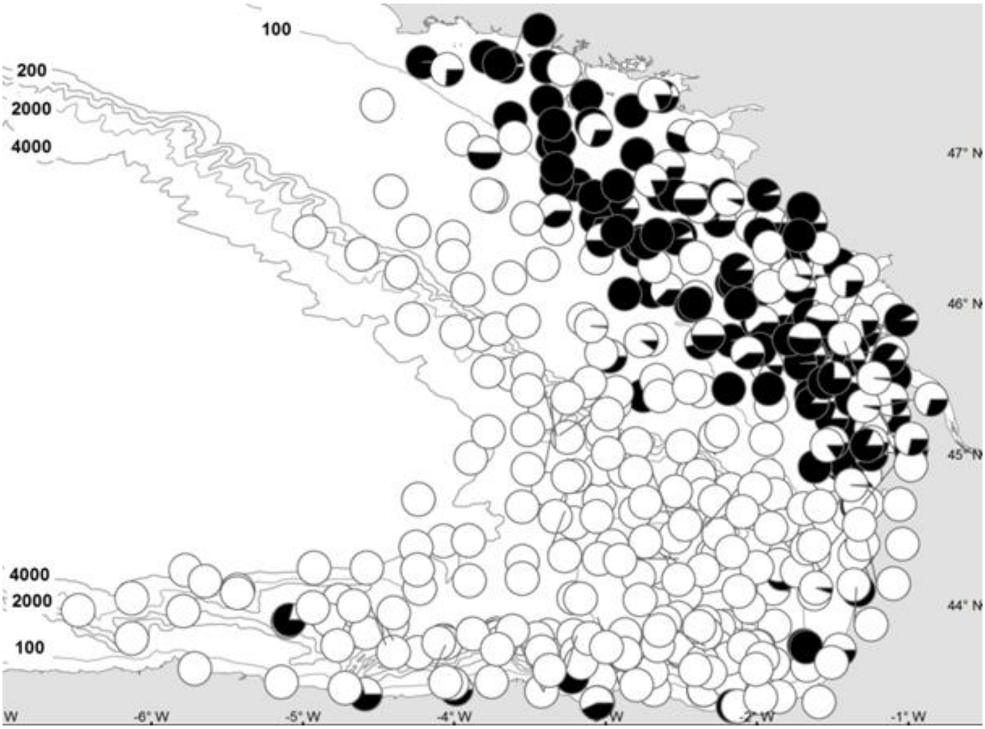


Figure 4-2. Age composition of anchovy for the ten years of the survey. The pie charts represent the mean percentage of juveniles (white) and adults (black) of the fishing hauls at each fishing site.

Yearly maps of anchovy NASC values by ESDU along the survey transects plus SST based on the CTD casts were produced. Also, in order to estimate the recruitment predictive capability, the annual biomass estimates for anchovy juveniles were compared with the estimates of anchovy recruitment the following year. The recruitment is the biomass of age-1 anchovy in January of the following year, estimated using a Bayesian-based model (ICES, 2013). The biomass estimates were fitted by linear, log-linear and rank regressions between variables using the R software version 2.14.0 (R Development Core Team, 2011).

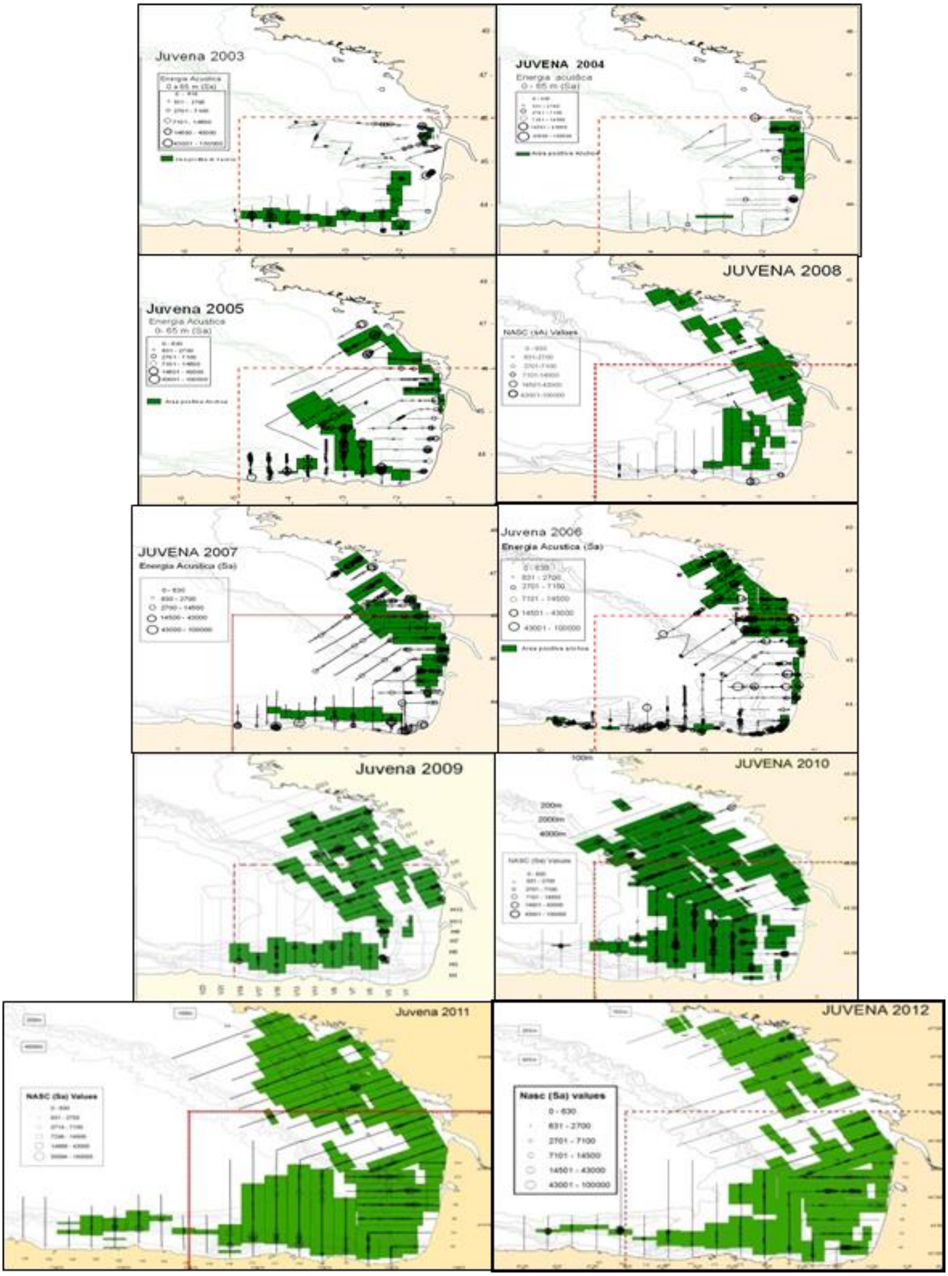


Figure 4-3. Positive area of presence of anchovy and total acoustic energy echo-integrated (from all the species) for JUVENA 2003-2012. The area delimited by the dashed line is the minimum or standard area used for inter annual comparison.

4.4 Results and discussion

The sampling coverage over the surveys (Figure 4-1) reflects the adaptive sampling scheme followed and shows the methodological changes made to improve the coverage, particularly since 2005. For example, the northern coverage along the French coast was considerably enlarged. The northern limit changed from 46º N in the first two years to beyond 47º N in the following years. The number of fishing operations increased from 40 in 2003 to over 60 in the years since 2005. The incorporation of the pelagic trawler in 2006 improved the fishing flexibility, making it possible to fish near the bottom. This is shown in the fishing maps (Figure 4-1) by the increase in species variability (due to the addition of the close-to-the-bottom species).

Every year the juvenile anchovy population could be divided into two clearly distinguishable groups. One part of the population consisted in practically pure juvenile anchovy (not mixed with adults) and the other part was mixed with, or in the proximity of, adults. The pure juvenile group was located in the south-western part of the Bay of Biscay, normally off the shelf or in the outer part of it (Figure 4-2), and the mixed group was located to the north-east in shelf waters of less than 130 m depth. In each group, juveniles were found in a different species composition context and bathymetrical distribution pattern. In the pure juvenile region, anchovy were generally the only or the largely predominant species (the percentage of anchovy individuals in these strata was always higher than 90%) mixed sometimes with smaller proportions of salp, jellyfish and juvenile horse mackerel (Figure 4-1). In the mixed group, juvenile anchovy was found mixed in variable proportions with adult anchovy (the adult proportion increasing towards the north-east, Figure 4-2) and other pelagic species, mainly sardine, horse mackerel, mackerel and sprat (Figure 4-1).

For the years that had the highest juvenile biomass estimates, the largest biomass contributions were invariably observed in the pure-juvenile areas (Figure 4-3). This region contained on average 58% of the total biomass. This average increased to 75% when the least abundant years (2004, 2007 and 2008) were excluded, and reached up to 95% of the total biomass in 2010, when the strongest recruitment in the JUVENA series was recorded (Table 4-3, Figure 4-4). The contribution of the mixed-juvenile region to the biomass was quite constant across the series, and in the years with the highest total juvenile abundance the contribution was relatively weak. The occupation of the off-shelf waters by pure juvenile anchovy is consistent throughout the series and agrees with previous works on juvenile anchovy in the Bay of Biscay (Carrera et al., 2006; Lezama-Ochoa et al., 2010; Uriarte et al., 1996; Uriarte et al., 2001). Uriarte et al. (2001) described a large juvenile abundance in the French outer-shelf waters (as in 2009 and 2010) in the 1999 JUVESU survey, which was followed by strong recruitment in 2000 (ICES, 2010).

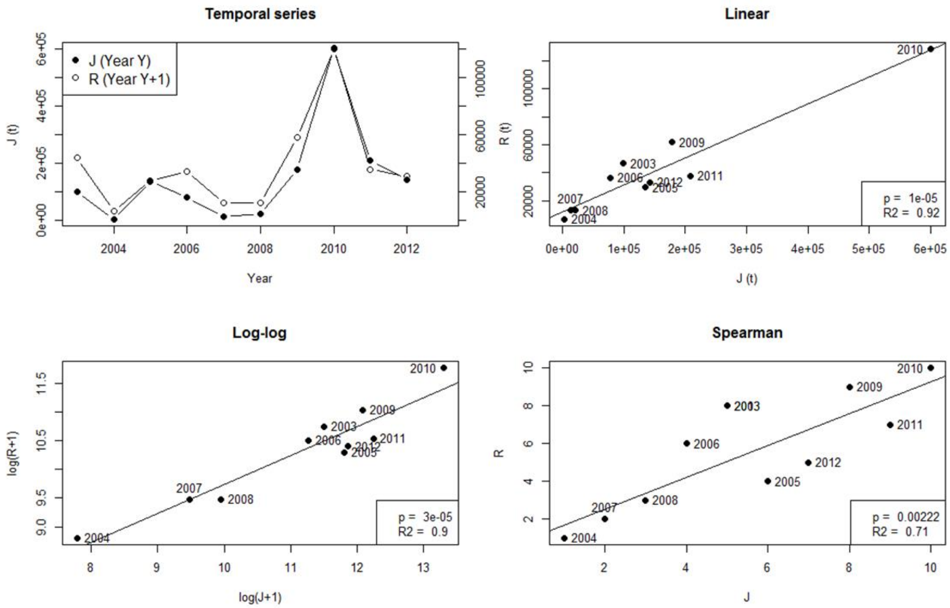


Figure 4-4. Temporal series of juvenile (J) against recruitment (R) indices and fitting of different regression models between them: linear, log-linear and Spearman.

A wide range of acoustic estimates of juvenile anchovy biomass was assessed over the JUVENA series (Figure 4-4). The estimates showed differences of more than two orders of magnitude between the lowest value in 2004 and the highest value obtained in 2010. The series of juvenile anchovy biomass estimates showed a good parallelism to the independent estimates of anchovy biomass at age-1 recruitment at the beginning of the following year (Figure 4-4). Both quantitative linear (Pearson) and non-parametric rank (Spearman) correlations showed highly significant values (the coefficients of determination were 0.92 and 0.71 respectively, with probabilities of being random below 0.00001 and 0.00222 respectively). These significant relationships were not dependent on the extreme values of the series: Both correlation results (at an alpha of 1%) continued to be significant even when the highest or lowest juvenile index from the JUVENA series was excluded from the analysis. Several quantitative linear or log-linear models can be fitted to series of recruitment based on the juvenile abundance indexes from JUVENA. The best fitting was achieved by the linear model, i.e., a potential model in linear scale, with coefficient of determination of 0.95 and p-value=5e-5 (Figure 4-4). Concerning the main observed groups, the biomass of the purely juvenile group was significantly correlated with recruitment, explaining 87% of the recruitment variability, while the biomass of the mixed juvenile and adult group showed no significant relationship and explained less than 20% of the recruitment variability.

Table 4-3. Synthesis of the abundance estimation (acoustic index of biomass) for the eight years of surveys.

Year	Sampled area (mn2)	Posit area (mn2)	Size juv (cm)	Biom Juvenile (year y)	Recruits age 1 (year y+1)
2003	16,829	3,476	7.9	98,601	46,500
2004	12,736	1,907	10.6	2,406	6,648
2005	25,176	7,790	6.7	134,131	29,530
2006	27,125	7,063	8.1	78,298	36,350
2007	23,116	5,677	5.4	13,121	12,960
2008	23,325	6,895	7.5	20,879	13,010
2009	34,585	12,984	9.1	178,028	61,755
2010	40,500	21,110	8.3	599,990	128,400
2011	37,500	21,063	6.0	207,625	37,650
2012	31,724	14,271	6.4	142,083	32,860

The main aim of these surveys was to test whether the abundance of juveniles in autumn constitutes a reliable indicator of the strength of recruitment to the adult stock each year in the Bay of Biscay. The hypothesis has been confirmed by the significant positive correlations between the biomass estimates of juveniles and the next year's age-1 recruits (Figure 4-4). Boyra et al (2013) showed that there exists a significant correlation between juvenile and recruitment indices, thus supporting the reliability of the JUVENA index to anticipate abundance trends in the Bay of Biscay anchovy. In the present work, after the addition of two more medium to high recruitment years, the correlations between juvenile and recruitment are still significant, further supporting the validity of the JUVENA index. In the study period there has been a broad range of recruitment levels, from an extremely low level in 2004, which caused the collapse of the fishery, to one of the highest recruitment levels of the entire recruitment time-series in 2011 (Table 4-3). The relationship between the juvenile and the recruitment indices is not too dependent on any particular point of the series, neither the maximum nor the minimum. The relationship was independent also of the model chosen. Although linear and log-linear models were shown to be good candidates, the definition of the best quantitative model has been left to be investigated in the near future when a few more medium and strong year classes become available.

4.5 Acknowledgements

This project was funded by the Basque Government “Viceconsejería de Agricultura, Pesca y Politicas Alimentarias - Departamento de Desarrollo Económico y Competitividad” - Gobierno Vasco” and the Spanish Government, ” Secretaría General de Pesca, Ministerio de Agricultura, Alimentación y Medio Ambiente – Gobierno Español”. We would like to acknowledge also to the skippers and crew of the vessels that had participated in the survey: F/V Divino Jesús de Praga, F/V Nuevo Erreinezubi, F/V Mater Bi, F/V Gure Aita Joxe, F/V Itsas Lagunak, R/V Emma Bardán and R/V Ramon Margalef.

4.6 Addendum (update to year 2016)

4.6.1 Use of the JUVENA index for the management of Bay of Biscay anchovy

The first use of the JUVENA index for the management of the anchovy fishery in the Bay of Biscay occurred in year 2009: based on its good perspectives for recruitment (Figure 4-4), the five-year-long closure of the fishery ended with a reopening with small TAC (Total Allowed Capture) of 5000 tones (COM374, 2010). The JUVENA index has been systematically taken into account since then to accommodate the TACs to the recruitment perspectives. Finally, in December 2014, the assessment of anchovy in the Bay of Biscay done by ICES in the Working Group HANSA was updated based on a new index, the CBBM, (ICES, 2014) which replaces the former BBM index by combining the information of juvenile biomass provided by JUVENA with the information of the spring surveys and the catches.

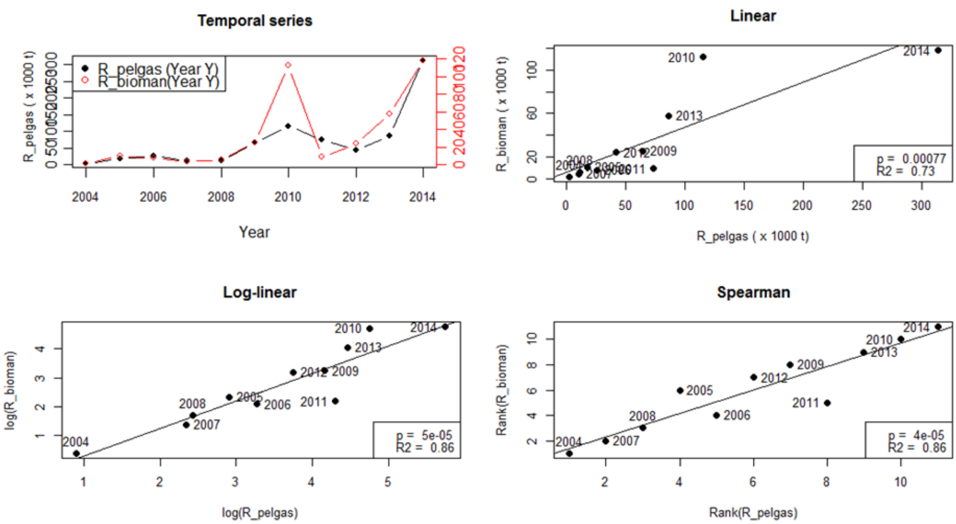


Figure 4-5. Temporal series of recruits obtained in BIOMAN (R_bioman) against the recruitment obtained in PELGAS (R_pelgas) from 2004 to 2014 and fitting of different regression models between both indices.

Since the inclusion of the JUVENA index, the new CBBM has changed also its time of application: instead of being provided in June, now it is provided in December, just when the biomass estimation of JUVENA is ready (ICES, 2015). The information is then used to determine the annual TACs, thus fulfilling one of the main purposes of this work and the JUVENA index, which is to provide an early estimation of the recruitment to improve the management of the resource.

The JUVENA index can be considered now fully operative and integrated in the management of anchovy fishery. Regarding the management of Bay of Biscay anchovy fishery, the BBM was a sophisticated and robust management system, based on two sources that, despite being independent from the fishery and mutually independent, have a highly significant relationship between the two (Figure 4-5). Now, the new CBBM synthetic estimate, with the addition of another source of information based on the JUVENA index, increases the robustness of an already robust index (by means of increasing the number of independent surveys that it is based on). In addition, with the change of application from June to December, thanks to its ability to anticipate recruitment failures and successes, it has considerably improved its ability to promote effective management measures. Thus, with the inclusion of these recent upgrades, I think that it can be said that the Bay of Biscay anchovy fishery benefits from a unique, robust, flexible and sophisticated management strategy.

4.6.2 Validation of the JUVENA index in the CBBM era

With the integration of the JUVENA index into the CBBM in year 2014, given that now JUVENA is used as an input to the CBBM, the validation of the index based on regression models between the juvenile index and the synthetic abundance of recruits is no longer valid, as it would constitute a circular relationship. In order to demonstrate that the predictive strength of the juvenile index still works with the addition of these last two years (2014 and 2015), we compared the JUVENA index with each of the individual indices used to obtain the BBM and the CBBM synthetic biomass indices (i.e., the biomass estimation of age 1 anchovy in the

BIOMAN and PELGAS spring surveys). In both cases, there remains a highly significant relationship between the JUVENA index and the individual indices of abundance of recruits (Figure 4-6 and Figure 4-7) regardless of the regression model used, parametric or non-parametric.

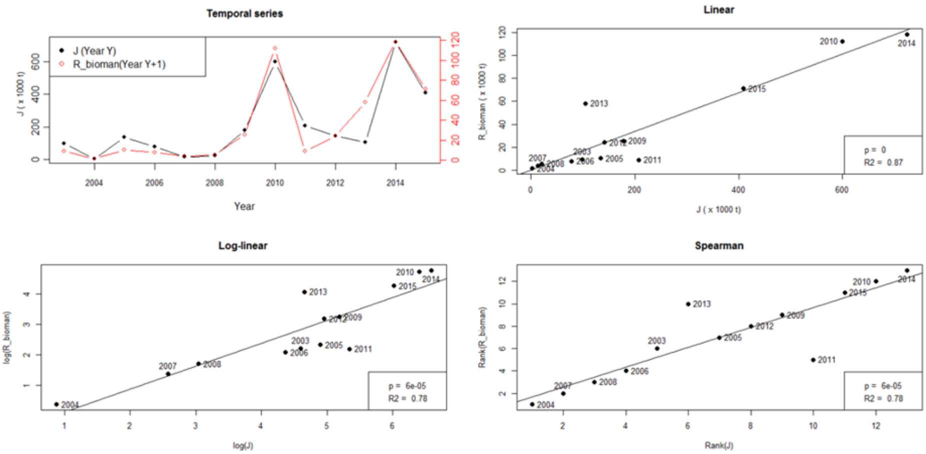


Figure 4-6. Temporal series of juvenile (J) against the recruitment obtained in BIOMAN (R_bioman) from 2003 to 2015 and fitting of different regression models between both indices.

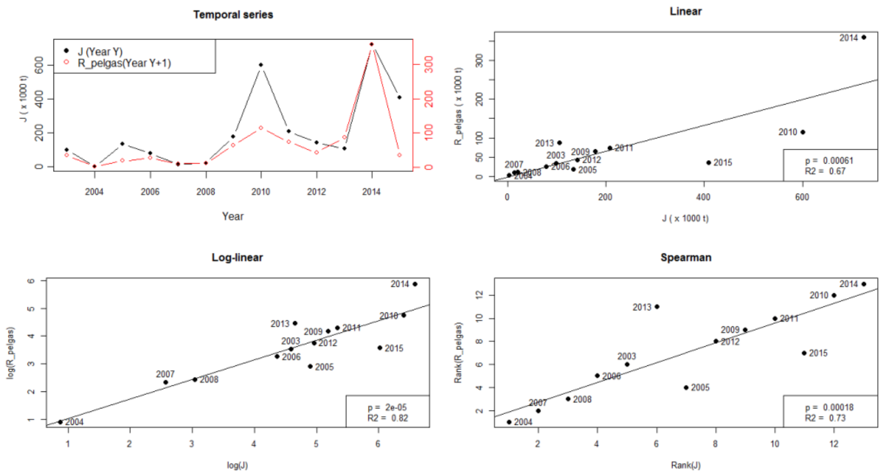


Figure 4-7. Temporal series of juvenile (J) against the recruitment obtained in PELGAS (R_pelgas) from 2004 to 2014 and fitting of different regression models between both indices

This confirms the consistency of the forecasting performance of the JUVENA index: the correlation and significance are maintained after the inclusion of two more high recruitment values (one of whom, the one of year 2014, constitutes the highest recruitment value recorded in the BIOMAN series, coinciding also with the highest juvenile biomass of the JUVENA series). The agreement between both series of abundances, in addition to the agreement between the BIOMAN and PELGAS series (ICES, 2012) confirms also the robustness of the full CBBM index of abundance which provides the foundation for the correct management of the fishery.

4.7 Publication data

Type	Book chapter
Title	Anchovy juvenile acoustic surveys JUVENA 2003-2012.
Authors	Boyra, G.
Journal	In "Pelagic Surveys series for sardine and anchovy in ICES Areas 8 and 9 (WGACEGG) - Towards an ecosystem approach". Massé, J. and Uriarte, A. (ed.) ICES CRR 332.
Year	2016
Chapter	4
Pages	11 pp.

Foto: B.O. Emma Bardán (Fuente: propia).

Chapter 5

Spatial dynamics of juvenile anchovy in the Bay of Biscay

Dinámica espacial de anchoa juvenil en el Golfo de Vizcaya

Este capítulo representa una suerte de epílogo ecológico establecido como continuación del estudio iniciado en el Capítulo 2 sobre distribución espacial de anchoa juvenil en el Golfo de Vizcaya. Sin embargo, en este caso se hace hincapié en la dinámica, que ya se esbozaba en el Capítulo 2, al incorporar más explícitamente el factor tiempo. La dinámica horizontal de anchoa juvenil se estudió comparando la distribución espacial de dos campañas que se centraban en el estudio de la anchoa juvenil, y que se realizaron consecutivamente en el año 2009: la campaña JUVENA 2009 desarrollada por AZTI y la campaña PELACUS10 2009 realizada por el Instituto Español de Oceanografía. La comparación de las distribuciones verticales y horizontales de anchoa juvenil en ambas campañas proporcionó dos "fotografías" consecutivas con unos 20 días de demora entre ambas, a partir de las cuales se obtuvo la dinámica espacial de los juveniles para esas fechas y durante ese año. Los resultados se analizaron en el contexto ambiental de los juveniles obtenido a partir de perfiles de CTD, datos de satélite y mediciones de temperatura y salinidad en continuo a bordo de las embarcaciones.

5.1 Abstract

In autumn 2009, the implementation of two successive acoustic surveys targeting juvenile anchovy (*Engraulis encrasicolus*) in the Bay of Biscay allowed us to monitor the changes in the spatial distribution and aggregation patterns of juveniles of this species during 45 days under fairly stable meteorological conditions. Juvenile anchovy changed its biological condition and behavior in a different manner in two distinct areas. In the Spanish sector the juveniles migrated 20 n.mi. toward the coast, but they remained off the shelf and near the surface during the whole surveyed period. As the advance towards the shelf break progressed, their area of distribution decreased, their density increased and the juveniles spread in fewer but heavier shoals. In the French sector the juveniles migrated also from slope waters toward the coast at similar velocity, but they crossed the shelf break into the continental shelf, where they increased significantly their mean depth until gradually adopting the typical nyctemeral migrations of adult anchovy. The mean length of the juveniles that adopted the nyctemeral migrations was significantly higher than that of the juveniles remaining at the surface, suggesting that body size is relevant to accomplish this change. Besides, the stronger temperature gradients between shelf and oceanic waters in the Spanish sector, favored by a narrow shelf, may have acted as a barrier influencing the distinct observed spatial patterns in the two areas.

5.2 Introduction

The behavior of fish during juvenile stages of the life cycle plays a key role in the survival of individuals and therefore in their recruitment to the population. For example, the migratory pattern of juveniles towards the spawning grounds are of critical importance for the closure of the life cycle and thus for the recruitment to the fisheries (Sinclair, 1988). Aggregation of juveniles in shoals, which reduces the predation risk and hence increases the probability of survival of individuals (Hoare et al. 2000) or the adoption of the aggregation behavior of the adults, their ability to perform nyctemeral migrations or to aggregate in organized schools, are other examples of behavioral features that could be critical for persistence (Petitgas *et al.*, 2010). We generally lack, however, field data on juvenile fish to discern changes in spatial distribution and behavior. This is also the case for Bay of Biscay anchovy (*Engraulis encrasicolus*), a small pelagic species with a short life span. Anchovies reach maturity and spawn for the first time, thus closing their life cycle, in their first birthday (Motos *et al.*, 1996b). In the last thirty years there have been a number of spring-time stock assessment surveys targeting Bay of Biscay anchovy spawning population (ICES, 2015b), but the other stages of its life cycle are not as well known.

In the last decade there has been an increasing effort to better understand the distribution of juveniles in late summer/early autumn to study recruitment (Boyra et al. 2013;Carrera *et al.*, 2006). The comparison of the observations of anchovy made by the spring and autumn surveys has changed our understanding of the overall spatial distributions during the recruitment process (Irigoien *et al.*, 2007). The spatial dynamics of anchovy during the early stages of the life cycle involves spawning in spring, mainly on the continental shelf, followed by an advective transport of the eggs and larvae to the southwest, i.e. mainly towards off-shelf waters, thorough the summer (Allain *et al.*, 2007b; Cotano *et al.*, 2008; Irigoien *et al.*, 2008a; Uriarte *et al.*, 2001a). In the beginning of autumn most juveniles are distributed off the shelf, whereas in the spring of the following year, the one-year-old anchovies (i.e. the survivor juveniles of last autumn) are normally spread over the mid and inner shelf. The difference between these two spatial distributions of the same cohort can be explained as the result of two different spatial dynamic mechanisms: (i) the autumn juveniles move from off-shelf towards continental shelf waters during autumn and winter (Uriarte *et al.*, 2001a) and/or (ii) the higher mortality of the farthest off-shelf juveniles (Allain *et al.*, 2007b) causes an "appearance of movement" of the juveniles toward the shelf.

Previous studies have found evidences supporting the homing migration of the juveniles to the continental shelf. Some of them have focused on the study of the evolution of the center of gravity of different length groups (Boyra *et al.*, 2013;

Irigoien *et al.*, 2008a) and some have used other techniques, as the analysis of otolith microchemistry (Aldanondo *et al.*, 2010) to infer the migration of the juveniles. Nevertheless, so far, this migration has been inferred by indirect means, which makes it subjected to interpretation ambiguity.

In the year 2009, two consecutive scientific surveys studied the spatial distribution and abundance of juvenile anchovy in the Bay of Biscay with acoustic-trawl methodology (Simmonds and Maclennan, 2005a): JUVENA 2009 and PELACUS10 2009. Both surveys were coordinated and shared a common sampling strategy and methodology (ICES, 2009). Given the temporal delay of 20 days between them, they also provided the infrequent opportunity of taking two consecutive "snapshots" of the spatial distribution of juvenile anchovy in autumn, thus providing direct insight of the temporal evolution of the juvenile stock.

The objective of this work is to study the spatial dynamics of juvenile anchovy in autumn in the Bay of Biscay based on these two surveys, by comparing their spatial distribution, aggregation patterns, size and age structure. According to this, direct measures of horizontal and vertical displacement, growth and behavior of juveniles were obtained. These direct measures allowed us studying the spatial dynamic patterns of juvenile anchovy in autumn along a period of about 45 days of stable weather conditions.

5.3 Material and methods

5.3.1 Data acquisition

The surveys took place in autumn 2009 in the Bay of Biscay to estimate the biomass and the spatial distribution of anchovy juveniles and adults. The first survey to take place was JUVENA, conducted by AZTI from August 26th to September 25th (Boyra *et al.*, 2013; ICES, 2009), and the second one was PELACUS10, conducted by the Spanish Institute of Oceanography (IEO) from September 14th to October 9th (ICES, 2009). Both surveys were coordinated and shared a common sampling design (ICES, 2009) of transects perpendicular to the bathymetry with an inter-transect distance of 15 nautical miles (n.mi.) (Figure 5-1). The surveys followed alternate transects, JUVENA following the odd numbered transects and PELACUS10 the even ones, thus resulting in an inter-transect distance of 7.5 n.mi when both cruises are combined. Both surveys followed an acoustic-trawl methodology (Simmonds and Maclennan, 2005a) with some differences between the two (Boyra *et al.*, 2013; ICES, 2009), the most important being that JUVENA used two vessels (the pelagic trawler R/V Emma Bardán and the commercial purse seiner Itsas Lagunak) and PELACUS10 used only one (R/V Thalassa; also a pelagic trawler). Due to the different sampling effort (38 and 23 effective vessel-days respectively), JUVENA covered a larger area than PELACUS10 (Figure 5-1). All the potential methodological issues of JUVENA survey, including those related to the use of purse seiners were discussed by Boyra *et al.* (2013).

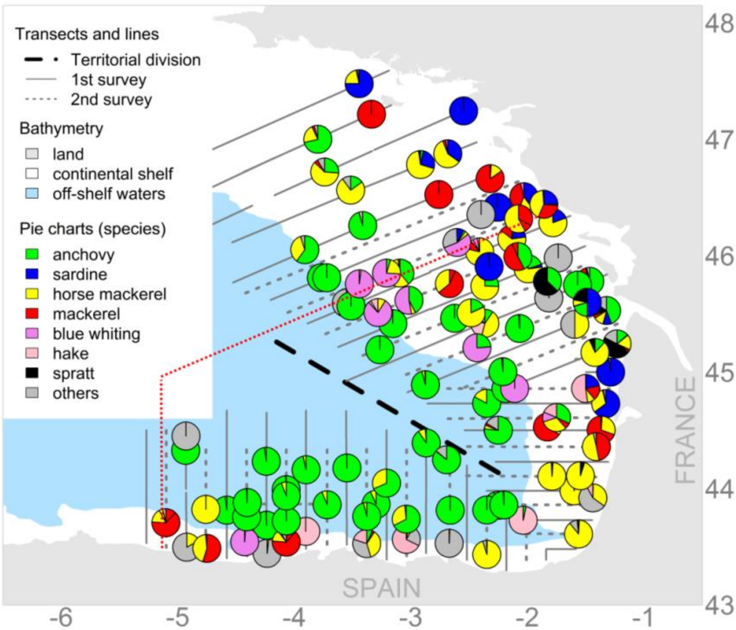


Figure 5-1. Sampling strategy of both surveys and species composition of the hauls. The red dotted line marks the common area sampled by both surveys.

Table 5-1. Configuration of the acoustic equipment in both surveys

	Thalassa	Emma Bardan	Itsas Lagunak
Survey	PELACUS10	JUVENA	JUVENA
Acoustic instalation - depth (m)	Drop keel - 7	Hull - 3	Side perch - 3
Power (W)	2000	1200	1200
Pulse length (ms)	1.024	1.024	1.024
Gain (dB)	25.46	24.43	22.26
Sa correction (dB)	-0.55	-0.6	-0.41
Minor-axis beam width (degrees)	7.06	6.72	6.75
Major-axis beam width (degreees)	6.98	6.76	6.75
Absorption coefficient (dB/m)	0.009	0.007	0.007

The acoustic acquisition was done with Simrad EK60 echosounders with split beam 38 kHz transducers in all the vessels, operating with a pulse duration of 1.024 ms and collecting data down to 200 m depth (

Table 5-1). The acoustic equipment of the three vessels was calibrated using the sphere method (Foote, 1987). In addition, several inter-calibration exercises (Simmonds and Maclennan, 2005a) were carried out between the three vessels, obtaining differences of less than 10% that ensured consistent acoustic recordings and that no important selective avoidance was occurring. Complementary information of other ecosystem components was also acquired during both cruises: hydrography was recorded using CTD casts in both surveys and concurrent continuous records of sea surface (5 m depth) temperature, salinity and fluorescence only in the PELACUS10 survey.

5.3.2 Data processing

The echograms were subjected to standard acoustic pre-processing: removal of multiple bottom echoes and interferences, and correction of the bottom detection. Then, they were visually scrutinized with the aid of the species composition of the catches, classifying them in strata according to the anchovy composition: only juveniles and mixed juveniles and adults

Given that these were anchovy-focused surveys, only the areas where anchovy was present (positive areas) were processed. Acoustic data were echo-integrated by schools using Echoview (Myriax inc.), applying a -60 dB threshold and the school module analysis (Lawson *et al.*, 2001) with the default school definition parameters. This threshold was, in some cases, not enough to remove all the plankton from the echograms and, consequently, the remaining plankton had to be manually removed. The data were integrated in both surveys from 10 m depth down to the maximum depth reached by anchovy. Once echo-integrated, the acoustic data plus the biological data were merged using R (R Core Team, 2014) to obtain abundance and biomass per school based on the standard trawl-acoustic biomass estimation routines (Boyra *et al.*, 2013; Simmonds and Maclennan, 2005a). The areas were post-stratified based on the species composition and size structure of the catches. Thus, the fishing stations with similar species composition were aggregated into single "virtual" average hauls, which provided a single mixed species echo integrator conversion factor. All the ESDUs (elementary sampling distance units) inside each of these post-stratification areas applied the same echo integrator conversion factor, thus partitioning the acoustic backscattering energy into the same percentage of species and size structure. Additional details of the processing procedures can be found in Boyra et al (2013), Boyra et al (2016), as well as in the annual reports of the ICES working group on acoustics and egg surveys (ICES-WGACEGG 2006 and 2009).

The spatial dynamics analyses were done following three steps. In the first step we studied the spatial age and depth structure of the population, focusing on the common area sampled by both surveys (leaving out the northernmost transect of each survey to avoid losses due to advection, Figure 5-1). The age was determined examining the otoliths according to the methodology described by (Uriarte *et al.*, 2016). In terms of biomass estimation, anchovy juveniles (age 0) and adults (age ≥ 1) were separated and treated as "different species" by using separate mean TS values (based on separate mean body lengths) for each age class. To separate juveniles from adults, the length–frequency distribution of anchovy by haul was multiplied by a corresponding age–length key. The key was determined for three broad areas: the purely juvenile area, the mixed juvenile area (with a mix of juveniles and adults) and the surroundings of the Garonne river mouth. The depth structure was analyzed by classifying the acoustic recorded schools in two coarse vertical layers, "surface" or "bottom", depending on whether the schools were found closer to one or the other. The data were mapped using the R packages "maptools" (Bivand and Lewin-Koh, 2015) plus "mapplots" (Gerritsen, 2013) for pie charts.

In the second step we removed the adults to study the spatial dynamics of juvenile anchovy. The horizontal dynamics of juvenile anchovy was studied by comparing their spatial distribution in both surveys, plotting the biomass per school in log scale. The centers of gravity (CG) of anchovy in both surveys were computed, also in log scale. Due to the particular L-shaped coastline of the Bay of Biscay, in order to simplify the search for horizontal patterns, we split the juvenile anchovy positive areas in two regions (the Spanish and French sectors, see Figure 5-1), each of them with approximately straight, parallel coastline and isobaths. With this procedure we avoided having the CG of the juvenile population placed in meaningless locations outside the positive areas and were able to simplify the analyses and interpretations of the observed spatial patterns.

Centers of gravity and inertial ellipses of the juvenile data were calculated using an implementation in R (R Core Team, 2014) of the spatial patterns indicator functions by Woillez et al. (2007). The displacement of the CG provided a measure of the mean net direction and magnitude of the horizontal migration of juvenile anchovy between surveys. From this, and taking into account also the time lapse between surveys, we computed mean net displacement velocities of juvenile anchovy in this season and area. In addition, the displacements of the mean inshore and offshore boundaries of the positive areas of juvenile anchovy were also measured.

Finally in this step, some aggregation parameters, both individual (per shoal) and collective (per nautical mile), were compared to study the evolution of the state of aggregation in the time elapsed between the two surveys. The increment of mean school depth provided a measure of vertical displacement, and the number of schools and fish individuals per nautical mile provided the evolution of school and fish density. The temporal evolution of the different parameters was plotted using the R toolbox “ggplot2” (Wickham, 2009).

The evolution of the aggregation patterns was analyzed only in the Spanish sector. The reasons for this were that (i) this is an isolated sector, well covered and delimited in both surveys, whereas the French sector was only partially covered by the PELACUS10 survey (Figure 5-1); (ii) the mean depth was very stable between surveys (Figure 5-5), no distinct pressure compression of the swimbladder was expected and hence the mean TS was supposed to be constant (Ona, 2003; Zhao et al. 2008), allowing a consistent abundance comparison between surveys (contrarily to the French sector in which there was a mean depth change between surveys of about 80 m); and (iii) this sector was completely off the shelf, containing only pure juvenile anchovy aggregations (contrarily to the French sector, see Figure 5-1) thus assuring that the findings are attributed to isolated juvenile anchovy shoals.

In the third step, we studied the physical environment of juvenile anchovy in search of possible explanations to the observed spatial patterns. Horizontal fields of temperature, salinity, and density were obtained by objective analysis of the CTD profiles carried out in both surveys using the Optimal Statistical Interpolation (OSI) scheme described in (Gomis *et al.*, 2001). The analysis was applied in a regular 39x60 grid, covering the study area with regular node distances of 0.075°x 0.075°. For the OSI, a Gaussian function for the correlation model between observations (assuming 2D isotropy) was set up, with a correlation length scale of 25 km, chosen according to the observed correlation scales between individual profiles. Finally, all fields were spatially smoothed, with an additional low-pass filter with a cut-off length scale of 30 km, in order to avoid aliasing errors due to unresolved structures. To obtain 3D fields, horizontal analyses were performed independently at 5 m intervals from 5 to 250 m. Then, characteristic across-shelf sections of these variables for the each area and survey were obtained by averaging in longitude and latitude, respectively, the sections from the 3D matrix in the area from 4º W to 2.95º W (mean longitude of the nodes at 3.47º W) for the Spanish sector and from 43.8º N to 44.7 º N (mean latitude of the nodes at 44.28º N) for the French sector.

In addition, continuous surface records of temperature, salinity and chlorophyll carried out underway during PELACUS10 survey (SBE21 SeaCAT thermosalinograph plus Turner fluorimeter) were also analyzed. Mean sea surface salinity, temperature and chlorophyll per transect were computed to look for statistical differences between regions. Additionally, the sea surface temperature drop through the shelf break per transect, estimated as the temperature difference at the 1500 and 125m isobaths normalized by the along-transect distance between these two locations, was also tested using both two-sample parametrical (t-test) and non-parametrical (Wilcoxon) statistical tests using R (R Core Team, 2014).

5.4 Results

5.4.1 Spatial distribution of anchovy

The species composition of the trawls showed that in off-shelf waters the predominant species was anchovy, accompanied only by small amounts of horse mackerel (Figure 5-1), while on the shelf there was a heterogeneous mixture of small pelagic species. In the Cantabrian shelf (Spanish sector), there was no anchovy, and the main pelagic species found were horse mackerel (*Trachurus trachurus*), mackerel (*Scomber scombrus*) and hake (*Merluccius merluccius*). In the French shelf, anchovy was found in the company of other small pelagic species, mainly horse mackerel and mackerel, distributed all over the shelf, plus sardine (*Sardina pilchardus*) in the inner shelf (<100 m isobath) and blue whiting (*Micromesistus poutassou*) at the outer shelf and slope. There was also some sprat (*Sprattus sprattus*) near the mouth of the Garonne River.

The comparison of species composition of the fishing hauls (Figure 5-1) showed a general consistency between both surveys. The main discrepancy was the larger amount of blue whiting caught in the second survey in the outer part of the French shelf. This was caused by the vertical displacement of the juvenile anchovy from the surface in the first survey, where they were isolated from other species, to the bottom in the second survey, where they were mixed with blue whiting. Thus, the change in the companion species of anchovy caused the change in species composition of the catches of these two anchovy-oriented surveys.

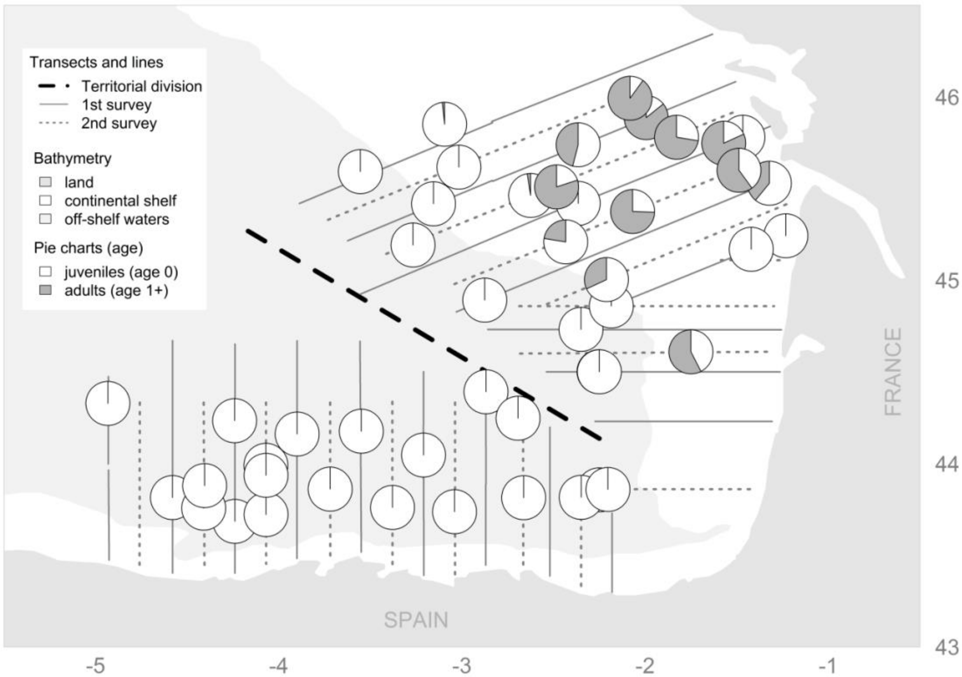


Figure 5-2. Age composition of the anchovy catches in the common sampling area of both surveys.

The age distribution of anchovy showed also a clear pattern (Figure 5-2), with only juvenile aggregations off the shelf and a combination of juveniles and adults on the shelf. Therefore, anchovy juveniles were isolated in off-shelf waters, whereas they were exposed to the contact with both anchovy adults and other pelagic species on the shelf.

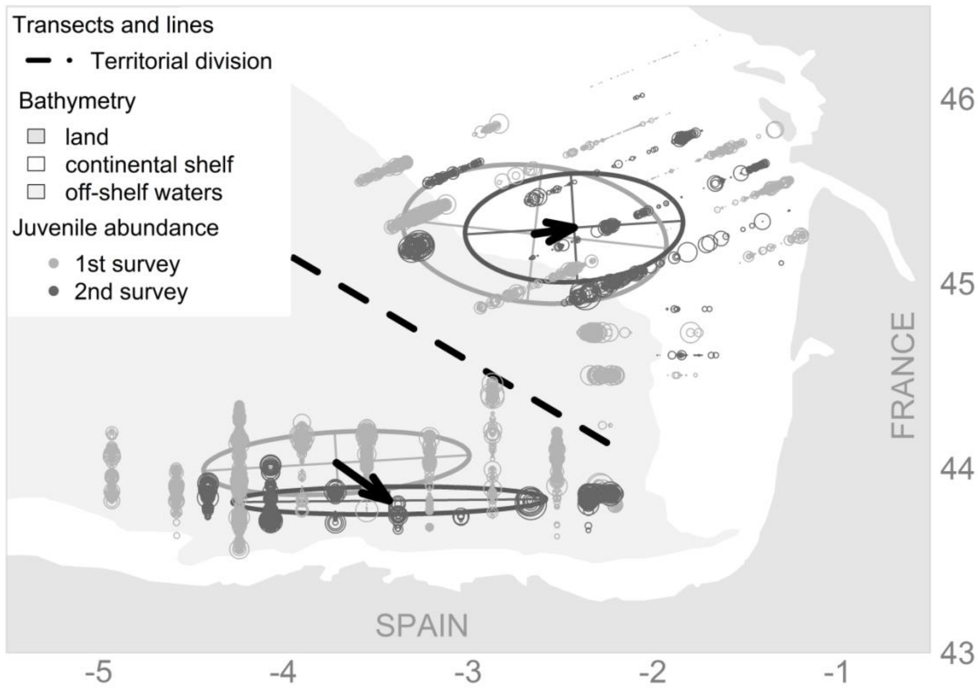


Figure 5-3. Horizontal centers of gravity and inertial axis and ellipses of the biomasses of juvenile anchovy in the two main regions. The arrows mark the displacement of the centers of gravity in the time elapsed between the surveys.

5.4.2 Horizontal distribution

The between-cruises comparison of the horizontal distribution of the CG of juvenile anchovy showed a net displacement during the time elapsed between surveys (Figure 5-3). In the Spanish sector, the displacement was about 20 nautical miles (n.mi.) to the southeast; whereas in the French sector, the mean displacement was about 10 nautical miles but eastward. In both cases, the displacements of the CG were basically directed towards the coastal area. From these displacements we inferred mean net speeds around 0.5-1 n. mi. per day (i.e., around 0.9-1.8 km $\cdot$ day^{-1}) during the sampled period.

In the Spanish sector, the juvenile population was located completely off the shelf in both surveys. In addition, the displacement towards the coast of the offshore boundary of the positive area of juvenile presence in the time elapsed between surveys was higher than that of the inshore boundary, which caused a narrowing of the spatial distribution of juveniles in the second survey compared to the first one (Figure 5-3). In the French sector, the juvenile population was spread both on-shelf and off-shelf waters. Here, the displacements of the offshore and inshore boundaries were of similar magnitude and, consequently there was no narrowing of the positive area between surveys.

5.4.3 Vertical distribution of anchovy

Focusing on anchovy in the common sampled area, the schools were organized in coarse vertical layers according to a clear pattern independently of the survey (Figure 5-4). Off-shelf, the aggregations were found near the surface, above 50 m depth, whereas on the continental shelf the schools tended to be near the bottom at mean depths higher than 50 m (except in the very coastal areas, for obvious reasons).

The evolution of the average depth of juvenile schools was different in the two sectors (Figure 5-5). In the Spanish sector, the mean depth was stationary; juvenile schools remained near the surface during the whole sampling period (average depth changed from 15.8 to 14.1 m between surveys, Table 5-2). In the French sector, juveniles stayed in the surface layer during the first 20 days (average depth 16.5 m), but increased about 80 m their mean depth afterwards, especially those juvenile aggregations located over the continental shelf (Figure 5-4 and Figure 5-5-top). Near the surface (<50 m depth), the size of juveniles ranged from 7 to 13 cm, whereas near the bottom the mean size of juveniles increased 2 cm (from 10 to 12 cm approximately). In general, there was an overall (significant, $p < 0.001$) difference in mean body length between surface and bottom juveniles of more than 3 cm.

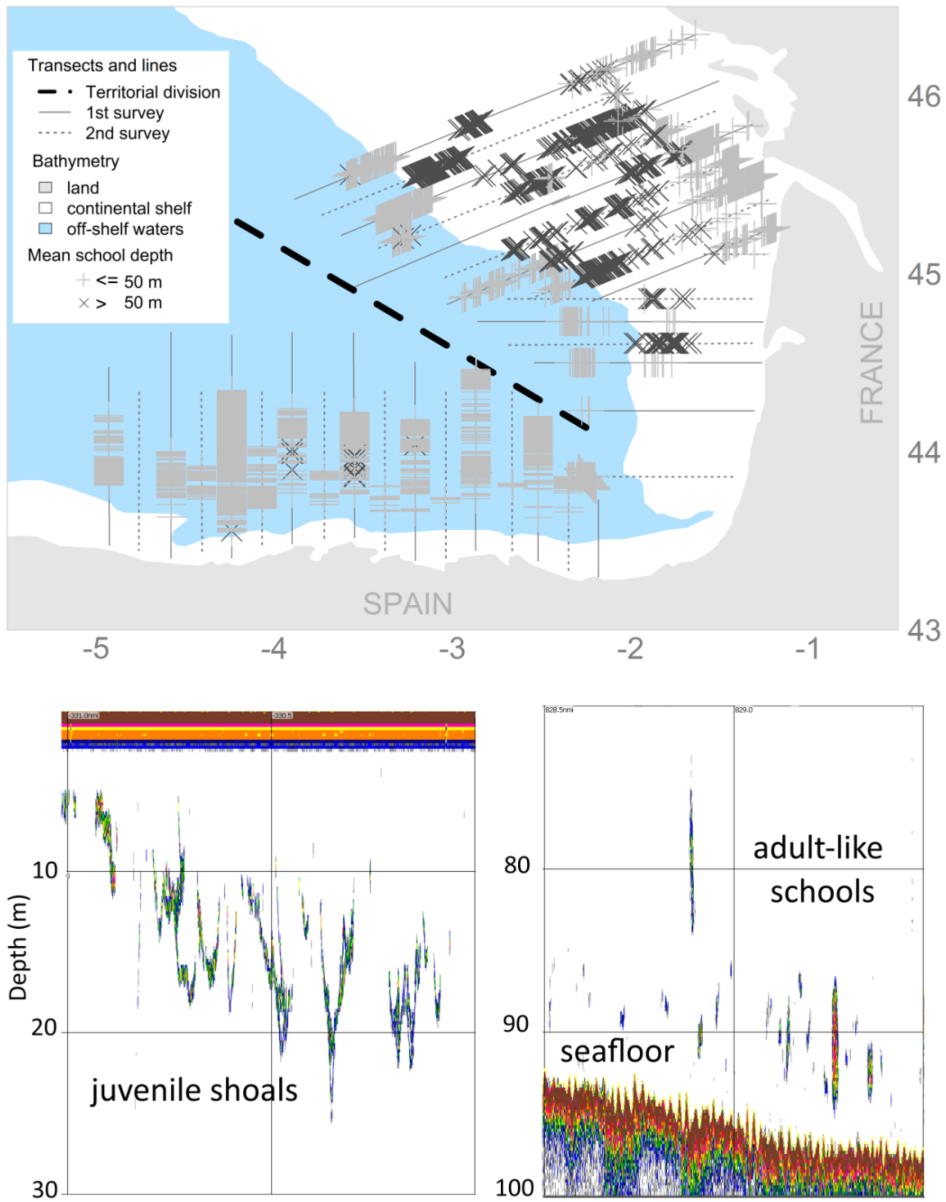
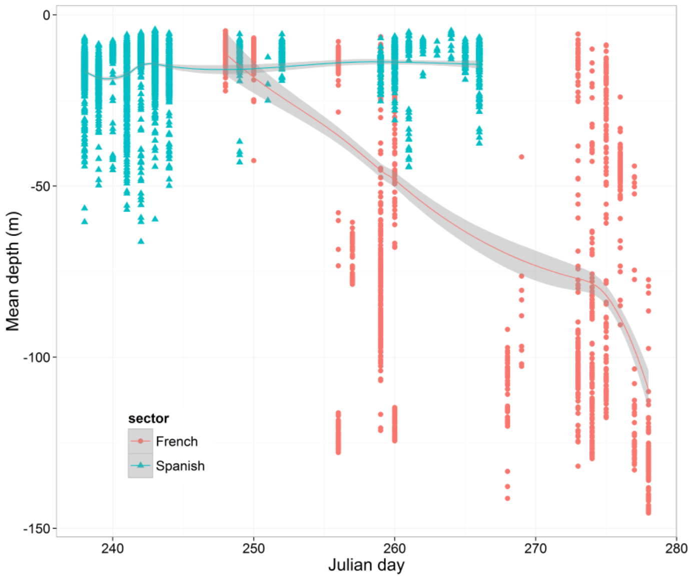


Figure 5-4. Top: Spatial organization of juvenile anchovy in coarse vertical layers (surface and bottom) in the common sampling area of both surveys. Bottom: Sample echograms of anchovy from each vertical layer at – 60 dB threshold. The dimensions of the echograms are 30 m height x 1 nmi wide approximately. Left: typical juvenile shoals near the surface. Right: adult-like schools above the seafloor.



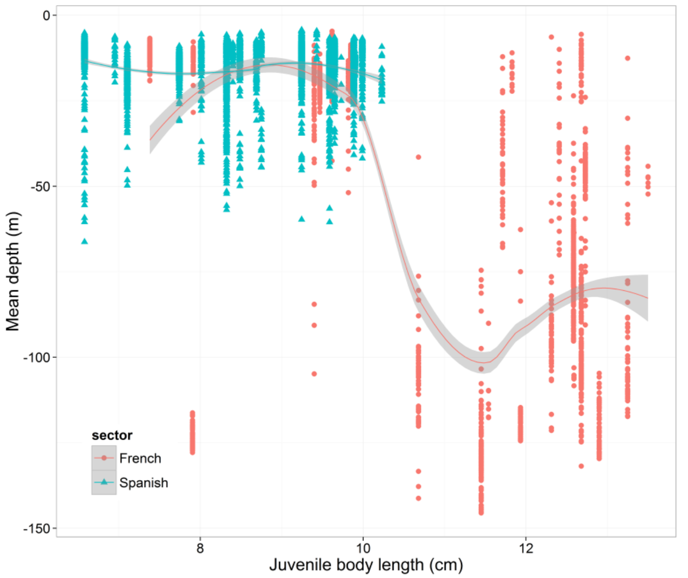


Figure 5-5. Top: Temporal evolution of the mean depth of juvenile schools in the period of study, distinguishing the Spanish and French sectors. Bottom: Scatterplot of mean depths against body length of juvenile anchovy obtained in the fishing hauls per sector. The analyses were carried out on juveniles from the common area sampled by both surveys, the first survey comprising Julian days 238 to 260 and the second survey 259 to 278. Loess regression model lines with confidence intervals are included to highlight the tendencies.

Table 5-2. Change of some characteristics of juvenile aggregations along the surveying period in the two areas (mean values and standard deviations)

	1st Survey						**2nd Survey**					
	Spain			**France**			**Spain**			**France**		
Julian day	241.5	±	3	257.5	±	3	262	±	2.5	274.5	±	2.5
Depth (m)	15.8	±	7.6	40.8	±	32	14.1	±	6.3	87.1	±	36.6
Body length (cm)	8.5	±	1.1	10.8	±	1.7	9	±	0.8	12.1	±	1.1
Schools per n.mi	10	±	9.5	4	±	5	6.5	±	5.5	5.5	±	5.5
Fish density (1000*individuals/n.mi.)	94	±	311	23	±	89	340	±	1080	106	±	564
Transect length (n.mi.)	33.6	±	10	67.4	±	17.4	12.7	±	5.9	53.5	±	0
Minimum bathymetry (m)	-850			-50			-1400			-36		

5.4.4 Evolution of the state of aggregation

In the Spanish sector, where juveniles formed pure aggregations in surface off-shore waters, schooling parameters changed trough the surveyed period. The average density of juvenile anchovy schools per nautical mile decreased from the first to the second survey (Figure 5-6-top, Table 5-2), while the fish density per nautical mile increased (Figure 5-6-bottom, Table 5-2). This means that in this sector, the state of aggregation of the juveniles along the surveying time evolved from many smaller to fewer and denser shoals. The level of biomass was of the same order of magnitude in both surveys, showing a slight increase from the first to the second one.

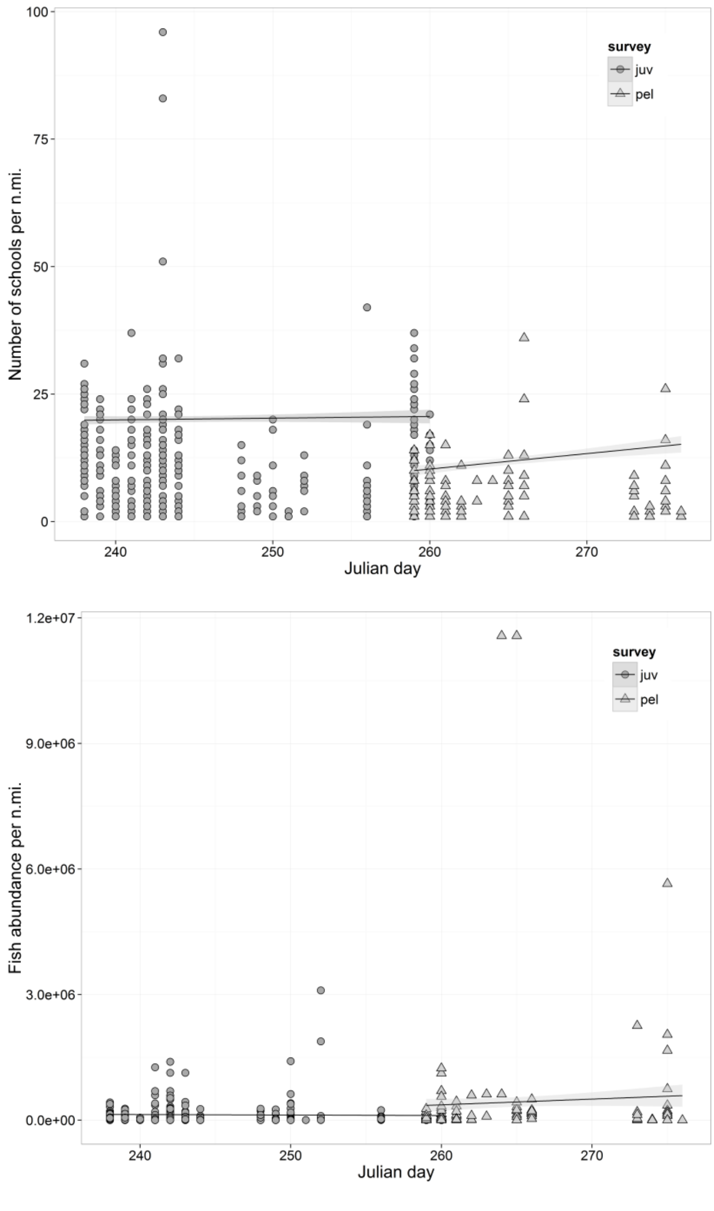


Figure 5-6. Top: Temporal evolution of the density of schools (number of schools per nautical mile) in the Spanish sector along the surveys. Bottom: Temporal evolution of fish density (fish number per nautical mile) along the surveys. The school density was significantly higher ($p < 0.001$) and the fish density significantly lower ($p < 0.001$) in the first than in the second survey. Linear regression model lines with confidence intervals are included to highlight the tendencies.

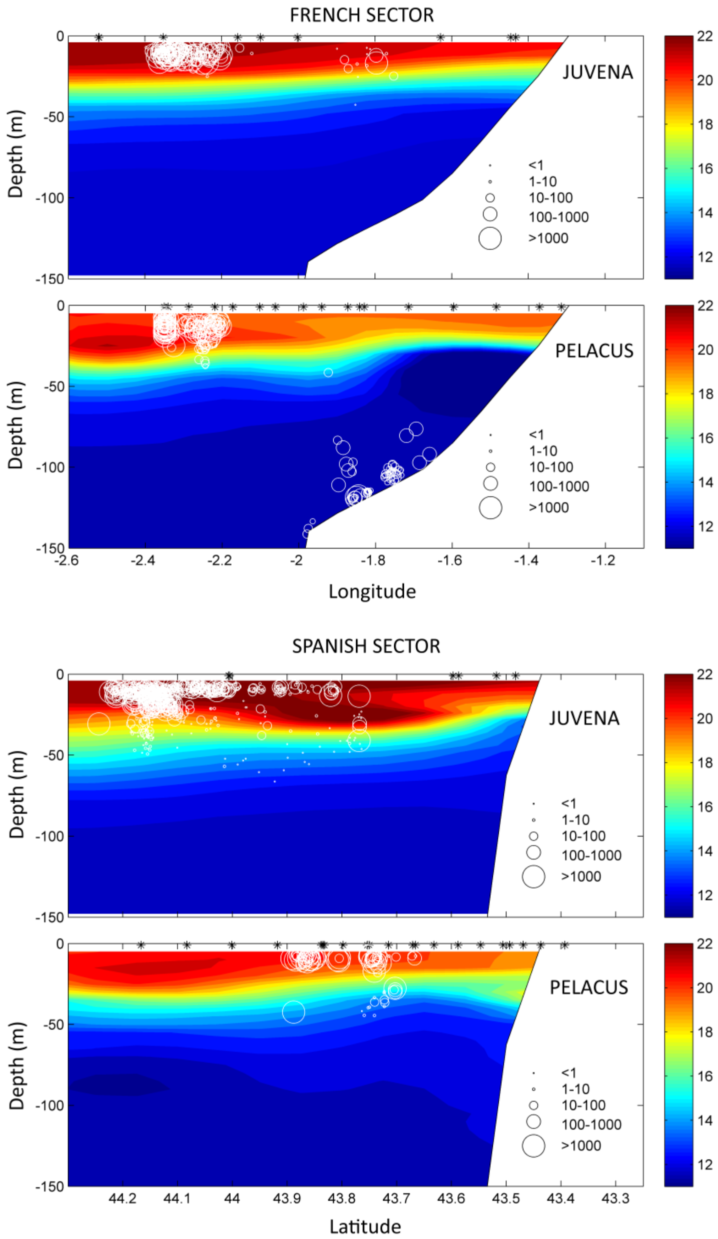


Figure 5-7. Cross-shelf characteristic sections of water density in both surveys and sectors. The white area depicts the mean bathymetry of the transects (from the average of individual bathymetric sections considered for each case) and the white bubbles represent the juvenile schools detected in each area, with the diameters proportional to the biomass in kg.

5.4.5 Pelagic environment

In general, there were rather stationary environmental conditions during the surveyed period. Vertically, the juvenile schools were mostly above the thermocline off-shelf in both surveys, whereas in the continental shelf they were above the thermocline in some spots in the first survey but sank below it in the second one (Figure 5-7). This change of vertical distribution didn't seem to be associated to changes in the physical environment of the water column, which remained basically stable due to the calmed weather conditions that prevailed during both surveys.

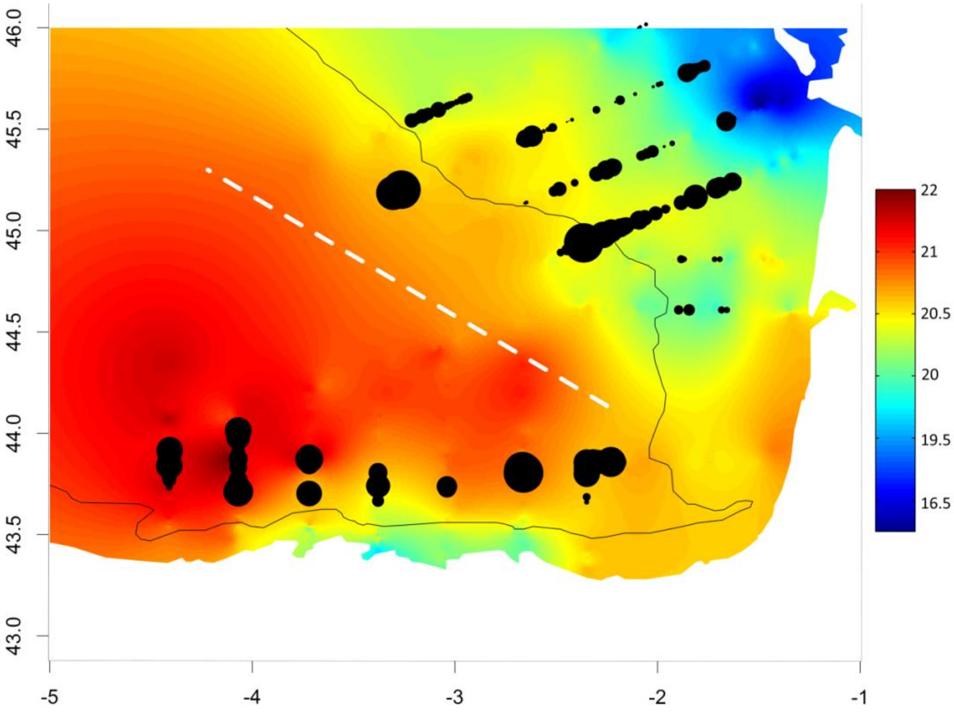


Figure 5-8. Juvenile anchovy biomass distribution in PELACUS10 survey (black bubbles) against a concurrently recorded SST in the same survey (ºC). The continuous black line marks the 200 m bathymetry and the dashed white line divides the French (north-east) and Spanish (south) sectors.

The distribution of sea surface temperature (SST) showed higher temperatures in the southern than in the eastern region, which is characteristic in the Bay of Biscay during this season of the year (Figure 5-8). Juveniles stayed in the warmer part of the slope waters at the Spanish sector, while they occupied colder shelf waters at the French sector. Among the environmental variables tested to explain the different spatial distribution found between both areas, only SST (at both ESDU and transect scales) and the across-shelf temperature gradient (Figure 5-9) showed a significant difference between areas (p-value < 0.001 in a two-value Wilcoxon test). The mean drop of temperature in the Spanish sector was about 0.25 ºC per kilometer, about five times higher than in the French sector (Figure 5-9).

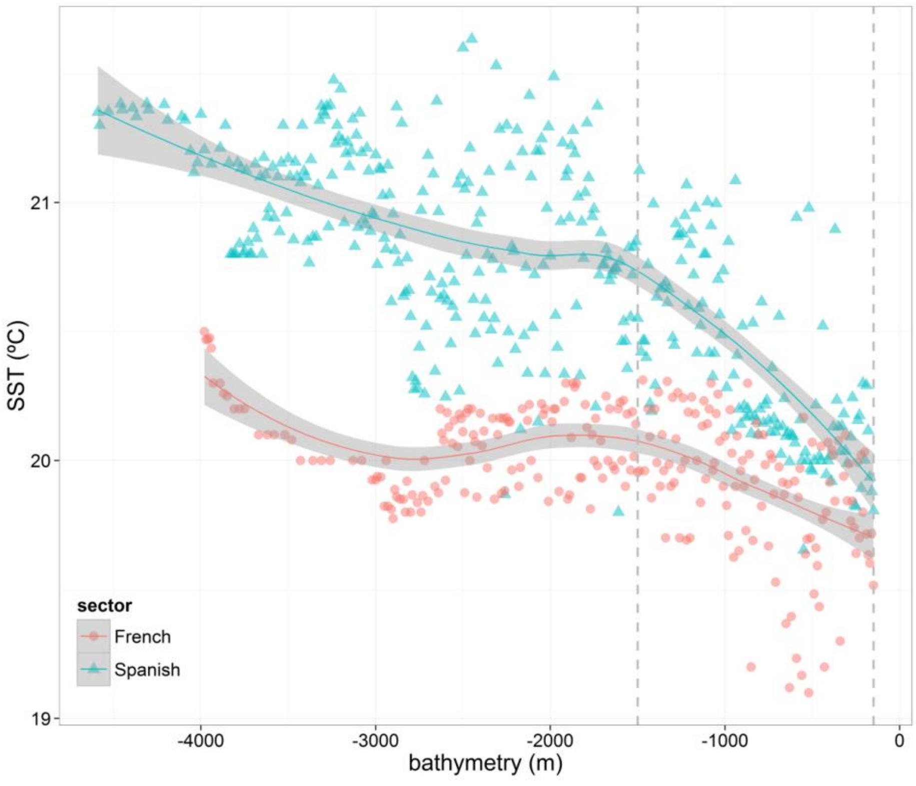


Figure 5-9. Scatterplot of temperature against bathymetry in each sector for the PELACUS10 survey, including a loess smoothing line for each. Grey dashed vertical lines mark the 1500 m and 150 m isobaths.

5.5 Discussion

5.5.1 Migration from the ocean towards the inner shelf and coastal areas

This study is the first direct observation of anchovy juvenile schools moving from off-shelf to on-shelf waters, and confirms previous hypothesis inferred from the analysis of otolith and seasonal distribution (Aldanondo *et al.*, 2010; Irigoien *et al.*, 2007; Uriarte *et al.*, 2001a). This conclusion can be inferred from the combination of two results: (i) the displacement of the CG of the distribution of juveniles towards the coast from the first survey to the second one (Figure 5-3), and (ii) the maintenance of the biomass levels plus the increase of density of individuals per nautical mile in the second survey (Figure 5-6-bottom). The observed displacement could be the result of two causes: the real and gradual displacement of the juveniles to the coast and/or the increased mortality of the offshore juveniles compared to the inshore ones, which could provide an appearance of movement. If the displacement of the CG were only caused by a selective mortality of the off-the-shelf juveniles, the biomass of juveniles in the second survey should be considerably less than that observed in the first one due to the mortality experienced by the off-shore juveniles during the 20 days of delay between surveys. Consequently, the maintenance of the biomass levels and the observed increase of juvenile density in the second survey prove that a direct displacement of juveniles towards the coast has occurred.

The observed displacement of juveniles occurs opposite to the general surface oceanic and slope circulation in the Bay of Biscay. From the analysis of the geostrophic fields derived from OSI dynamic heights (not shown), the geostrophic current regime in the study area and during both surveys is anticyclonic, with currents oriented towards the west (south) along the Spanish (French) slope. The observed regime is thus in accordance with the general regime described in the literature for this area and period (e.g. Charria et al. 2013). Indeed, between April and September of 2009, surface currents run southward and westward in the

French and Spanish sectors respectively, with average velocities around 5 cm · s^{-1} or even higher (Charria *et al.*, 2013). In this season, the slope current regime is much more variable, less intense and in opposite direction than in winter when it is dominated by the presence of an intense eastward flow: the Iberian Poleward Current (Pingree and Le Cann, 1990; Solabarrieta *et al.*, 2014). Since the slope circulation would not favor the observed horizontal movement of the juveniles towards the coastal areas, we can conclude that the observed displacement results from an active migration of the juveniles and not a passive drift. The displacement of the CG provides a mean velocity of the migration of around 1 n.mi. per day. To what extent the observed movement responds to a strict homing migration, with juveniles swimming towards the birth place, or is driven by salinity and/or productivity gradients cannot be determined. The fact that in each area the displacement is towards the closer shelf area supports the second hypothesis, but a very large scale genetic parentage study would be needed to discard one or the other hypothesis.

5.5.2 Vertical dynamics

Regarding vertical movements, the juveniles show a distinct pattern depending on their location: while they remain off the shelf, they are located near the surface above the thermocline (mostly at less than 50 m depth, Figure 5-4 and Figure 5-5) and they don't show any tendency to increase their depth (Figure 5-5). But at some stage after they cross the shelf break into the continental shelf, they start to perform vertical nyctemeral migrations, staying close to the bottom during the day and thus drastically increasing the mean daytime depth.

These tendencies in the vertical dynamics are coupled with changes in the body length of juveniles. There is an overall highly significant difference in mean body length between surface and bottom juveniles of about 3 cm, (from 9 to 12 cm approximately, i.e., around 33%). If we restrict to the French sector, the size difference decreases to about 2 cm, remaining however highly significant. This increase of body length observed when moving from the surface to the bottom could be a consequence of the juveniles meeting and following the adults in their daily vertical migrations once in the continental shelf. A higher body length at the bottom could be caused by (i) the inability of the smallest juveniles to perform such migrations, probably because they can't follow the swimming speed of the larger adults necessary to join their schools (Pitcher and Parrish, 1993); or (ii) a higher mortality of the smaller juveniles at the bottom, possibly due to the increase in the range of predators (such as mackerel, horse mackerel and hake) that can feed on them (Figure 5-1). Nevertheless, we find unlikely that an increment in body length of 3 cm may cause such a difference in the mortality of a species and thus we consider the first explanation more likely to be correct. The increased body length of the juveniles at the bottom fit with the hypothesis of Petitgas et al. (2006) concerning the juveniles receiving the entrainment from the adults to change their behavior and accomplish the necessary migrations to close the life cycle.

The coupling of body length and school depth is in general agreement with the observations made by Boyra et al. (2013) for juvenile anchovy in the same area and season from 2003 to 2010, where a linear relationship was observed between mean depth and mean body length of juveniles. In this work, we were able to provide some more detail, by showing that this relationship holds only after the juveniles have entered the continental shelf in their way to the coast. While the juveniles stay off the shelf, the mean depth remains constant regardless of the mean body length of the juveniles (Figure 5-5).

5.5.3 Distinct spatial dynamics on the Spanish and French sectors

Another interesting result is the drastically different dynamic patterns of anchovy observed in the Spanish and French sectors. In the Spanish sector, anchovy was located off-shelf in both surveys (Figure 5-3) and the extension of the positive area was narrowed to one third from the first survey to the second one. This occurred because the offshore edge of the distribution area displaced 20 n.mi. towards the shelf break during the period between both surveys, while the inshore edge remained relatively stable, not trespassing the shelf break. In addition, in this sector juvenile anchovy was completely isolated from adults (Figure 5-2) and almost completely from other pelagic fish species (Figure 5-1). And last, the juveniles remained near the surface in both surveys (Figure 5-4). Contrastingly, in the French sector, the spatial distribution of juvenile anchovy reached also off-shelf waters, but crossed the shelf break into the continental shelf even during the first survey, although more clearly in the second one. The off- shelf juveniles in this area, as in the south, were mostly isolated from adults and other species, whereas the ones found on the continental shelf were mixed with adult anchovy and other species (Figure 5-1and Figure 5-2). Finally, while the off -shelf juveniles were found near the surface, juveniles over the shelf were found approaching the bottom, as explained in the previous section. The differences between areas found in this work agree with the differences found in other years in this region (Boyra *et al.*, 2013).

In the search for possible explanations of these different dynamic patterns between the two areas, several environmental variables were tested at ESDU and transect scale. At ESDU scale, both SST and sea surface salinity (SSS) showed significant difference between areas ($p = 0$ in two sample Wilcoxon tests). Absolute values of SST in the French sector were lower than that in the Spanish sector, according to its higher latitude and hence colder ambient temperature. The higher river discharges in the French sector contributes also to the higher mean SST and lower SSS in this area. However, we could not find any reason that could explain why this overall temperature and salinity difference could cause the barrier effect in the Spanish and not in the French sector.

In order to look for variables that could justify a barrier effect, we analyzed the gradients of environmental variables along transects (i.e. normal to the bathymetry). We found that the temperature gradient could act as such variable. The temperature drop across the shelf break showed a significant difference between areas (p-value of 0.0069 in a two-value Wilcoxon test). The mean drop of temperature in the Spanish sector was about 0.25 ºC per kilometer, about five times faster than the drop of temperature in French waters (Figure 5-9). The steeper temperature gradient indicates a stronger frontal system at the Spanish than at the French shelf break, favored by the narrower continental shelf of the Spanish sector compared with that of the French one. This could explain the reluctance of the southern juveniles to enter the colder continental shelf waters along both surveys and thus the compression of these juveniles against the shelf break during the surveyed period (Figure 5-3). The preference of warm temperatures is in agreement with previous works (Raab *et al.*, 2013; Takasuka and Aoki, 2006) that reported the importance of temperature for juvenile overwinter survival. These authors reported also that the importance of the temperature was higher than the amount of food for the juveniles' survival, in agreement with the Bay of Biscay juveniles observed in this work, which during the summer appear to favor the higher temperature off the shelf over the higher food quantity on the shelf. This view is in agreement also with observations made by several authors (Bachiller *et al.*, 2013; Irigoien *et al.*, 2007) which also reported the preference of juvenile anchovy for areas of less food quantity and higher temperature. Irigoien *et al.* (2007) interpreted this as the juveniles taking profit of a loophole of predation off-shelf to increase their survival chances, i.e. as an evolutionary recruitment dynamics strategy. The tendency of the juveniles to remain off-shelf reported in this work is consistent with this potential strategy.

We are aware that the existence of a significantly different temperature gradient between areas in one particular year does not prove that the temperature gradient causes their different horizontal dynamic pattern. In order to properly confirm this particular hypothesis, a study of the relationship between continental shelf juvenile penetrations versus temperature gradients across the shelf break should be accomplished for several years. In such analysis, other environmental variables should be also tested, especially the turbidity, which may have an influence in the feeding success of an specialized active feeder as juvenile anchovy (Bachiller *et al.*, 2013; Van Der Lingen *et al.*, 2006).

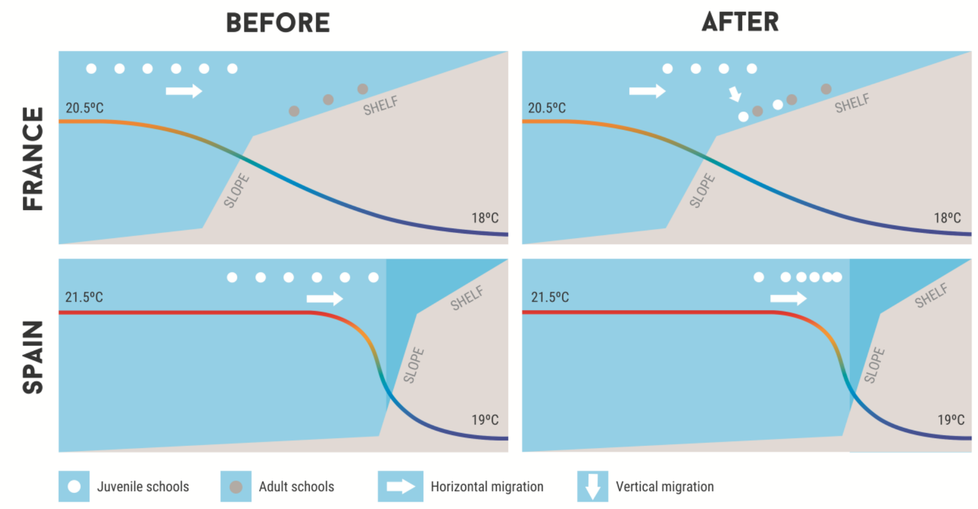


Figure 5-10. Synoptic conceptual diagram of the spatial dynamics of juvenile anchovy in the Bay of Biscay.

5.5.4 Summary of the spatial dynamics of juvenile anchovy in the Bay of Biscay

In order to summarize the findings of this work, we have built a synoptic conceptual diagram (Figure 5-10) that highlights the differential spatial dynamics patterns of juvenile anchovy in the two studied regions. Along the spring and summer seasons, the larval and post-larval anchovies are transported from the spawning grounds on the shelf towards the slope and oceanic waters by the predominant geostrophic currents. The particular shape of the Bay of Biscay coastline and bathymetry affects the life cycle strategy of anchovy at the larval and juvenile stage. The L-shaped bathymetry (Figure 5-1), among other effects, causes the apparition of eddies during the summer that maintain the stability and retention, thus producing a temperature increase of the off-shelf waters (Koutsikopoulos and Le Cann, 1996; Pingree and Le Cann, 1992).

After the larval drift (Allain *et al.*, 2007a; Cotano *et al.*, 2008), the anchovy juveniles remain off the shelf for some weeks and seem to take profit of this situation by increasing the metabolic rate growing rapidly (Aldanondo *et al.*, 2010; Bachiller *et al.*, 2013) and exploiting the loophole of predation characteristic of these regions (Irigoien *et al.*, 2007). When they are large enough, they start to migrate gradually towards the coast (Aldanondo *et al.*, 2010; Boyra *et al.*, 2013; Irigoien *et al.*, 2007). This migration takes place differently according to the width of the continental shelf, perhaps depending on the temperature gradient across the shelf break (Figure 5-9):

(i) In the Spanish sector, where the temperature gradient is stronger (due to high temperature differences and narrower continental shelf) there is a "barrier effect": the juveniles stop the migration at the shelf break, without entering the continental shelf. Given that the most outer juveniles keep migrating toward the shelf break, the area of distribution narrows and compresses against the shelf break during the autumn. The compression increases the fish density and changes the aggregation patterns, the schools becoming fewer and heavier. The off-shelf juveniles remain isolated from the rest of the small pelagic community and stay near the surface behaving like typical juveniles.

(ii) In the French sector, where the temperature gradient is weaker (because of similar temperatures at both sides of the shelf break and a wider continental shelf), there is no barrier effect at the shelf break and the juveniles continue their migration onto the continental shelf. Once on the shelf, the largest juveniles join the small pelagic fish community (including anchovy adults, thus, starting the recruitment process) and start following their behavior performing the adult-like nyctemeral vertical migrations (Petitgas *et al.*, 2006).

The coupling of the described gradual spatial dynamic patterns and the recruitment strategy of juvenile anchovy would involve (i) remaining off the shelf for some time exploiting the favorable temperature and predation conditions until reaching sufficient sizes to assure winter survival; and, afterwards, (ii) entering the continental shelf waters to meet anchovy adults and start following their behavior and thus receiving from them entrainment vital to accomplish the closure of the life cycle. The gradual migration pattern normally lasts until mid-October, until the appearance of the first autumn storms, which trigger the entrance of the winter regime, with the sudden drop of ambient temperature, the increase of the poleward slope current and generation of stronger and more persistent currents towards the east in the Spanish slope and the north in the French slope (Pingree and Le Cann, 1990). This change seems to cause the sudden end of the remaining off-shelf accumulation of juveniles. At that stage the juveniles start to appear in coastal waters, sometimes detected in the scientific surveys of juvenile anchovy, as reported in year 2006 (Boyra et al. 2013), and sometimes even causing the stranding of juveniles in the beaches along the Spanish coast. After this, we can only infer that the juveniles (especially the southern ones) keep migrating to the east along the Spanish coast until they eventually reach the French shelf or different estuary mouths along the northern Spanish coast, where they will be observed spawning during the next spring.

5.6 Acknowledgements

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5.7 Publication data

Type	Peer-reviewed article
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Journal	Fisheries Oceanography
Year	2016
Volume	25
Issue	3
Pages	520-543


RAMÓN MARGALEF

Foto: B.O. Ramón Margalef (Fuente. Udane Martínez).

Conclusiones generales

Capítulo 1 | **LIDAR frente a acústica**

- Se encuentra una relación moderada entre los registros acústicos y LIDAR.
- Pero el LIDAR no posee un rango de detección ni capacidad de discriminación suficiente para proporcionar un índice de abundancia de anchoa juvenil fiable.
- Se proponen mejoras para el LIDAR:
  - Estimar TS óptico de las especies objetivo.
  - Campañas mixtas acústicas-LIDAR.
  - Mejorar el procesado de datos.
- Se elige la acústica como metodología adecuada para desarrollar el índice de reclutamiento.

Capítulo 2 | **Índice de reclutamiento**

- Relación significativa entre biomasa de juveniles y reclutas al año siguiente.
- La relación no depende de ningún año en particular.
- Relación independiente del modelo de regresión.
- La elección del modelo óptimo debería ser investigada.
- El índice de juveniles constituye una predicción valida del reclutamiento.
- La campaña JUVENA se empleó para reabrir la pesquería parcialmente en el año 2009.

Capítulo 3 | **Incertidumbres del índice JUVENA**

- La combinación errores aleatorios presenta un valor bajo comparado con los valores de las estimas, por lo que la tasa señal/ruido de los datos es alta (2.5).
- La diferencia entre estimas alternativas es pequeña comparada con las diferencias entre niveles de biomasa interanuales.
- La capacidad predictiva del reclutamiento es significativa para todas las estimas alternativas (sin corregir o con cualquiera de las correcciones propuestas).
- En definitiva: las incertidumbres obtenidas presentan un impacto pequeño en el objetivo de proporcionar un indicador del reclutamiento.

Capítulo 4 | **Actualización del índice**

- La adición de dos años más mantiene o mejora la significación y no hace sino reforzar el índice.
- La campaña JUVENA anticipó la recuperación de la anchoa en el año 2012, favoreciendo a la reapertura de la pesquería.
- A partir del año 2014, la campaña JUVENA se integra en la estima sintética de abundancia realizada por el ICES, denominada a partir de entonces CBBM.
- La capacidad predictiva a partir de ese año ya no se puede evaluar por comparación con las estimas del CBBM, ya que se incurriría en una relación circular.
- Pero sí se puede analizar comparando el índice JUVENA con las estimas de reclutamiento de las campañas de primavera individualmente. De hecho, la capacidad predictiva del índice calculada de esta manera se mantiene incluyendo los reclutamientos de hasta el año 2106.

Capítulo 5 | Dinámica espacial de anchoa juvenil

- A principios de otoño, la anchoa juvenil migra hacia la costa a un ritmo de una milla náutica por día aproximadamente.
- En la zona cantábrica (plataforma estrecha) se produce un efecto “barrera”: la anchoa permanece fuera de la plataforma continental, apretándose contra el cantil. En la zona francesa (plataforma ancha) no hay efecto “barrera”, los juveniles continúan la migración a través del cantil penetrando en aguas de la plataforma.
- La anchoa juvenil aumenta su profundidad con el tiempo sólo después de haber entrado en aguas de plataforma.
- La diferencia de comportamiento en zonas de plataforma ancha y estrecha, probablemente sea debido al gradiente de temperatura y quizá al gradiente de turbidez.

Validación de la hipótesis

La correlación significativa obtenida entre la biomasa de anchoa juvenil y reclutas, independientemente del modelo de regresión elegido, valida la hipótesis planteada en esta tesis. Por consiguiente se puede afirmar que la variabilidad en la mortalidad de juveniles durante el invierno no es tan alta como para eliminar la relación entre la abundancia de juveniles y reclutas en el Golfo de Vizcaya. Por tanto el índice de abundancia de anchoa juvenil a principios de otoño, unos cuatro meses después de la puesta, proporciona un índice válido (y por tanto una estima anticipada) del reclutamiento que se producirá al año siguiente.

General conclusions

Chapter 1 | LIDAR Vs acoustics

- The positive correlation between LIDAR and echo sounders prove that LIDAR is able to detect and map the aggregations of the pelagic species targeted in the present work.
- However, LIDAR doesn't provide enough detection range. In addition it provides poor discrimination between fish and plankton
- Consequently, the following improvements are recommended so that airborne LIDAR can provide abundance estimates:
    - Measure LIDAR target strengths for the fish and plankton of the region.
    - Design mixed aircraft/ship surveys that take advantage of the strengths of each platform.
    - Improve LIDAR signal processing to better distinguish between different targets.
- Acoustics is chosen as the proper methodology to develop the recruitment index.

Chapter 2 | Recruitment index

- Significant relationship between juvenile biomass and recruit biomass the following year.
- This relationship doesn't depend on any particular year.

- The relationship is independent from the regression model (parametric or non-parametric)
- The optimum regression model should be further investigated.
- The juvenile index provides a valid recruitment prediction.
- The JUVENA survey 2009 was used to partially reopen the fishery in year 2010.

Chapter 3 | Uncertainties of the JUVENA index

- The combination of random errors is low compared with the abundance estimates, i.e., high SNR (2.5).
- The difference between alternative estimates is small compared with the inter-annual biomass differences.
- The recruitment forecasting capacity is significant for every tested alternative estimates (without corrections or with any of the tested corrections)
- In summary, the uncertainties cause a small impact on the objective of providing a recruitment index.

Chapter 4 | Update of the index

- The addition of two year maintains or improves the significance of the index.
- The JUVENA index predicted the recovery of anchovy stock in year 2012, favoring the reopening of the fishery.
- Since year 2014, the JUVENA survey is included in the new CBBM synthetic abundance estimate done by ICES.
- Since the switch to CBBM in 2014, the forecasting capacity of the index can no longer be estimated by comparison between JUVENA and the synthetic estimate, because it would constitute a circular relationship.
- But it can be estimated by comparing the JUVENA index with the individual abundance indices provided by the assessment surveys (BIOMAN and PELGAS). These relationships are also highly significant, thus proving the

maintenance of the forecasting capacity of the JUVENA index in the CBBM era.

Chapter 5 | Spatial dynamics of juvenile anchovy

- At the beginning of autumn the juveniles are migrating towards the coast at a pace of about 1 nautical mile per day.
- In the Spanish sector (narrow shelf), there is a "barrier effect": the juveniles stop the migration at the shelf break, without entering the continental shelf. In the French sector (wide shelf), there is no barrier effect at the shelf break and the juveniles continue their migration onto the continental shelf.
- Juvenile anchovy increases its depth with time only when in continental shelf waters.
- The difference of behavior between juveniles from narrow and wide shelf are probably due to the temperature gradient and perhaps also to the turbidity gradient between areas.

Validation of the hypothesis

The significant correlation obtained between juvenile anchovy biomass and recruit biomass, independently of the chosen regression model, validates the hypothesis of this thesis. Consequently, it can be said that the variability in the mortality of juveniles during winter is not as high as to remove the relationship between the juvenile and recruitment abundance in the Bay of Biscay. Therefore the index of abundance of juvenile anchovy at the beginning of Autumn, four months after the spawning season, provides a valid index (and, thus, an early estimate) of the next year recruitment.

Foto: Pesca de atún con caña y cebo vivo a bordo del Gure Aita Joxe durante la campaña JUVENA 2005 (Fuente: propia).

Agradecimientos

Llevo trabajando en esta tesis doctoral desde el año 1999, aunque en aquel momento no era consciente de que esto fuera a convertirse algún día en una tesis. De hecho, en el año 2006 me inscribí en un programa de doctorado de la UPV para hacer otra tesis en una línea de investigación completamente distinta. No fue hasta el año 2008 que me di cuenta de las posibilidades de la campaña JUVENA y le di un golpe de timón a mi incipiente proyecto doctoral. Y aún han tenido que pasar otros nueve años hasta poder terminarla. Dieciocho años en total. Si en vez de una tesis fuera una persona, podría votar, conducir y beber alcohol legalmente. Dieciocho años y quince campañas oceanográficas en diez embarcaciones distintas, dos avionetas, no sé cuántos científicos involucrados, tripulaciones, becarios… y el dineral que ha costado todo esto. Así que, si normalmente las tesis doctorales acumulan deudas, crisis, colaboraciones, ayudas y asistencias varias, un proyecto tan largo y ambicioso acumula muchas más, por lo que la lista de agradecimientos se alarga proporcionalmente. Espero ser capaz de acordarme de todos los que me han ayudado de una forma u otra a lo largo de este camino, pero en caso de que me olvide de alguien, vayan por delante mis disculpas y la esperanza de comprensión por su parte.

Este proyecto ha tenido dos pilares fundamentales. El primero es Andrés Uriarte, la persona que me trajo a AZTI como becario y me formó hasta convertirme en un científico. Andrés fue quien imaginó este proyecto y luego me lo fue contando despacito, paso a paso, para que yo lo entendiera y lo realizara sin equivocarme. Fue por tanto el padre de la criatura y un apoyo constante y fundamental, sobre todo cuando hizo falta, en los años difíciles del cierre de la pesquería, cuando cada grupo de trabajo era una batalla para sacar la campaña adelante. Andrés habría sido obviamente el director natural de esta tesis si la vorágine de este mundo de locos no le hubiera impedido tener su doctorado a tiempo. El otro pilar de este proyecto ha sido Udane Martínez, que es quien ha hecho la mayor parte del trabajo y ha sostenido la peor mitad de la campaña sobre sus hombros durante más de diez años. Udane ha sido mi socia principal y cómplice en la campaña, y sin su implicación y eficacia contrarrestando mi naturaleza caótica, el proyecto hace años que habría naufragado. Esta tesis está dedicada a Andrés y Udane, porque sin ellos no habría existido. Gracias a los dos.

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Winston

Foto: Pesca de anchoa juvenil con red de cerco. JUVENA 2005 (Fuente: propia).

Appendix

Sample echograms from JUVENA 2003-2009

Ecogramas de ejemplo de JUVENA 2003-2009

A set of echogram images is provided as examples of juvenile anchovy detections during the JUVENA surveys. This is a selection from the ones that were included in the paper that constitutes Chapter 2 of this Thesis and can be found in the ICESJMS web site. The main purpose of these echogram images is to try to give a "flavor" of the type of scrutinization process of the JUVENA echograms to the readers.

A continuación se muestra una selección de la serie de ecogramas de ejemplo que se incluyeron como información suplementaria al artículo que constituye el Capítulo 2 de esta tesis en su publicación en el ICES Journal of Marine Science. Esta incorporación se realizó en su momento para dar una idea visual del tipo de datos acústicos que se recogían en la campaña JUVENA y constituía una recopilación exhaustiva de todos los ecogramas de ejemplo incluidos en los informes anuales presentados al ICES y al Gobierno Vasco desde el comienzo de la campaña en el año 2003 hasta el año 2009. En esta tesis se incluyen por el mismo motivo.

YEAR 2003 1/2

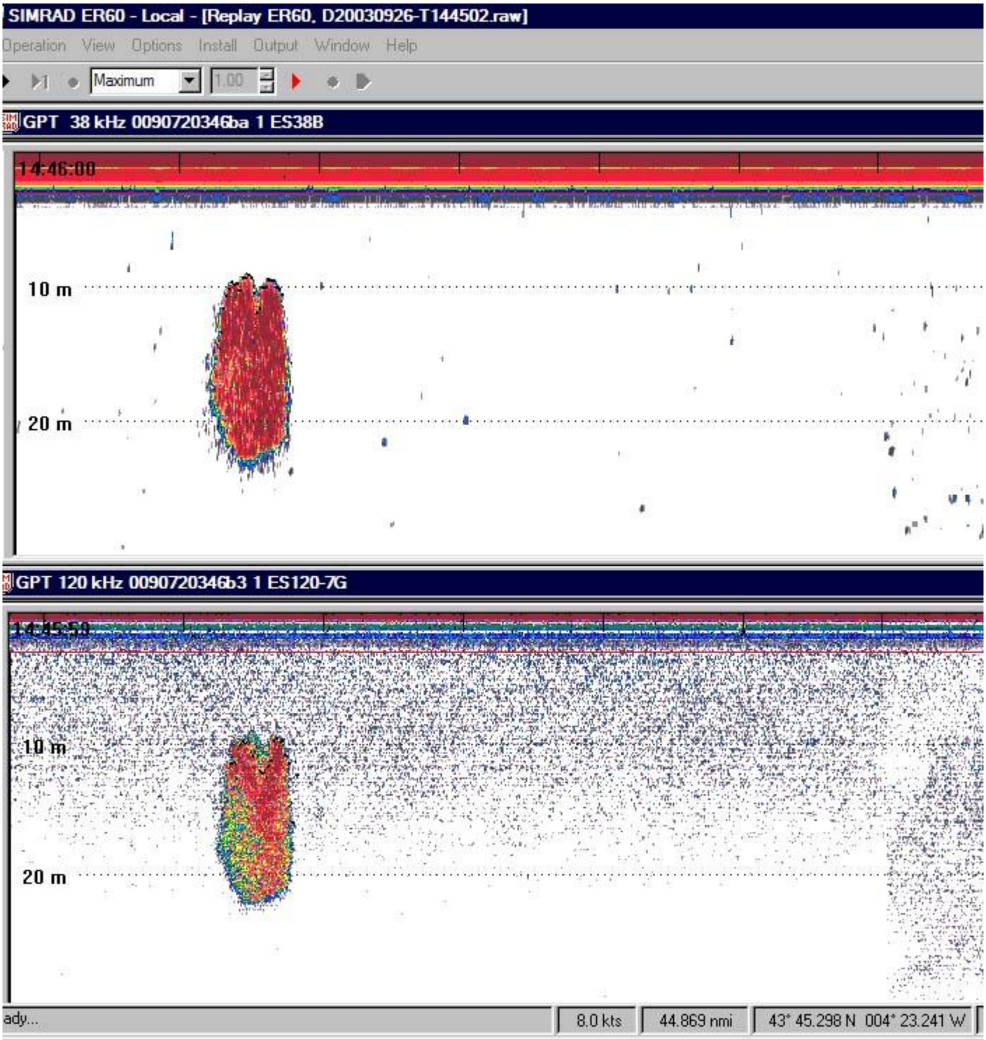

Figure E1. Dense school of juvenile anchovy observed off the shelf in the Western part of the Cantabric Sea in 2003 (-70 dB threshold).

YEAR 2003 2/2

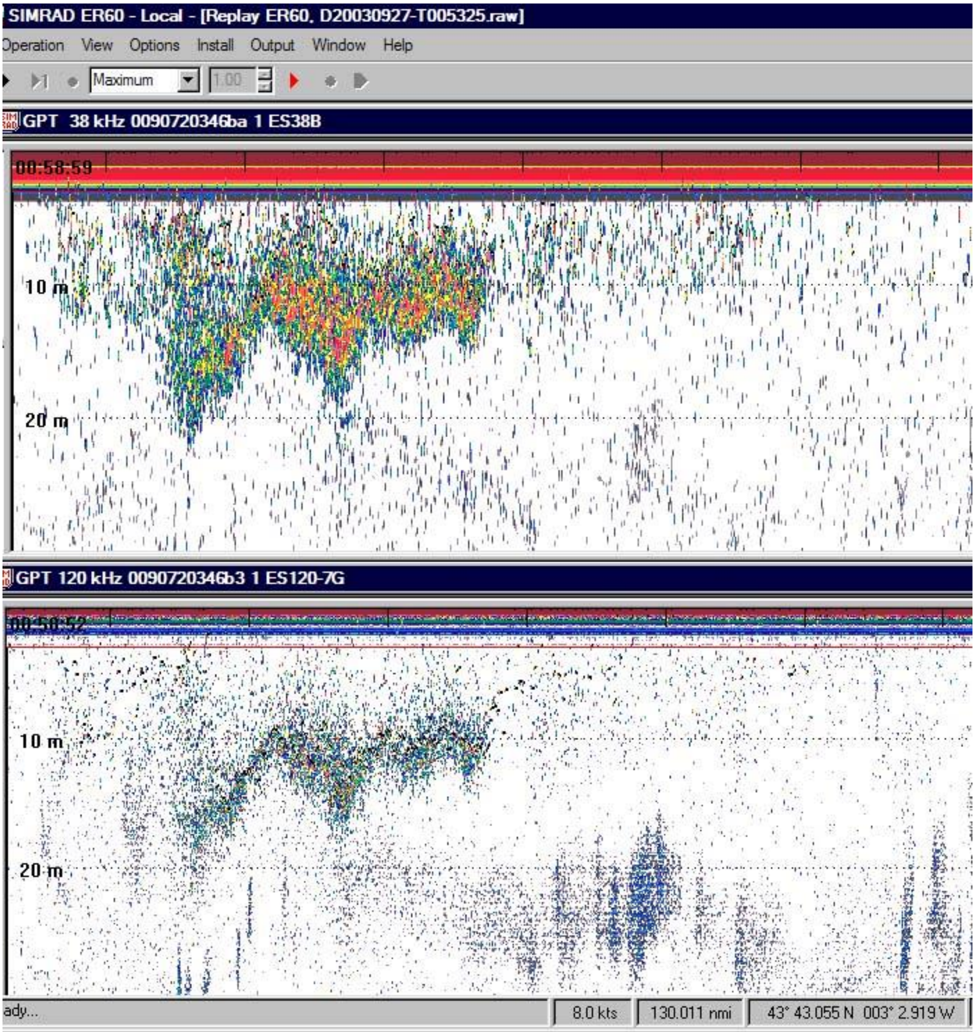

Figure E2. Dense school of juvenile anchovy in the process of dispersing 2 hours after sunset observed off the shelf in the central part of the Cantabric Sea in 2003 (-70 dB). Below it, some schools of krill can be distinguished at the 120 kHz.

YEAR 2004 1/2

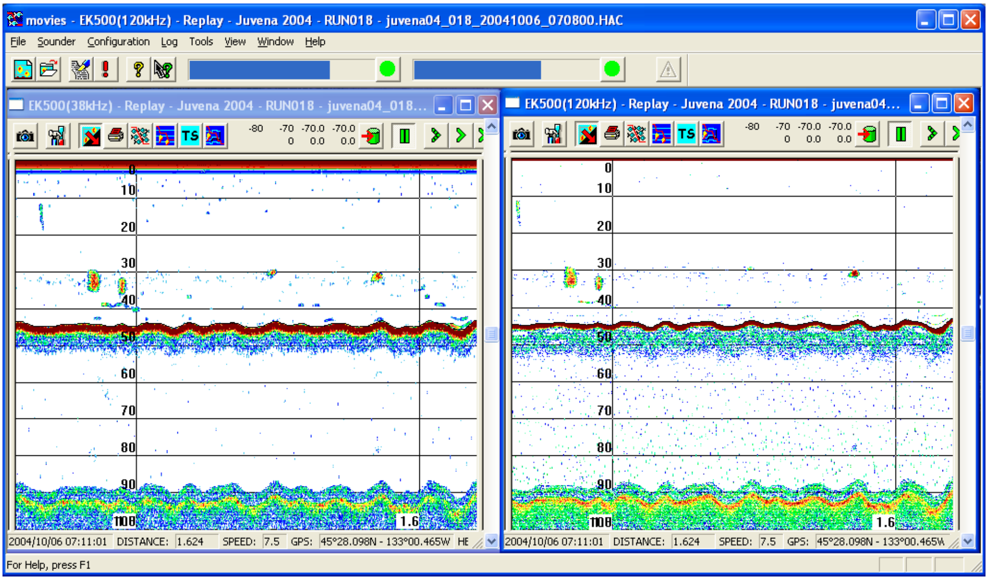

Figure E3. Fish schools detected in front of the Garonne mouth in 2004 just before making a haul that resulted in about 50% adult anchovy mixed with spratt and sardine (-70 dB).

YEAR 2004 2/2

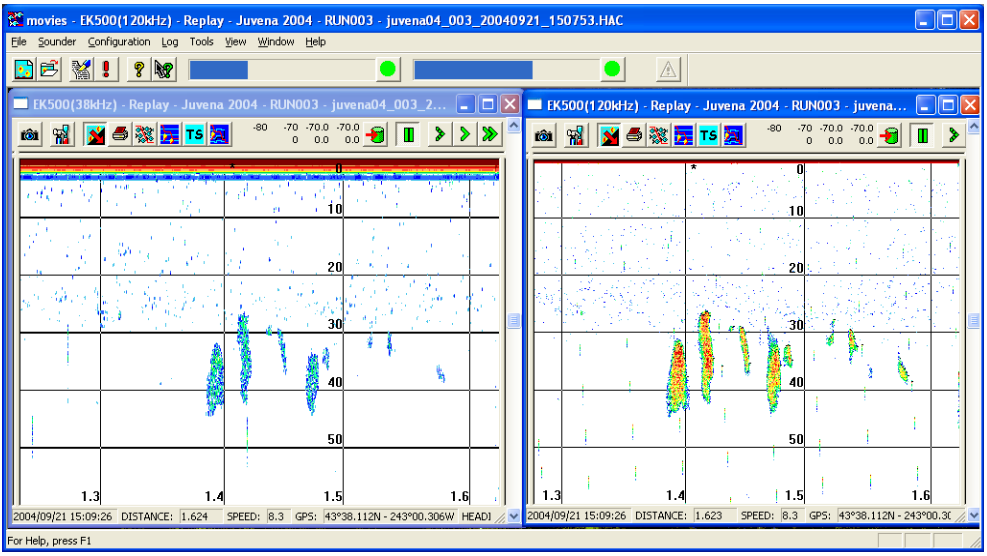

Figure E4. Typical dense aggregations of krill detected at the off-shelf part of the Cantabrian Sea, showing higher frequency response at 120 (right) than 38 (left) kHz. Some spikes produced by the sonar of the purse seiner are also visible in both frequencies. The display threshold is set at -70 dB.

YEAR 2005 1/3

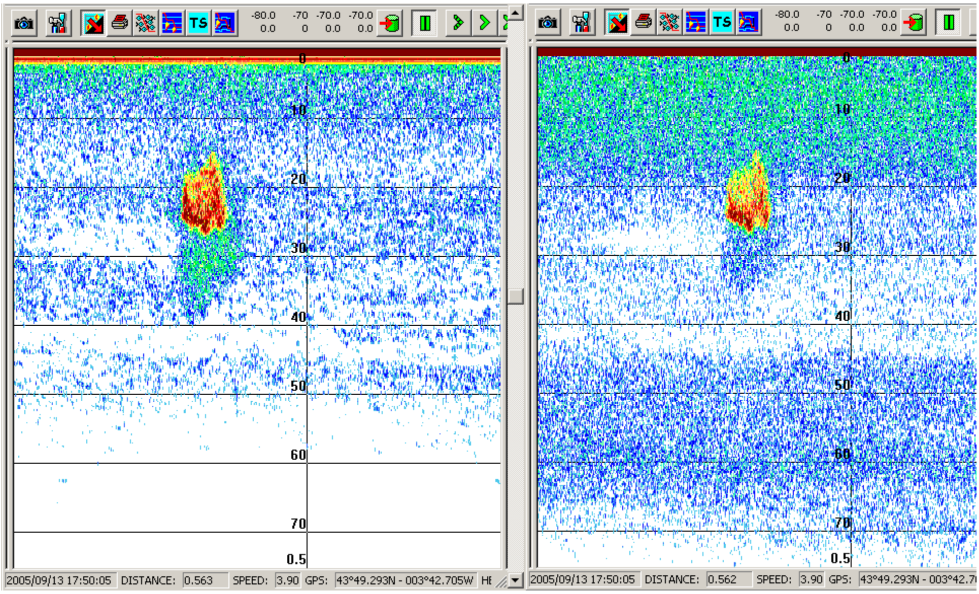

Figure E5. Example of school of good size found off the shelf in the Cantabric area in year 2005. The haul provided 500 kg of pure juvenile anchovy of 75 mm of standard lenth (mode). This is one of the rare occasions (if not the only one) in which anchovy schools were detected surrounded by a thick plankton layer and the image of the echogram was stored for this reason. The display threshold is set at -70 dB. Note that the plankton layer is denser at the 120 (right) than the 38 (left) kHz transducer.

YEAR 2005 2/3

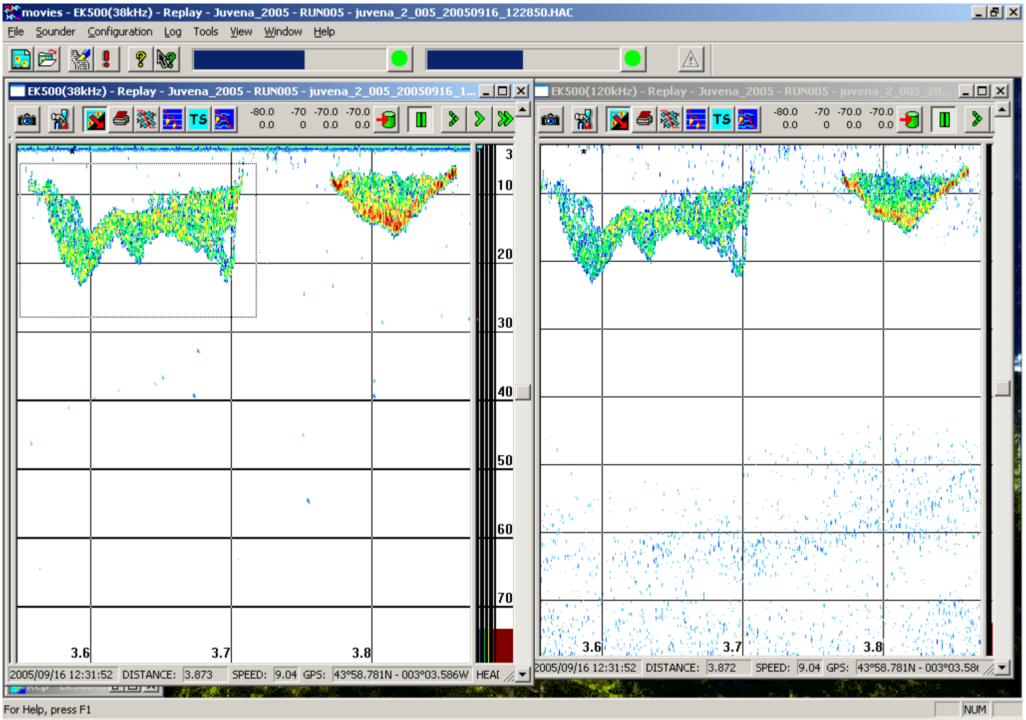

Figure E6. End of long layer of anchovy juveniles detected off the Cantabric shelf, in one of the most abundant areas found during the JUVENA 2005 survey. The haul provided 100 kg of pure juvenile anchovy, of 79 mm of standard length (mode). Note the considerable size of the aggregations: about 250 (L) x 15 (H) m the one at the left and about 150x10 m the next one. The display threshold is set at -70 dB. The left window shows the 38 kHz frequency echogram and the right side window the 120 kHz.

YEAR 2005 3/3

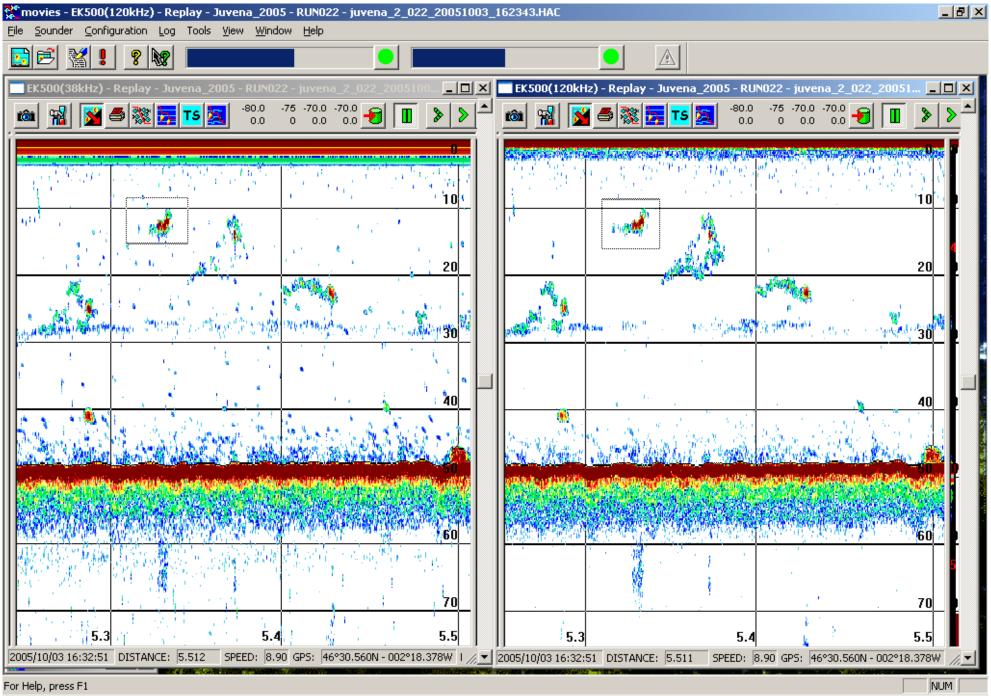

Figure E7. Aggregation of schools detected to the North of the Garonne mouth, attributed to mackerell. These particular schools were not captured, but several hauls performed in the vicinity of this area caught significant abundances of this specie. The display threshold is set at -70 dB. The left window shows the 38 kHz frequency echogram and the right side window the 120 kHz.

YEAR 2006 1/2

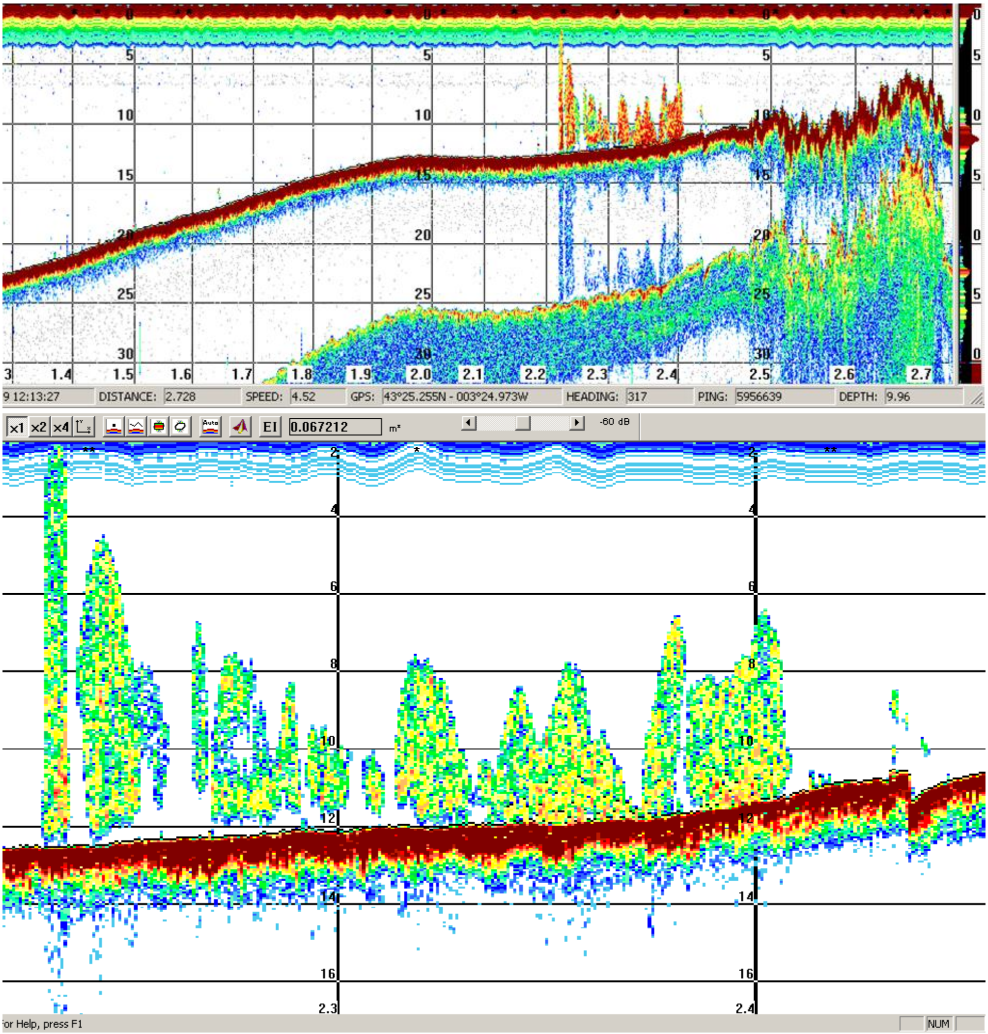

Figure E8. Shallow aggregation of anchovy juveniles at the Bay of Santoña. Top: 38 kHz echogram of the last 2 n.mi. of the transect that finished in Santoña showing the typical situation of 100 % juvenile anchovy aggregations in the southern part of the stock that year: concentration in dense but slim areas in shallow waters. This type of shallow aggregations were repeatedly and continuously detected from Cape of Peñas up to North of Arcachon (45ºN). Display threshold -70 dB. Bottom: Zoom of the juvenile anchovy aggregation shown above at -60 dB threshold.

YEAR 2006 2/2

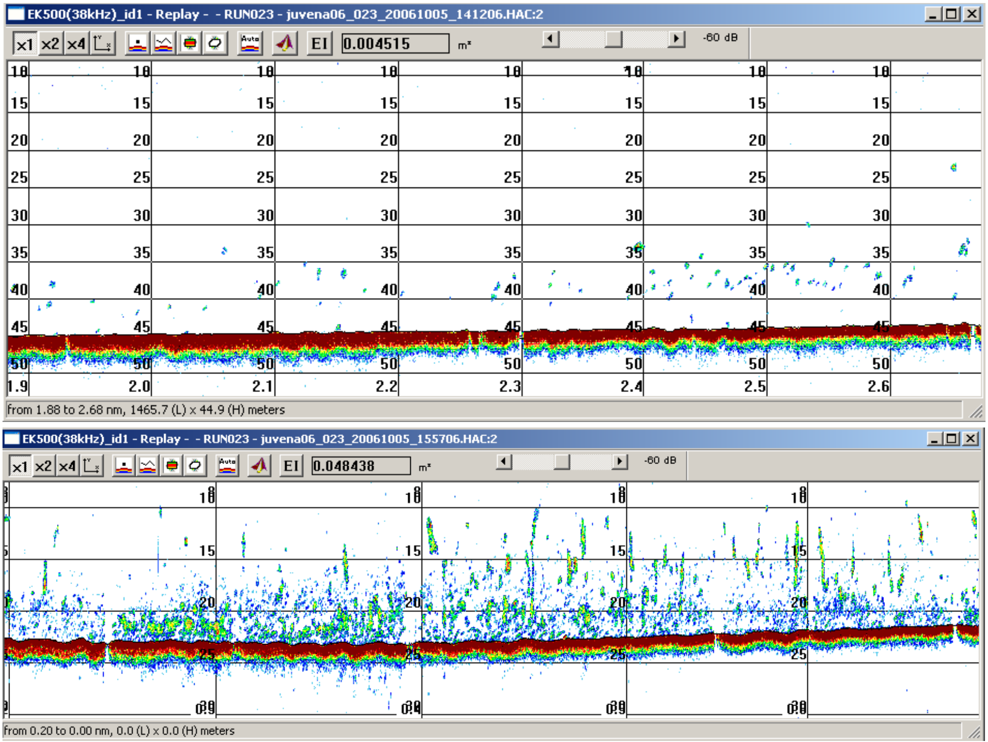

Figure E9. Top: Typical deep structure of mixed anchovy in the Garonne area at 38 kHz frequency in year 2006. The display threshold is set at -60 dB. Bottom: Anchovy structure gets denser a little bit closer to the coast in the same transect of the Garonne area (a haul provided 95% of anchovy; 156 kg total weight). The display threshold is set at -60 dB.

YEAR 2007 2/2

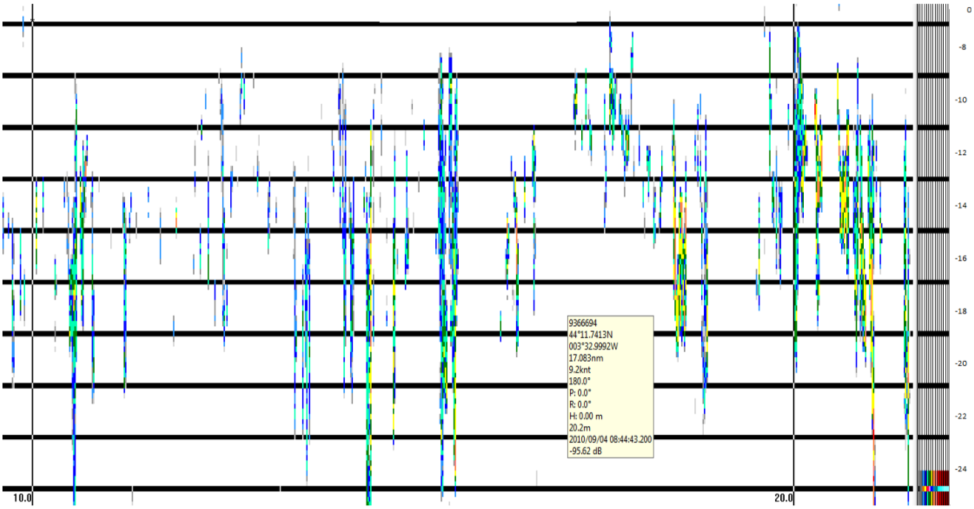

Figure E10. Condensed echogram showing about 12 n.mi. of a typical continuity of aggregations of juvenile anchovy off the Cantabrian shelf in year 2007 distributed from7 to 25 m depht. The frequency is 38 kHz and the display threshold is set at -60 dB.

YEAR 2008 1/1

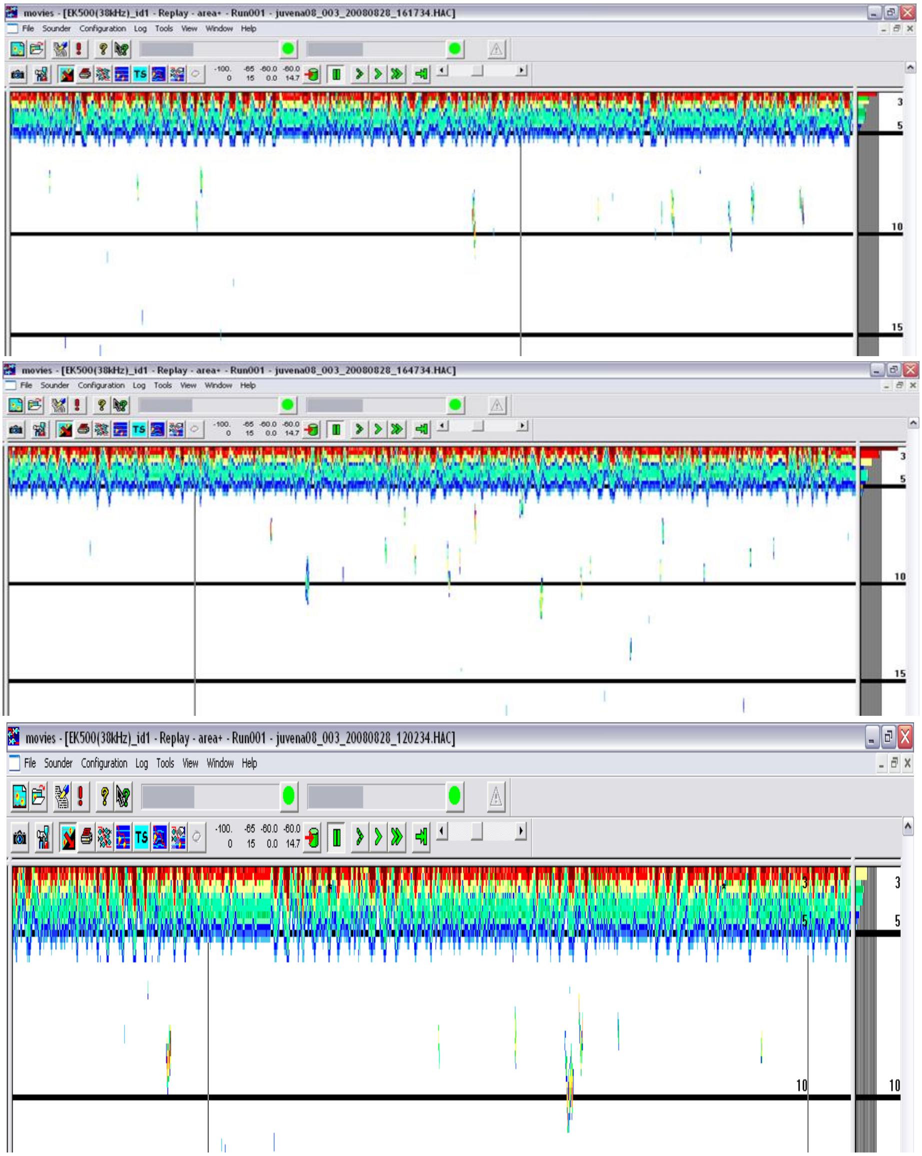

Figure E11. Three examples of 38 kHz echograms showing disperse and weak aggregations of juvenile anchovy off the shelf shelf in year 2008. These can be considered the characteristic offshore aggregations in years of low abundance. The display threshold is set at -65 dB.

YEAR 2009 1/2

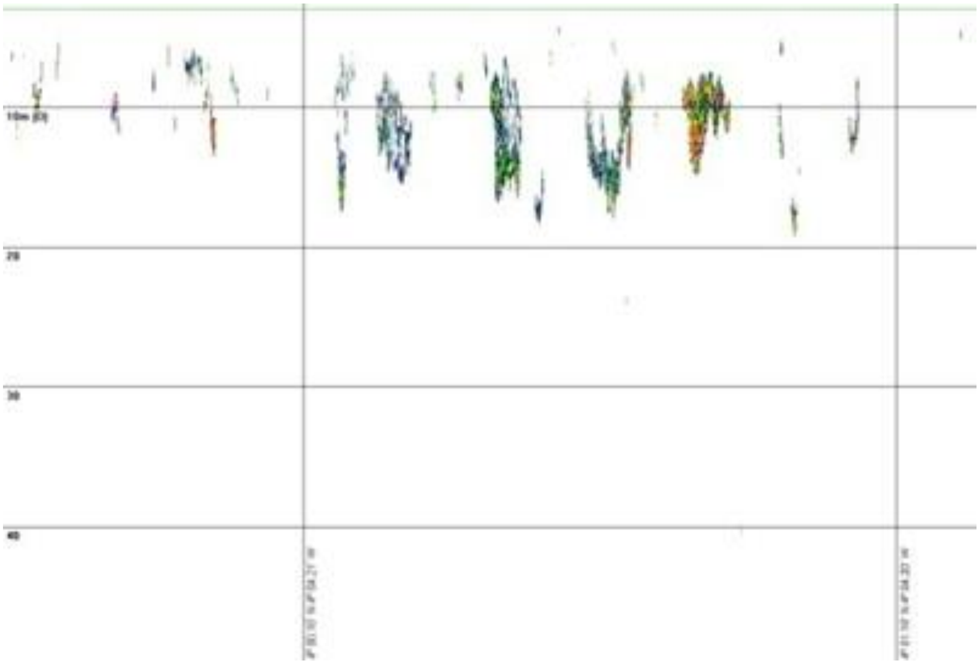

Figure E12. Near-surface juvenile anchovy aggregations observed off the shelf in year 2009. The frequency is 38 kHz and the display threshold is set at -60 dB.

YEAR 2009 2/2

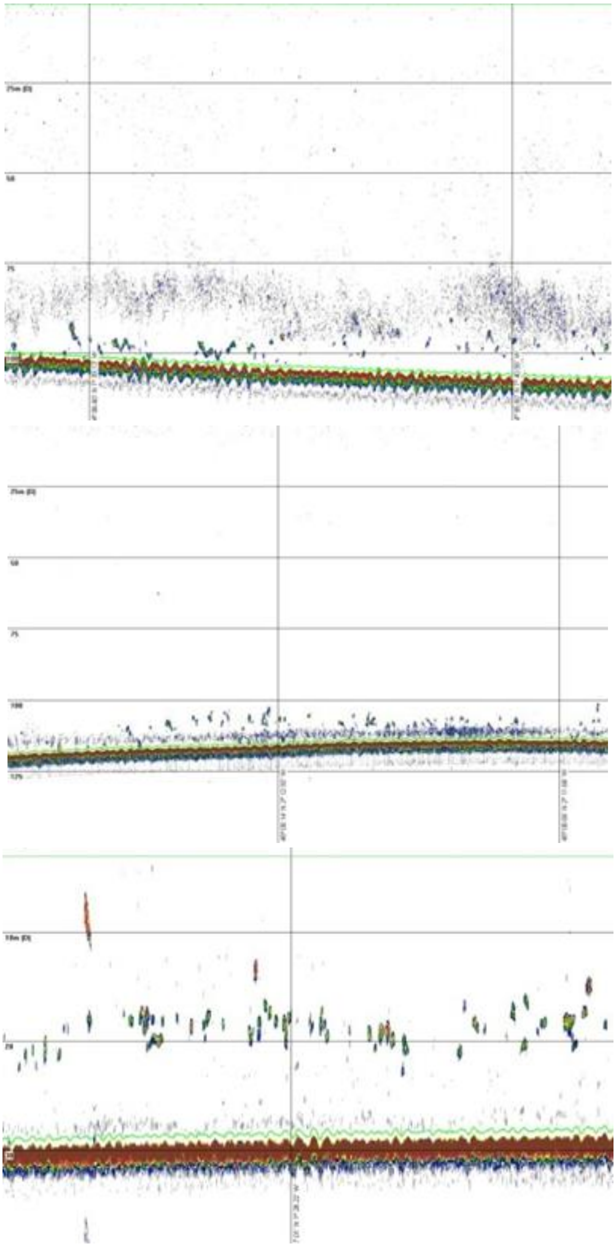

Figure E13. Anchovy juveniles mixed with adults and other species close to the bottom on the French shelf waters in year 2009. The display threshold is set at -60 dB.

Foto: Estiba y limpieza de la red de cerco tras el lance. JUVENA 2005 (Fuente: propia).

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Bibliography

Bibliografía

Bibliografía de la introducción

Albaina, A., Irigoien, X., Aldalur, U., Cotano, U., Santos, M., Boyra, G. and Estonba, A. 2015. A real-time PCR assay to estimate invertebrate and fish predation on anchovy eggs in the Bay of Biscay. Progress in Oceanography, 131, 82-99.

Albaina, A., Irigoien, X., Aldalur, U., Boyra, G., Santos, M. and Estonba, A. 2015. Macrozooplankton predation impact on anchovy (Engraulis encrasicolus) eggs mortality at the Bay of Biscay shelf break spawning centre. ICES Journal of Marine Science, 72(5), 1370–1379.

Aldanondo, N., Cotano, U., Tiepolo, M., Boyra, G., and Irigoien, X. 2010. Growth and movement patterns of early juvenile European anchovy (Engraulis encrasicolus L.) in the Bay of Biscay based on otolith microstructure and chemistry. Fisheries Oceanography, 19: 196–208.

Allain, G., Petitgas, P., and Lazure, P. 2001. The influence of mesoscale ocean processes on anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography, 10: 151–163. John Wiley \& Sons.

Bachiller, E., Cotano, U., Boyra, G., and Irigoien, X. 2013. Spatial distribution of the stomach weights of juvenile anchovy (Engraulis encrasicolus L.) in the Bay of Biscay. ICES Journal of Marine Science, 70: 362–378.

Aldanondo, N., Cotano, U., Tiepolo, M., Boyra, G., and Irigoien, X. 2010. Growth and movement patterns of early juvenile European anchovy (Engraulis encrasicolus L.) in the Bay of Biscay based on otolith microstructure and chemistry. Fisheries Oceanography, 19: 196–208.

Allain, G., Petitgas, P., and Lazure, P. 2001. The influence of mesoscale ocean processes on anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography, 10: 151–163. John Wiley \& Sons.

Allain, G., Petitgas, P., and Lazure, P. 2007a. The influence of environment and spawning distribution on the survival of anchovy (Engraulis encrasicolus) larvae in the Bay of Biscay (NE Atlantic) investigated by biophysical simulations. Fisheries Oceanography, 16: 506–514.

Allain, G., Petitgas, P., Lazure, P., and Grellier, P. 2007b. Biophysical modelling of larval drift , growth and survival for the prediction of anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay (NE Atlantic). Fisheries Oceanography, 16: 489–505.

Bachiller, E., Cotano, U., Boyra, G., and Irigoien, X. 2013. Spatial distribution of the stomach weights of juvenile anchovy (Engraulis encrasicolus L.) in the Bay of Biscay. ICES Journal of Marine Science, 70: 362–378.

Bachiller, E., and Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay. Ecological effects of trophic interactions.

Bivand, R., and Lewin-Koh, N. 2015. maptools: Tools for Reading and Handling Spatial Objects.

Borja, A., Fontan, A., Saenz, J., and Valencia, V. 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (Engraulis encrasicolus) ´. Fisheries Oceanography, 17: 477–493.

Borja, A., Uriarte, A., Egaña, J., Motos, L., and Valencia, V. 1998. Relationships between anchovy (Engraulis encrasicolus) recruitment and environment in the Bay of Biscay (1967±1996). Fisheries Oceanography, 7: 375–380.

Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. ICES Journal of Marine Science, 70: 1354–1368.

Carrera, P., Churnside, J. H., Boyra, G., Marques, V., Scalabrin, C., and Uriarte, A. 2006. Comparison of airborne lidar with echosounders: a case study in the coastal Atlantic waters of southern Europe. ICES Journal of Marine Science, 63: 1736–1750.

Charria, G., Lazure, P., Le Cann, B., Serpette, A., Reverdin, G., Louzael, S., Batifoulier, F., *et al.* 2013. Surface layer circulation derived from Lagrangian drifters in the Bay of Biscay. Journal of Marine Systems, 109-110: S60–S76.

COM374. 2010. Establishing the fishing oportunities for Anchovy in the Bay of Biscay for the 2010-2011 fishing season and amending Regulation (EU) No 53/2010. Brussels.

Cort, J. L., Cendrero, O., and Iribar, X. 1977. La anchoa (engraulis encrasicholus) (L.) del Cantábrico. Bol. Inst. Espa. Oceano., 220.

Cotano, U., Irigoien, X., Etxebeste, E., Alvarez, P., Zarauz, L., Mader, J., and Ferrer, L. 2008. Distribution, growth and survival of anchovy larvae (Engraulis encrasicolus L.) in relation to hydrodynamic and trophic environment in the Bay of Biscay. Journal of Plankton Research, 30: 467–481.

Fernandes, J. a., Irigoien, X., Goikoetxea, N., Lozano, J. a., Inza, I., Pérez, A., and Bode, A. 2010. Fish recruitment prediction, using robust supervised classification methods. Ecological Modelling, 221: 338–352.

Foote, K. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. International Council for the Exploration of the Sea. 81 pp.

Gerritsen, H. 2013. mapplots: Data visualisation on maps.

Gomis, D., Ruiz, S., and Pedder, M. 2001. Diagnostic analysis of the 3D ageostrophic circulation from a multivariate spatial interpolation of CTD and ADCP data. Deep Sea Research, 48: 269–295.

Hoare, D. J., Krause, J., Peuhkuri, N., and Godin, J.-G. J. 2000. Body size and shoaling in fish. Journal of Fish Biology, 57: 1351–1366.

Ibaibarriaga, L., Fernandez, C., Uriarte, A., Roel, B. a., Ibaibarriaga, L., and Ferna, C. 2008. A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES Journal of Marine Science, 65: 191.

ICES. 2009. Report of the Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VIII and IX (WGACEGG). ICES CM, LRC:20: 181.

ICES. 2015a. . Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA), 24–29 June 2015, Lisbon, Portugal.: 612 pp.

ICES. 2015b. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES CM, ACOM:16: 580.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008a. From egg to juvenile in the Bay of Biscay: spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008b. From egg to juvenile in the Bay of Biscay: Spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Fiksen, Ø., Cotano, U., Uriarte, A., Alvarez, P., Arrizabalaga, H., Boyra, G., *et al.* 2007. Could Biscay Bay Anchovy recruit through a spatial loophole? Progress in Oceanography, 74: 132–148.

Kondrashev, S. L., Gnyubkina, V. P., and Zueva, L. V. 2012. Structure and spectral sensitivity of photoreceptors of two anchovy species: Engraulis

japonicus and Engraulis encrasicolus. Vision Research, 68: 19–27. Elsevier Ltd.

Koutsikopoulos, C., and Le Cann, B. 1996. Physical processes and hydrological structures related to the Bay of Biscay anchovy. Scientia Marina, 60: 9–19.

Lawson, G. L., Barange, M., Freon, P., and Fre, P. 2001. Species identification of pelagic fish schools on the South African continental shelf using acoustic descriptors and ancillary information. ICES Journal of Marine Science, 58: 275–287.

Maclennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365.

Massé, J. 1996. Acoustic observations in the Bay of Biscay : Schooling , vertical distribution , species assemblages and behaviour *. Scientia Marina, 60: 227–234.

Motos, L., Uriarte, A., and Valencia, V. 1996a. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L.). Scientia Marina, 60: 117–140. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Motos, L., Uriarte, A., and Valencia, V. 1996b. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L). Scientia Marina, 60: 117–140.

Novales Flamarique, I. 2011. Unique photoreceptor arrangements in a fish with polarized light discrimination. Journal of Comparative Neurology, 519: 714–737.

Ona, E. 2003. An expanded target-strength relationship for herring. ICES Journal of Marine Science, 60: 493–499.

Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay.

Petitgas, P., Reid, D. G. D., Planque, B., Nogueira, E., Hea, B. O., Cotano, U., and O'Hea, B. 2006. The entrainment hypothesis: an explanation for the

persistence and innovation in spawning migrations and life cycle spatial patterns. ICES CM: 9pp.

Petitgas, P., Secor, D. H., McQuinn, I., Huse, G., and Lo, N. 2010. Stock collapses and their recovery: mechanisms that establish and maintain life-cycle closure in space and time. ICES Journal of Marine Science, 67: 1841–1848.

Pingree, R. ., and Le Cann, B. 1992. Three anticyclonic slope water oceanic eDDIES (SWODDIES) in the Southern Bay of Biscay in 1990. Deep Sea Research Part A. Oceanographic Research Papers.

Pingree, R. D., and Le Cann, B. 1990. Structure, strength and seasonality of the slope currents in the bay of Biscay region. J. Mar. Biol. Ass. U.K.

Pitcher, T. J., and Parrish, J. K. 1993. The functions of shoaling behaviour. *In* The behaviour of teleost fishes, 2nd ed., pp. 363–439. Ed. by T. J. Pitcher. Chapman and Hall, London.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raab, K., Llope, M., Nagelkerke, L. a J., Rijnsdorp, A. D., Teal, L. R., Licandro, P., Ruardij, P., *et al.* 2013. Influence of temperature and food availability on juvenile European anchovy Engraulis encrasicolus at its northern boundary. Marine Ecology Progress Series, 488: 233–245.

Simmonds, J. E., and Maclennan, D. N. 2005a. Fisheries Acoustics Theory and Practice. Second Edition. Chapman & Hall, New York: 472pp.

Simmonds, J. E., and Maclennan, D. N. 2005b. Fisheries acoustics - Theory and practice. Blackwell Publishing. 437 pp.

Sinclair, M. 1988. Marine populations. An assay on population regulation and speciation. 251 pp.

Solabarrieta, L., Rubio, A., Castanedo, S., Medina, R., Charria, G., and Hernández, C. 2014. Surface water circulation patterns in the southeastern

Bay of Biscay: New evidences from HF radar data. Continental Shelf Research, 74: 60–76.

Takasuka, A., and Aoki, I. 2006. Environmental determinants of growth rates for larval Japanese anchovy Engraulis japonicus in different waters. Fisheries Oceanography, 15: 139–149.

Uriarte, A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Scientia Marina, 60: 237–255. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Uriarte, A., Rico, I., Villamor, B., Duhamel, E., Dueñas, C., Aldanondo, N., and Cotano, U. 2016. Validation of age determination in European anchovy. Journal of Marine and Freshwater Research, in press.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Cermeño, P., De Miguel, E., Gómez Sánchez, J., *et al.* 2001a. Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning: do they form part of the plankton. ICES CM, W:20.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Miguel, E. De, Sanchez, J. A. G., Jimenez, M., *et al.* 2001b. 2001 ICES Annual Science Conference ICES CM 2001 / W : 20 Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning : Do they form part of the plankton ? ICES CM, 20.

Van Der Lingen, C., Hutchings, L., and Field, J. 2006. Comparative trophodynamics of anchovy Engraulis encrasicolus and sardine Sardinops sagax in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated. African Journal of Marine Science, 28: 465–477. Taylor \& Francis.

Wickham, H. 2009. ggplot2: elegant graphics for data analysis. Springer New York.

Woillez, M., Poulard, J., Rivoirard, J., Petitgas, P., and Bez, N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES Journal of Marine Science, 64: 537–550.

Zhao, X., Wang, Y., and Dai, F. 2008. Depth-dependent target strength of anchovy (Engraulis japonicus) measured in situ. ICES Journal of Marine Science, 65: 882–888.

Borja, A., Fontan, A., Saenz, J., and Valencia, V. 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (Engraulis encrasicolus) ´. Fisheries Oceanography, 17: 477–493.

Cort, J. L., Cendrero, O., and Iribar, X. 1977. La anchoa (engraulis encrasicholus) (L.) del Cantábrico. Bol. Inst. Espa. Oceano., 220.

Fernandes, J. a., Irigoien, X., Goikoetxea, N., Lozano, J. a., Inza, I., Pérez, A., and Bode, A. 2010. Fish recruitment prediction, using robust supervised classification methods. Ecological Modelling, 221: 338–352.

Ibaibarriaga, L., Fernandez, C., Uriarte, A., Roel, B. a., Ibaibarriaga, L., and Ferna, C. 2008. A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES Journal of Marine Science, 65: 191.

ICES. 2015. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES CM, ACOM:16: 580.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., et al. 2008a. From egg to juvenile in the Bay of Biscay: spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., et al. 2008b. From egg to juvenile in the Bay of Biscay: Spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Fiksen, Ø., Cotano, U., Uriarte, A., Alvarez, P., Arrizabalaga, H., Boyra, G., et al. 2007. Could Biscay Bay Anchovy recruit through a spatial loophole ? Progress in Oceanography, 74: 132–148.

Kawasaki, T. 1992. Mechanisms governing fluctuations in pelagic fish populations. South African Journal of Marine Science, 12: 873–879.

Kondrashev, S. L., Gnyubkina, V. P., and Zueva, L. V. 2012. Structure and spectral sensitivity of photoreceptors of two anchovy species: Engraulis japonicus and Engraulis encrasicolus. Vision Research, 68: 19–27. Elsevier Ltd.

Koutsikopoulos, C., and Le Cann, B. 1996. Physical processes and hydrological structures related to the Bay of Biscay anchovy. Scientia Marina, 60: 9–19.

Massé, J. 1996. Acoustic observations in the Bay of Biscay : Schooling , vertical distribution , species assemblages and behaviour *. Scientia Marina, 60: 227–234.

Motos, L., Uriarte, A., and Valencia, V. 1996. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L.). Scientia Marina, 60: 117–140. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Novales Flamarique, I. 2011. Unique photoreceptor arrangements in a fish with polarized light discrimination. Journal of Comparative Neurology, 519: 714–737.

Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay.

Pingree, R. ., and Le Cann, B. 1992. Three anticyclonic slope water oceanic eDDIES (SWODDIES) in the Southern Bay of Biscay in 1990. Deep Sea Research Part A. Oceanographic Research Papers.

Uriarte, A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Scientia Marina, 60: 237–255. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Miguel, E. De, Sanchez, J. A. G., Jimenez, M., et al. 2001. 2001 ICES Annual Science Conference ICES CM 2001 / W : 20 Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning : Do they form part of the plankton ? ICES CM, 20.

Van Der Lingen, C., Hutchings, L., and Field, J. 2006. Comparative trophodynamics of anchovy Engraulis encrasicolus and sardine Sardinops sagax in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated. African Journal of Marine Science, 28: 465–477. Taylor \& Francis.

Bibliography of Chapter 1

Alshuth, S. 1988. Seasonal variations in length-frequency and birthdate distribution of juvenile sprat (Sprattus sprattus). ICES CM 1988/H:44.

Anon. 1982. Report of the Working Group for the Appraisal of Sardine Stocks in Divisions VIIIc and IXa. ICES CM 1982/Assess:10,41 pp.

Anon. 1998. EU Sardine Study Group, 1998 Report. Vigo (Spain) 4-8 Mayo de 1998.

Anon. 2000a. Report of the Northern Pelagic and Blue Whiting Fisheries Working Group. April/May 2000. ICES C.M. 2000/ACFM:16.

Anon. 2000b. Report of the Working Group on the assessment of mackerel, horse mackerel, sardine and anchovy. Copenhagen 14-23 September 1999. ICES C.M. 2000/ACFM: 5.

Bailey, K.M. and Spring, S.M.. 1992. Comparison of larval, age-0 juvenile and age-2 recruit abundance indices of walleye pollock, Theragra chalcogramma, in the western Gulf of Alaska. ICES Journal of Marine Science 49:297-304.

Blaxter, J.H.S., Gray, J.A.B., and Denton, E.J. 1981. Sound and startle responses in herring shoals. J. mar. boil. Ass. U. K. 61: 851-869.

Boyd, A.J., Shannon, L.L., Schulein, F.H., and Tauton-Clark, J. 1997. Food, transport and anchovy recruitment in the southern Benguela upwelling system off South Africa. In : Global vs. Local Changes in Upwelling Systems. M.H. Durand, P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly (eds) pp 195-210. Paris edition de l'Orstom.

Brown, E.D., Churnside, J.H., Collins, R.L., Veenstra, T., Wilson, J.J., and Abnett, K. 2002. Remote sensing of capelin and other biological features in the north Pacific using LIDAR and video technology. ICES Journal of Marine Science 59:1120–1130.

Butterworth, D.S. and Bergh., M.O. 1993. The development of a management procedure for the South African anchovy resource. p. 83-99. In S.J. Smith, J.J. Hunt and D. Rivard (ed.) Risk Evaluation and biological reference points for fisheries management. Can. Spec. Publ. Fish. Aquat. Sci. 120.

Carrera, P. and Porteiro, C. 2003. Stock dynamic of the Iberian sardine (Sardina pilchardus, W.) and its implication on the fishery off Galicia. SCI. MAR., 67 (Suppl. 1): 245-258.

Churnside, J.H. and Hunter, J.R. 1996. Laser Remote Sensing of epipelagic fishes. In V.I. Feigels and Y.I. Kpilevich eds. "Laser Remote Sensing of Natural Waters: From Theory to Practice." Proceedings SPIE. 2964:3-53.

Churnside, J.H., Demer, D.A., and Mahmoudi, B. 2003. A comparison of LIDAR and echosounder measurements of fish schools in the Gulf of Mexico. ICES Journal of Marine Science 60:147–154.

Churnside, J.H. and McGillivary, P.A.. 1991. Optical properties of several Pacific fishes. Applied Optics 30:2925-2927.

Churnside, J.H., Tatarskii, V.V., and Wilson, J.J. 1997. LIDAR profiles of fish schools. Applied Optics 36:6011-6020.

Churnside, J.H. and Thorne, R.E. 2005. Comparison of airborne LIDAR measurements with 420 kHz echo-sounder measurements of zooplankton. Appl. Opt. 44:5504-5511.

Churnside, J.H., Wilson, J.J., and Tatarskii, V.V. 2001. Airborne LIDAR for fisheries applications. Optical Engineering 40:406-414.

Cort, J.L., Cendrero, O., and Iribar, X. 1976. La anchoa, Engraulis Encrasicholus (L.), del Cantábrico. Bol. Inst.Espa.Oceano 220:3-34.

Dias, C.A., Soares, E., and Marques, V. 1988. Distribuição e Estimação Acústica da Abundância de Sardinha na Costa Portuguesa em Março de 1988. Resultados do cruzeiro "SAR88MAR" do projecto "SARAS". Anexo II do relatório de Progresso do Projecto JNICT 87344/Mar, Novembro 1988. INIP, 40pp.

Dias, C.A., Soares, E., and Marques, V. 1989. Acoustic Abundance Estimation of Sardine (Sardina pilchardus, Walb.) of the Portuguese Coast, July-August 1988. ICES, C.M. 1989/H:52, 24pp.

Dias, C.A., Marques, V., and Soares, E. 1993. Spanish- Portuguese sardine acoustic survey off Iberian Atlantic coast (ICES Sub-areas VIII and IX)- "Ibersar -92 ".November 1992. Working Document in Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy.1993

Dias, C.A., Pestana, G., Soares, E., Marques, V. 1996. Present state of sardine stock in ICES Divisions VIIc and IXa. WD 1996.

Dragesund, O. and Olsen, S. 1965. On the possibility of estimating year-class strength by measuring echo-abundance of 0-group fish. FiskDir. Skr. Ser. Habunders., 13:47-75.

Fredriksson, K., Galle, B., Nyström, K., Svanberg, S., and Öström, B. 1978. Underwater laser-radar experiments for bathymetry and fish-school detection. GIPR-162 Göteborg Institute of Physics, Göteborg, Sweden.

Fernandes, P. G., Brierley, A., Simmonds, E. J., Millard, N. W., McPhail, S. D., Armstrong, F., Stevenson, P., and Squires, M., 2000a. Fish do not avoid survey vessels. Nature, 404: 35–36.

Fernandes, P. G., Brierley, A., Simmonds, E. J., Millard, N. W., McPhail, S. D., Armstrong, F., Stevenson, P., and Squires, M., 2000b. Addendum to fish do not avoid survey vessels. Nature, 407: 152.

Fréon P. and Misund, O. A. 1999. Schooling behaviour In Dynamics of Pelagic Fish Distribution and Behaviour: Effects on Fisheries and Stock Assessment. Fishing News Book Pp. 56-100.

Gauldie, R.W., Sharma, S.K., and Helsley, C.E. 1996. LIDAR applications to fisheries monitoring problems. Canadian Journal of Fisheries and Aquatic Science 53:1459-1468.

Hampton, I. 1992. The role of acoustic surveys in the assessment of pelagic fish resources on the South African continental shelf. In Benguela Trophic Functioning,

Houde, E.D. 1996. Evaluating stage-specific survival during the early life of fish. In Y. Watanabe, Y. Yamashita and Y. Oozeki (eds) Survival strategies in early life stages of marine resources. P-51-66, Balkema Rotterdam.

Hunter, J.R. and Churnside, J.H.(eds.). 1995. Airborne Fishery Assessment Technology- a NOAA workshop report. SWFSC Admin. Rep., La Jolla, LJ-95-02, 71 pp.

Krekova, M.K., Krekov, G.M., Samokhvalov, I.V., and Shamanaev, V.S. 1994. Numerical evaluation of the possibilities of remote sensing of fish schools. Applied Optics 33:5715-5720.

Leblanc, C.H., Mello, L., Dupuis, H.M.C. 1998. Analysis of juvenile Atlantic herring catches in the southern Gulf of St. Lawrence September groundfish surveys. Can. Tech. Rep. Fish. Aquat. Sci. Rapp. Tech. Can. Sci. Halieut. Aquat. 1997 35 pp.

Lockwood, S. J. 1988 The mackerel. Its biology, assessment and the management of a fishery. Fishinf news Books, LTd. 181 pp.

MacLennan, D.N. and Simmonds, J.E. 1992: Fisheries Acoustics. Chapman and Hall. London 325 pp.

Martín, I. 1989. Catch of small pelagic species by the life bait boats of the Basque Country in 1987 and 1988. ICES C.M. 1989/H:34.

Massé, J., Scalabrin, C., Liorzou, B., and Weill, A. 1992. Distribution and spatio-temporal description of fish school's acoustic detections observed in the Bay of Biscay, Workshop Echospace, Montpellier, 18-20 May 1992.

Massé, J. 1996. Acoustic observations in the Bay of Biscay: Schooling, vertical distribution, species assemblages and behaviour. Sci. Mar. 60 (Supl.2): 227-234.

Matheron, G. 1971. The theory of regionalised variables and its applications. Les cahiers du CMM, 5, Ecole Nat. Sup. Mines Paris, Fontainebleau, 211 pp.

Mays, K.F. 1974. Pelagic fish surveys in the California Current. Calif. Fish. Game, Fish Bull., 162, 79 pp.

McBlatchie, S., Thorne, R. E., Grimes, P., and Hanchet, S. 2000. Ground truth and target identification for fisheries acoustics. Fisheries Research, 47.173-191.

Oliver, C.W., Armstrong, W.A., and Young, J.A. 1994. Development of an airborne LIDAR system to detect tunas in the eastern tropical Pacific purse-seine fishery. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-204, La Jolla. 67 pp.

Pestana, G. 1989. Manancial Ibero Atlântico de Sardinha (Sardina pilchardus, Walb.) sua Avaliaçao e medidas de gestao.Thesis. IWIP 192 pp.(mimeo in portugal).

Petitgas, P. 1991. Contribution géostatistiques à la biologie des pêches maritimes. Thèse doctorat, Centre Géostatisteque, Fontainebleau, 211 pp.

Petitgas, P. 1993. Geostatistics for fish stock assessments: a review and an acoustic application. ICES Journal of Marine Science, 50: 285-298.

Petitgas, P. and Prampart, A. 1993. EVA (Estimation VAriance). A geostatistical software on IBM-PC for structure characterization and variance computation. ICES CM 1993/D:65l.

Porteiro, C., Alvarez, F., and Pereiro, J.A. 1986. Sardine (Sardina pilchardus, Walb.) Stock differential distribution by age class in ICES Divisions VIIIc and IXa. ICES CM 1986 /H:28,19 pp.

Porteiro, C., Miquel, J., Carrera, P., Meixede, M., and Cabanas, J.M. 1993. Abundance estimation and distribution of sardine in northern Spain (North of IX and VIIIc Divisions). ICES CM 1993/H:28,19 pp.

Porteiro, C., Carrera, P., and Miquel, J. 1996. Analysis of Spanish acoustic surveys for sardine, 1991-1993: abundance estimates and inter-annual variability. ICES Journal of Marine Science, 53: 429-433.

Prouzet, P., Metuzals, K., and Caboche, C.. 1994. L´anchois du golfe de Gascogne: Caracteristiques biologiques et campagne de peche francaise en 1992. Rapport CNPM-IMA-IFREMER, 29 pages.

Ralston, S. and Howard, D.F. 1995. On the development of year-class strength and cohort variability in two northern California rockfishes. Fisheries Bulletin 93:710-720.

Santiago, J. and Sanz, A. 1992. Egg production estimates of the Bay of Biscay anchovy, Engraulis encrasicolus (L.), spawning stock in 1987 and 1988 (Estimaciones de la producción de hevos de l stock reproductor de anchoa, Engraulis encrasicolus (L.), del golfo de Vizcaya en 1987 y 1988). Bol. Inst. Esp. Oceanogr. 8 (1):225-230.

Scalabrin, C. and Massé, J. 1993. Acoustic detection of the spatial and temporal distribution of fish shoals in the Bay of Biscay. Aquatic Living Resources 6: 269-283.

Schwarz, A.L. and G.L.Greer. 1984. Responses of Pacific herring, Clupea harengus pallasi, to some underwater sounds. Can. J. Fish Aquat. Sci. 41: 1183-1192.

Smith, P.E. 1985. Year-class strength and survival of 0-group clupeoid. Canadian Journal of Fisheries and Aquatic Science. 42 (Suppl. 1):69-82.

Soares, E. 1995. Contribuçao para o Estudo da Distribuçao e do Comportamento da Sadinha na Costa Continental Portuguesa. Trabalho de síntese apresentado para provas de acesso à categoria de Assistente de Investigaçao. Area Cientifica de Recursos Haliêuticos. INIP, 100 pp.

Squire, J.L., JR. and Krumboltz, H. 1981. Profiling pelagic fish schools using airborne optical lasers and other remote sensing techniques. Marine Technological Society Journal 15:27–31.

Uriarte A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Sci. Mar. 60 (Supl.2): 237-255.

Uriarte, A., Motos, L., Alvarez, P., Santos, M., Prouzet, P., and Massé, J. 1999. Population estimates of the Bay of Biscay anchovy by the Daily Egg Production Method. Final Report to European Commission of Project 96/034, issued in December 1999.

Villamor, B., Abaunza, P., Lucio, P., Porteiro, C. 1997. Distribution and age structure of mackerel (Scomber scombrus, L.) and horse mackerel (Trachurus trachurus, L.) in northern coast of Spain, 1989-1994. Sci. Mar., 61(3):345-366.

Bibliography of Chapter 2

Aldanondo, N., Cotano, U., Tiepolo, M., Boyra, G., and Irigoien, X. 2010. Growth and movement patterns of early juvenile European anchovy (Engraulis encrasicolus L.) in the Bay of Biscay based on otolith microstructure and chemistry. Fisheries Oceanography, 19: 196–208.

Allain, G., Petitgas, P., and Lazure, P. 2001. The influence of mesoscale ocean processes on anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography, 10: 151–163. John Wiley \& Sons.

Allain, G., Petitgas, P., and Lazure, P. 2007a. The influence of environment and spawning distribution on the survival of anchovy (Engraulis encrasicolus) larvae in the Bay of Biscay (NE Atlantic) investigated by biophysical simulations. Fisheries Oceanography, 16: 506–514.

Allain, G., Petitgas, P., Lazure, P., and Grellier, P. 2007b. Biophysical modelling of larval drift , growth and survival for the prediction of anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay (NE Atlantic). Fisheries Oceanography, 16: 489–505.

Bachiller, E., Cotano, U., Boyra, G., and Irigoien, X. 2013. Spatial distribution of the stomach weights of juvenile anchovy (Engraulis encrasicolus L.) in the Bay of Biscay. ICES Journal of Marine Science, 70: 362–378.

Bachiller, E., and Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay. Ecological effects of trophic interactions.

Bivand, R., and Lewin-Koh, N. 2015. maptools: Tools for Reading and Handling Spatial Objects.

Borja, A., Fontan, A., Saenz, J., and Valencia, V. 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (Engraulis encrasicolus) ´. Fisheries Oceanography, 17: 477–493.

Borja, A., Uriarte, A., Egaña, J., Motos, L., and Valencia, V. 1998. Relationships between anchovy (Engraulis encrasicolus) recruitment and environment in the Bay of Biscay (1967±1996). Fisheries Oceanography, 7: 375–380.

Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. ICES Journal of Marine Science, 70: 1354–1368.

Carrera, P., Churnside, J. H., Boyra, G., Marques, V., Scalabrin, C., and Uriarte, A. 2006. Comparison of airborne lidar with echosounders: a case study in the coastal Atlantic waters of southern Europe. ICES Journal of Marine Science, 63: 1736–1750.

Charria, G., Lazure, P., Le Cann, B., Serpette, A., Reverdin, G., Louzael, S., Batifoulier, F., *et al.* 2013. Surface layer circulation derived from Lagrangian drifters in the Bay of Biscay. Journal of Marine Systems, 109-110: S60–S76.

COM374. 2010. Establishing the fishing oportunities for Anchovy in the Bay of Biscay for the 2010-2011 fishing season and amending Regulation (EU) No 53/2010. Brussels.

Cort, J. L., Cendrero, O., and Iribar, X. 1977. La anchoa (engraulis encrasicholus) (L.) del Cantábrico. Bol. Inst. Espa. Oceano., 220.

Cotano, U., Irigoien, X., Etxebeste, E., Alvarez, P., Zarauz, L., Mader, J., and Ferrer, L. 2008. Distribution, growth and survival of anchovy larvae (Engraulis encrasicolus L.) in relation to hydrodynamic and trophic environment in the Bay of Biscay. Journal of Plankton Research, 30: 467–481.

Fernandes, J. a., Irigoien, X., Goikoetxea, N., Lozano, J. a., Inza, I., Pérez, A., and Bode, A. 2010. Fish recruitment prediction, using robust supervised classification methods. Ecological Modelling, 221: 338–352.

Foote, K. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. International Council for the Exploration of the Sea. 81 pp.

Gerritsen, H. 2013. mapplots: Data visualisation on maps.

Gomis, D., Ruiz, S., and Pedder, M. 2001. Diagnostic analysis of the 3D ageostrophic circulation from a multivariate spatial interpolation of CTD and ADCP data. Deep Sea Research, 48: 269–295.

Hoare, D. J., Krause, J., Peuhkuri, N., and Godin, J.-G. J. 2000. Body size and shoaling in fish. Journal of Fish Biology, 57: 1351–1366.

Ibaibarriaga, L., Fernandez, C., Uriarte, A., Roel, B. a., Ibaibarriaga, L., and Ferna, C. 2008. A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES Journal of Marine Science, 65: 191.

ICES. 2009. Report of the Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VIII and IX (WGACEGG). ICES CM, LRC:20: 181.

ICES. 2015a. . Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA), 24–29 June 2015, Lisbon, Portugal.: 612 pp.

ICES. 2015b. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES CM, ACOM:16: 580.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008a. From egg to juvenile in the Bay of Biscay: spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008b. From egg to juvenile in the Bay of Biscay: Spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Fiksen, Ø., Cotano, U., Uriarte, A., Alvarez, P., Arrizabalaga, H., Boyra, G., *et al.* 2007. Could Biscay Bay Anchovy recruit through a spatial loophole? Progress in Oceanography, 74: 132–148.

Kondrashev, S. L., Gnyubkina, V. P., and Zueva, L. V. 2012. Structure and spectral sensitivity of photoreceptors of two anchovy species: Engraulis

japonicus and Engraulis encrasicolus. Vision Research, 68: 19–27. Elsevier Ltd.

Koutsikopoulos, C., and Le Cann, B. 1996. Physical processes and hydrological structures related to the Bay of Biscay anchovy. Scientia Marina, 60: 9–19.

Lawson, G. L., Barange, M., Freon, P., and Fre, P. 2001. Species identification of pelagic fish schools on the South African continental shelf using acoustic descriptors and ancillary information. ICES Journal of Marine Science, 58: 275–287.

Maclennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365.

Massé, J. 1996. Acoustic observations in the Bay of Biscay : Schooling , vertical distribution , species assemblages and behaviour *. Scientia Marina, 60: 227–234.

Motos, L., Uriarte, A., and Valencia, V. 1996a. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L.). Scientia Marina, 60: 117–140. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Motos, L., Uriarte, A., and Valencia, V. 1996b. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L). Scientia Marina, 60: 117–140.

Novales Flamarique, I. 2011. Unique photoreceptor arrangements in a fish with polarized light discrimination. Journal of Comparative Neurology, 519: 714–737.

Ona, E. 2003. An expanded target-strength relationship for herring. ICES Journal of Marine Science, 60: 493–499.

Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay.

Petitgas, P., Reid, D. G. D., Planque, B., Nogueira, E., Hea, B. O., Cotano, U., and O'Hea, B. 2006. The entrainment hypothesis: an explanation for the

persistence and innovation in spawning migrations and life cycle spatial patterns. ICES CM: 9pp.

Petitgas, P., Secor, D. H., McQuinn, I., Huse, G., and Lo, N. 2010. Stock collapses and their recovery: mechanisms that establish and maintain life-cycle closure in space and time. ICES Journal of Marine Science, 67: 1841–1848.

Pingree, R. ., and Le Cann, B. 1992. Three anticyclonic slope water oceanic eDDIES (SWODDIES) in the Southern Bay of Biscay in 1990. Deep Sea Research Part A. Oceanographic Research Papers.

Pingree, R. D., and Le Cann, B. 1990. Structure, strength and seasonality of the slope currents in the bay of Biscay region. J. Mar. Biol. Ass. U.K.

Pitcher, T. J., and Parrish, J. K. 1993. The functions of shoaling behaviour. *In* The behaviour of teleost fishes, 2nd ed., pp. 363–439. Ed. by T. J. Pitcher. Chapman and Hall, London.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raab, K., Llope, M., Nagelkerke, L. a J., Rijnsdorp, A. D., Teal, L. R., Licandro, P., Ruardij, P., *et al.* 2013. Influence of temperature and food availability on juvenile European anchovy Engraulis encrasicolus at its northern boundary. Marine Ecology Progress Series, 488: 233–245.

Simmonds, J. E., and Maclennan, D. N. 2005a. Fisheries Acoustics Theory and Practice. Second Edition. Chapman & Hall, New York: 472pp.

Simmonds, J. E., and Maclennan, D. N. 2005b. Fisheries acoustics - Theory and practice. Blackwell Publishing. 437 pp.

Sinclair, M. 1988. Marine populations. An assay on population regulation and speciation. 251 pp.

Solabarrieta, L., Rubio, A., Castanedo, S., Medina, R., Charria, G., and Hernández, C. 2014. Surface water circulation patterns in the southeastern

Bay of Biscay: New evidences from HF radar data. Continental Shelf Research, 74: 60–76.

Takasuka, A., and Aoki, I. 2006. Environmental determinants of growth rates for larval Japanese anchovy Engraulis japonicus in different waters. Fisheries Oceanography, 15: 139–149.

Uriarte, A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Scientia Marina, 60: 237–255. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Uriarte, A., Rico, I., Villamor, B., Duhamel, E., Dueñas, C., Aldanondo, N., and Cotano, U. 2016. Validation of age determination in European anchovy. Journal of Marine and Freshwater Research, in press.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Cermeño, P., De Miguel, E., Gómez Sánchez, J., *et al.* 2001a. Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning: do they form part of the plankton. ICES CM, W:20.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Miguel, E. De, Sanchez, J. A. G., Jimenez, M., *et al.* 2001b. 2001 ICES Annual Science Conference ICES CM 2001 / W : 20 Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning : Do they form part of the plankton ? ICES CM, 20.

Van Der Lingen, C., Hutchings, L., and Field, J. 2006. Comparative trophodynamics of anchovy Engraulis encrasicolus and sardine Sardinops sagax in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated. African Journal of Marine Science, 28: 465–477. Taylor \& Francis.

Wickham, H. 2009. ggplot2: elegant graphics for data analysis. Springer New York.

Woillez, M., Poulard, J., Rivoirard, J., Petitgas, P., and Bez, N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES Journal of Marine Science, 64: 537–550.

Zhao, X., Wang, Y., and Dai, F. 2008. Depth-dependent target strength of anchovy (Engraulis japonicus) measured in situ. ICES Journal of Marine Science, 65: 882–888.

Bibliography of Chapter 3

Aldanondo, N., Cotano, U., Tiepolo, M., Boyra, G., and Irigoien, X. 2010. Growth and movement patterns of early juvenile European anchovy (Engraulis encrasicolus L.) in the Bay of Biscay based on otolith microstructure and chemistry. Fisheries Oceanography, 19: 196–208.

Allain, G., Petitgas, P., and Lazure, P. 2001. The influence of mesoscale ocean processes on anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography, 10: 151–163. John Wiley \& Sons.

Allain, G., Petitgas, P., and Lazure, P. 2007a. The influence of environment and spawning distribution on the survival of anchovy (Engraulis encrasicolus) larvae in the Bay of Biscay (NE Atlantic) investigated by biophysical simulations. Fisheries Oceanography, 16: 506–514.

Allain, G., Petitgas, P., Lazure, P., and Grellier, P. 2007b. Biophysical modelling of larval drift , growth and survival for the prediction of anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay (NE Atlantic). Fisheries Oceanography, 16: 489–505.

Bachiller, E., Cotano, U., Boyra, G., and Irigoien, X. 2013. Spatial distribution of the stomach weights of juvenile anchovy (Engraulis encrasicolus L.) in the Bay of Biscay. ICES Journal of Marine Science, 70: 362–378.

Bachiller, E., and Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay. Ecological effects of trophic interactions.

Bivand, R., and Lewin-Koh, N. 2015. maptools: Tools for Reading and Handling Spatial Objects.

Borja, A., Fontan, A., Saenz, J., and Valencia, V. 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (Engraulis encrasicolus) ´. Fisheries Oceanography, 17: 477–493.

Borja, A., Uriarte, A., Egaña, J., Motos, L., and Valencia, V. 1998. Relationships between anchovy (Engraulis encrasicolus) recruitment and environment in the Bay of Biscay (1967±1996). Fisheries Oceanography, 7: 375–380.

Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. ICES Journal of Marine Science, 70: 1354–1368.

Carrera, P., Churnside, J. H., Boyra, G., Marques, V., Scalabrin, C., and Uriarte, A. 2006. Comparison of airborne lidar with echosounders: a case study in the coastal Atlantic waters of southern Europe. ICES Journal of Marine Science, 63: 1736–1750.

Charria, G., Lazure, P., Le Cann, B., Serpette, A., Reverdin, G., Louzael, S., Batifoulier, F., *et al.* 2013. Surface layer circulation derived from Lagrangian drifters in the Bay of Biscay. Journal of Marine Systems, 109-110: S60–S76.

COM374. 2010. Establishing the fishing oportunities for Anchovy in the Bay of Biscay for the 2010-2011 fishing season and amending Regulation (EU) No 53/2010. Brussels.

Cort, J. L., Cendrero, O., and Iribar, X. 1977. La anchoa (engraulis encrasicholus) (L.) del Cantábrico. Bol. Inst. Espa. Oceano., 220.

Cotano, U., Irigoien, X., Etxebeste, E., Alvarez, P., Zarauz, L., Mader, J., and Ferrer, L. 2008. Distribution, growth and survival of anchovy larvae (Engraulis encrasicolus L.) in relation to hydrodynamic and trophic environment in the Bay of Biscay. Journal of Plankton Research, 30: 467–481.

Fernandes, J. a., Irigoien, X., Goikoetxea, N., Lozano, J. a., Inza, I., Pérez, A., and Bode, A. 2010. Fish recruitment prediction, using robust supervised classification methods. Ecological Modelling, 221: 338–352.

Foote, K. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. International Council for the Exploration of the Sea. 81 pp.

Gerritsen, H. 2013. mapplots: Data visualisation on maps.

Gomis, D., Ruiz, S., and Pedder, M. 2001. Diagnostic analysis of the 3D ageostrophic circulation from a multivariate spatial interpolation of CTD and ADCP data. Deep Sea Research, 48: 269–295.

Hoare, D. J., Krause, J., Peuhkuri, N., and Godin, J.-G. J. 2000. Body size and shoaling in fish. Journal of Fish Biology, 57: 1351–1366.

Ibaibarriaga, L., Fernandez, C., Uriarte, A., Roel, B. a., Ibaibarriaga, L., and Ferna, C. 2008. A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES Journal of Marine Science, 65: 191.

ICES. 2009. Report of the Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VIII and IX (WGACEGG). ICES CM, LRC:20: 181.

ICES. 2015a. . Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA), 24–29 June 2015, Lisbon, Portugal.: 612 pp.

ICES. 2015b. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES CM, ACOM:16: 580.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008a. From egg to juvenile in the Bay of Biscay: spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008b. From egg to juvenile in the Bay of Biscay: Spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Fiksen, Ø., Cotano, U., Uriarte, A., Alvarez, P., Arrizabalaga, H., Boyra, G., *et al.* 2007. Could Biscay Bay Anchovy recruit through a spatial loophole ? Progress in Oceanography, 74: 132–148.

Kondrashev, S. L., Gnyubkina, V. P., and Zueva, L. V. 2012. Structure and spectral sensitivity of photoreceptors of two anchovy species: Engraulis

japonicus and Engraulis encrasicolus. Vision Research, 68: 19–27. Elsevier Ltd.

Koutsikopoulos, C., and Le Cann, B. 1996. Physical processes and hydrological structures related to the Bay of Biscay anchovy. Scientia Marina, 60: 9–19.

Lawson, G. L., Barange, M., Freon, P., and Fre, P. 2001. Species identification of pelagic fish schools on the South African continental shelf using acoustic descriptors and ancillary information. ICES Journal of Marine Science, 58: 275–287.

Maclennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365.

Massé, J. 1996. Acoustic observations in the Bay of Biscay : Schooling , vertical distribution , species assemblages and behaviour *. Scientia Marina, 60: 227–234.

Motos, L., Uriarte, A., and Valencia, V. 1996a. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L.). Scientia Marina, 60: 117–140. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Motos, L., Uriarte, A., and Valencia, V. 1996b. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L). Scientia Marina, 60: 117–140.

Novales Flamarique, I. 2011. Unique photoreceptor arrangements in a fish with polarized light discrimination. Journal of Comparative Neurology, 519: 714–737.

Ona, E. 2003. An expanded target-strength relationship for herring. ICES Journal of Marine Science, 60: 493–499.

Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay.

Petitgas, P., Reid, D. G. D., Planque, B., Nogueira, E., Hea, B. O., Cotano, U., and O'Hea, B. 2006. The entrainment hypothesis: an explanation for the

persistence and innovation in spawning migrations and life cycle spatial patterns. ICES CM: 9pp.

Petitgas, P., Secor, D. H., McQuinn, I., Huse, G., and Lo, N. 2010. Stock collapses and their recovery: mechanisms that establish and maintain life-cycle closure in space and time. ICES Journal of Marine Science, 67: 1841–1848.

Pingree, R. ., and Le Cann, B. 1992. Three anticyclonic slope water oceanic eDDIES (SWODDIES) in the Southern Bay of Biscay in 1990. Deep Sea Research Part A. Oceanographic Research Papers.

Pingree, R. D., and Le Cann, B. 1990. Structure, strength and seasonality of the slope currents in the bay of Biscay region. J. Mar. Biol. Ass. U.K.

Pitcher, T. J., and Parrish, J. K. 1993. The functions of shoaling behaviour. *In* The behaviour of teleost fishes, 2nd ed., pp. 363–439. Ed. by T. J. Pitcher. Chapman and Hall, London.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raab, K., Llope, M., Nagelkerke, L. a J., Rijnsdorp, A. D., Teal, L. R., Licandro, P., Ruardij, P., *et al.* 2013. Influence of temperature and food availability on juvenile European anchovy Engraulis encrasicolus at its northern boundary. Marine Ecology Progress Series, 488: 233–245.

Simmonds, J. E., and Maclennan, D. N. 2005a. Fisheries Acoustics Theory and Practice. Second Edition. Chapman & Hall, New York: 472pp.

Simmonds, J. E., and Maclennan, D. N. 2005b. Fisheries acoustics - Theory and practice. Blackwell Publishing. 437 pp.

Sinclair, M. 1988. Marine populations. An assay on population regulation and speciation. 251 pp.

Solabarrieta, L., Rubio, A., Castanedo, S., Medina, R., Charria, G., and Hernández, C. 2014. Surface water circulation patterns in the southeastern

Bay of Biscay: New evidences from HF radar data. Continental Shelf Research, 74: 60–76.

Takasuka, A., and Aoki, I. 2006. Environmental determinants of growth rates for larval Japanese anchovy Engraulis japonicus in different waters. Fisheries Oceanography, 15: 139–149.

Uriarte, A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Scientia Marina, 60: 237–255. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Uriarte, A., Rico, I., Villamor, B., Duhamel, E., Dueñas, C., Aldanondo, N., and Cotano, U. 2016. Validation of age determination in European anchovy. Journal of Marine and Freshwater Research, in press.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Cermeño, P., De Miguel, E., Gómez Sánchez, J., *et al.* 2001a. Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning: do they form part of the plankton. ICES CM, W:20.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Miguel, E. De, Sanchez, J. A. G., Jimenez, M., *et al.* 2001b. 2001 ICES Annual Science Conference ICES CM 2001 / W : 20 Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning : Do they form part of the plankton ? ICES CM, 20.

Van Der Lingen, C., Hutchings, L., and Field, J. 2006. Comparative trophodynamics of anchovy Engraulis encrasicolus and sardine Sardinops sagax in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated. African Journal of Marine Science, 28: 465–477. Taylor \& Francis.

Wickham, H. 2009. ggplot2: elegant graphics for data analysis. Springer New York.

Woillez, M., Poulard, J., Rivoirard, J., Petitgas, P., and Bez, N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES Journal of Marine Science, 64: 537–550.

Zhao, X., Wang, Y., and Dai, F. 2008. Depth-dependent target strength of anchovy (Engraulis japonicus) measured in situ. ICES Journal of Marine Science, 65: 882–888.

Bibliography of Chapter 4

Barange, M., Bernal, M., Cercole, M.C., Cubillos, L.A., Daskalov, G.M., de Moor (formerly Cunningham), C.L., De Oliveira, J.A.A., Dickey-Collas, M., Gaughan, D.J., Hill, K., Jacobson, L.D., Köster, F.W., Massé, J., Ñiquen, M., Nishida, H., Oozeki, Y., Palomera, I., Saccardo, S.A., Santojanni, A., Serra, R., Somarakis, S., Stratoudakis, Y., Uriarte, A., van der Lingen, C.D. and A. Yatsu (2009). Current trends in the assessment and management of stocks. In Climate Change and Small Pelagic Fish, Chapter 9, pp 191-255. D. Checkley, J. Alheit, Y. Oozeki and C. Roy (Eds). Cambridge University Press. xii+ 372 pp.

Carrera, P., Churnside, J. H., Boyra, G., Marques, V., Scalabrin, C. and Uriarte, A. (2006), Comparison of airborne LIDAR with echosounders: a case study in the coastal Atlantic waters of southern Europe, ICES Journal of Marine Science, 63, 1736-1750

COM374. 2010. Establishing the fishing oportunities for Anchovy in the Bay of Biscay for the 2010-2011 fishing season and amending Regulation (EU) No 53/2010. Brussels.

Clay, A. and Castonguay, M. 1996. In situ target strengths of Atlantic cod (Gadus morhua) and Atlantic mackerel (*Scomber scombrus*) in the Northwest Atlantic. Can. J. Fish. Aquat. Sci. 53: 87–98

Degnbol, P., Lassen, H., and Stahr, K. J. 1985. In-situ determinations of target strength of herring and sprat at 38 and 120 kHz. Dana, 5, 45–54.

Ibaibarriaga, L., Fernández, C., Uriarte, A. and Roel, B. (2008). A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES Journal of Marine Science, 65: 191–205.

Ibaibarriaga, L., Uriarte, A., Sánchez, S., Fernandes, J. A. and Irigoien, X. (2010). Use of juvenile abundance indices for the management of the Bay of Biscay anchovy. Working document to WGANSA, 24-28 June 2010, Vigo (Spain)

ICES. 2006 Report of the working group on acoustic and egg surveys for sardine and anchovy in ICES Areas VIII and IX (WGACEGG) ICES Living Resources Commitee ICES CM 2006/LRC:18. Ref. ACFM

ICES. 2010. Report of the Working Group on Anchovy and Sardine (WGANSA), 24–28 June 2010, Lisbon, Portugal. ICES CM 2010/ACOM:16. 290 pp.

ICES. 2012. Report of the Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VIII and IX (WGACEGG). ICES CM 2012/SSGESST:16. Ref. SCICOM & ACOM

Aldanondo, N., Cotano, U., Tiepolo, M., Boyra, G., and Irigoien, X. 2010. Growth and movement patterns of early juvenile European anchovy (Engraulis encrasicolus L.) in the Bay of Biscay based on otolith microstructure and chemistry. Fisheries Oceanography, 19: 196–208.

Allain, G., Petitgas, P., and Lazure, P. 2001. The influence of mesoscale ocean processes on anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography, 10: 151–163. John Wiley \& Sons.

Allain, G., Petitgas, P., and Lazure, P. 2007a. The influence of environment and spawning distribution on the survival of anchovy (Engraulis encrasicolus) larvae in the Bay of Biscay (NE Atlantic) investigated by biophysical simulations. Fisheries Oceanography, 16: 506–514.

Allain, G., Petitgas, P., Lazure, P., and Grellier, P. 2007b. Biophysical modelling of larval drift , growth and survival for the prediction of anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay (NE Atlantic). Fisheries Oceanography, 16: 489–505.

Bachiller, E., Cotano, U., Boyra, G., and Irigoien, X. 2013. Spatial distribution of the stomach weights of juvenile anchovy (Engraulis encrasicolus L.) in the Bay of Biscay. ICES Journal of Marine Science, 70: 362–378.

Bachiller, E., and Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay. Ecological effects of trophic interactions.

Bivand, R., and Lewin-Koh, N. 2015. maptools: Tools for Reading and Handling Spatial Objects.

Borja, A., Fontan, A., Saenz, J., and Valencia, V. 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (Engraulis encrasicolus) ´. Fisheries Oceanography, 17: 477–493.

Borja, A., Uriarte, A., Egaña, J., Motos, L., and Valencia, V. 1998. Relationships between anchovy (Engraulis encrasicolus) recruitment and environment in the Bay of Biscay (1967±1996). Fisheries Oceanography, 7: 375–380.

Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. ICES Journal of Marine Science, 70: 1354–1368.

Carrera, P., Churnside, J. H., Boyra, G., Marques, V., Scalabrin, C., and Uriarte, A. 2006. Comparison of airborne lidar with echosounders: a case study in the coastal Atlantic waters of southern Europe. ICES Journal of Marine Science, 63: 1736–1750.

Charria, G., Lazure, P., Le Cann, B., Serpette, A., Reverdin, G., Louzael, S., Batifoulier, F., *et al.* 2013. Surface layer circulation derived from Lagrangian drifters in the Bay of Biscay. Journal of Marine Systems, 109-110: S60–S76.

COM374. 2010. Establishing the fishing oportunities for Anchovy in the Bay of Biscay for the 2010-2011 fishing season and amending Regulation (EU) No 53/2010. Brussels.

Cort, J. L., Cendrero, O., and Iribar, X. 1977. La anchoa (engraulis encrasicholus) (L.) del Cantábrico. Bol. Inst. Espa. Oceano., 220.

Cotano, U., Irigoien, X., Etxebeste, E., Alvarez, P., Zarauz, L., Mader, J., and Ferrer, L. 2008. Distribution, growth and survival of anchovy larvae (Engraulis encrasicolus L.) in relation to hydrodynamic and trophic environment in the Bay of Biscay. Journal of Plankton Research, 30: 467–481.

Fernandes, J. a., Irigoien, X., Goikoetxea, N., Lozano, J. a., Inza, I., Pérez, A., and Bode, A. 2010. Fish recruitment prediction, using robust supervised classification methods. Ecological Modelling, 221: 338–352.

Foote, K. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. International Council for the Exploration of the Sea. 81 pp.

Gerritsen, H. 2013. mapplots: Data visualisation on maps.

Gomis, D., Ruiz, S., and Pedder, M. 2001. Diagnostic analysis of the 3D ageostrophic circulation from a multivariate spatial interpolation of CTD and ADCP data. Deep Sea Research, 48: 269–295.

Hoare, D. J., Krause, J., Peuhkuri, N., and Godin, J.-G. J. 2000. Body size and shoaling in fish. Journal of Fish Biology, 57: 1351–1366.

Ibaibarriaga, L., Fernandez, C., Uriarte, A., Roel, B. a., Ibaibarriaga, L., and Ferna, C. 2008. A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES Journal of Marine Science, 65: 191.

ICES. 2009. Report of the Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VIII and IX (WGACEGG). ICES CM, LRC:20: 181.

ICES. 2015a. . Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA), 24–29 June 2015, Lisbon, Portugal.: 612 pp.

ICES. 2015b. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES CM, ACOM:16: 580.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008a. From egg to juvenile in the Bay of Biscay: spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008b. From egg to juvenile in the Bay of Biscay: Spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Fiksen, Ø., Cotano, U., Uriarte, A., Alvarez, P., Arrizabalaga, H., Boyra, G., *et al.* 2007. Could Biscay Bay Anchovy recruit through a spatial loophole ? Progress in Oceanography, 74: 132–148.

Kondrashev, S. L., Gnyubkina, V. P., and Zueva, L. V. 2012. Structure and spectral sensitivity of photoreceptors of two anchovy species: Engraulis japonicus and Engraulis encrasicolus. Vision Research, 68: 19–27. Elsevier Ltd.

Koutsikopoulos, C., and Le Cann, B. 1996. Physical processes and hydrological structures related to the Bay of Biscay anchovy. Scientia Marina, 60: 9–19.

Lawson, G. L., Barange, M., Freon, P., and Fre, P. 2001. Species identification of pelagic fish schools on the South African continental shelf using acoustic descriptors and ancillary information. ICES Journal of Marine Science, 58: 275–287.

Maclennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365.

Massé, J. 1996. Acoustic observations in the Bay of Biscay : Schooling , vertical distribution , species assemblages and behaviour *. Scientia Marina, 60: 227–234.

Motos, L., Uriarte, A., and Valencia, V. 1996a. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L.). Scientia Marina, 60: 117–140. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Motos, L., Uriarte, A., and Valencia, V. 1996b. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L). Scientia Marina, 60: 117–140.

Novales Flamarique, I. 2011. Unique photoreceptor arrangements in a fish with polarized light discrimination. Journal of Comparative Neurology, 519: 714–737.

Ona, E. 2003. An expanded target-strength relationship for herring. ICES Journal of Marine Science, 60: 493–499.

Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay.

Petitgas, P., Reid, D. G. D., Planque, B., Nogueira, E., Hea, B. O., Cotano, U., and O'Hea, B. 2006. The entrainment hypothesis: an explanation for the persistence and innovation in spawning migrations and life cycle spatial patterns. ICES CM: 9pp.

Petitgas, P., Secor, D. H., McQuinn, I., Huse, G., and Lo, N. 2010. Stock collapses and their recovery: mechanisms that establish and maintain life-cycle closure in space and time. ICES Journal of Marine Science, 67: 1841–1848.

Pingree, R. ., and Le Cann, B. 1992. Three anticyclonic slope water oceanic eDDIES (SWODDIES) in the Southern Bay of Biscay in 1990. Deep Sea Research Part A. Oceanographic Research Papers.

Pingree, R. D., and Le Cann, B. 1990. Structure, strength and seasonality of the slope currents in the bay of Biscay region. J. Mar. Biol. Ass. U.K.

Pitcher, T. J., and Parrish, J. K. 1993. The functions of shoaling behaviour. *In* The behaviour of teleost fishes, 2nd ed., pp. 363–439. Ed. by T. J. Pitcher. Chapman and Hall, London.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raab, K., Llope, M., Nagelkerke, L. a J., Rijnsdorp, A. D., Teal, L. R., Licandro, P., Ruardij, P., *et al.* 2013. Influence of temperature and food availability on juvenile European anchovy Engraulis encrasicolus at its northern boundary. Marine Ecology Progress Series, 488: 233–245.

Simmonds, J. E., and Maclennan, D. N. 2005a. Fisheries Acoustics Theory and Practice. Second Edition. Chapman & Hall, New York: 472pp.

Simmonds, J. E., and Maclennan, D. N. 2005b. Fisheries acoustics - Theory and practice. Blackwell Publishing. 437 pp.

Sinclair, M. 1988. Marine populations. An assay on population regulation and speciation. 251 pp.

Solabarrieta, L., Rubio, A., Castanedo, S., Medina, R., Charria, G., and Hernández, C. 2014. Surface water circulation patterns in the southeastern Bay of Biscay: New evidences from HF radar data. Continental Shelf Research, 74: 60–76.

Takasuka, A., and Aoki, I. 2006. Environmental determinants of growth rates for larval Japanese anchovy Engraulis japonicus in different waters. Fisheries Oceanography, 15: 139–149.

Uriarte, A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Scientia Marina, 60: 237–255. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Uriarte, A., Rico, I., Villamor, B., Duhamel, E., Dueñas, C., Aldanondo, N., and Cotano, U. 2016. Validation of age determination in European anchovy. Journal of Marine and Freshwater Research, in press.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Cermeño, P., De Miguel, E., Gómez Sánchez, J., *et al.* 2001a. Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning: do they form part of the plankton. ICES CM, W:20.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Miguel, E. De, Sanchez, J. A. G., Jimenez, M., *et al.* 2001b. 2001 ICES Annual Science Conference ICES CM 2001 / W : 20 Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning : Do they form part of the plankton ? ICES CM, 20.

Van Der Lingen, C., Hutchings, L., and Field, J. 2006. Comparative trophodynamics of anchovy Engraulis encrasicolus and sardine Sardinops sagax in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated. African Journal of Marine Science, 28: 465–477. Taylor \& Francis.

Wickham, H. 2009. ggplot2: elegant graphics for data analysis. Springer New York.

Woillez, M., Poulard, J., Rivoirard, J., Petitgas, P., and Bez, N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES Journal of Marine Science, 64: 537–550.

Zhao, X., Wang, Y., and Dai, F. 2008. Depth-dependent target strength of anchovy (Engraulis japonicus) measured in situ. ICES Journal of Marine Science, 65: 882–888.

Lezama-Ochoa, A., Boyra, G., Goñi, N., Arrizabalaga, H. and Bertrand, A. (2010) Investigating relationships between albacore tuna (Thunnus alalunga) CPUE and prey distribution in the Bay of Biscay. Progress in Oceanography, 86, 105-114.

Maclennan, D. N., Fernandes, P. G. and Dalen, J. (2002), A consistent approach to definitions and symbols in fisheries acoustics, ICES Journal of Marine Science, 59(2), 365.

R Development Core Team (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Simmonds, J. E. and Maclennan, D. N. (2005), Fisheries acoustics - Theory and practice, 2nd ed., edited by T. J. Pitcher, Blackwell Publishing.

Uriarte, A., Prouzet, P. and Villamor, B. (1996), Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries, Scientia Marina, 60(Suppl.2), 237–255.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Miguel, E. D., Sanchez, J. A. G. and Jimenez, M. (2001), Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning: Do they form part of the plankton?, ICES CM 2001/W:20

Uriarte, A. (editor), 2002: Experimental surveys for the assessment of juveniles . Final Report to the European Commission of FAIR Project CT97-3374 (JUVESU).

Bibliography of Chapter 5

Aldanondo, N., Cotano, U., Tiepolo, M., Boyra, G., and Irigoien, X. 2010. Growth and movement patterns of early juvenile European anchovy (Engraulis encrasicolus L.) in the Bay of Biscay based on otolith microstructure and chemistry. Fisheries Oceanography, 19: 196–208.

Allain, G., Petitgas, P., and Lazure, P. 2001. The influence of mesoscale ocean processes on anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography, 10: 151–163. John Wiley \& Sons.

Allain, G., Petitgas, P., and Lazure, P. 2007a. The influence of environment and spawning distribution on the survival of anchovy (Engraulis encrasicolus) larvae in the Bay of Biscay (NE Atlantic) investigated by biophysical simulations. Fisheries Oceanography, 16: 506–514.

Allain, G., Petitgas, P., Lazure, P., and Grellier, P. 2007b. Biophysical modelling of larval drift , growth and survival for the prediction of anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay (NE Atlantic). Fisheries Oceanography, 16: 489–505.

Bachiller, E., Cotano, U., Boyra, G., and Irigoien, X. 2013. Spatial distribution of the stomach weights of juvenile anchovy (Engraulis encrasicolus L.) in the Bay of Biscay. ICES Journal of Marine Science, 70: 362–378.

Bachiller, E., and Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay. Ecological effects of trophic interactions.

Bivand, R., and Lewin-Koh, N. 2015. maptools: Tools for Reading and Handling Spatial Objects.

Borja, A., Fontan, A., Saenz, J., and Valencia, V. 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (Engraulis encrasicolus) ´. Fisheries Oceanography, 17: 477–493.

Borja, A., Uriarte, A., Egaña, J., Motos, L., and Valencia, V. 1998. Relationships between anchovy (Engraulis encrasicolus) recruitment and environment in the Bay of Biscay (1967±1996). Fisheries Oceanography, 7: 375–380.

Boyra, G., Martınez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. ICES Journal of Marine Science, 70: 1354–1368.

Carrera, P., Churnside, J. H., Boyra, G., Marques, V., Scalabrin, C., and Uriarte, A. 2006. Comparison of airborne lidar with echosounders: a case study in the coastal Atlantic waters of southern Europe. ICES Journal of Marine Science, 63: 1736–1750.

Charria, G., Lazure, P., Le Cann, B., Serpette, A., Reverdin, G., Louzael, S., Batifoulier, F., *et al.* 2013. Surface layer circulation derived from Lagrangian drifters in the Bay of Biscay. Journal of Marine Systems, 109-110: S60–S76.

COM374. 2010. Establishing the fishing oportunities for Anchovy in the Bay of Biscay for the 2010-2011 fishing season and amending Regulation (EU) No 53/2010. Brussels.

Cort, J. L., Cendrero, O., and Iribar, X. 1977. La anchoa (engraulis encrasicholus) (L.) del Cantábrico. Bol. Inst. Espa. Oceano., 220.

Cotano, U., Irigoien, X., Etxebeste, E., Alvarez, P., Zarauz, L., Mader, J., and Ferrer, L. 2008. Distribution, growth and survival of anchovy larvae (Engraulis encrasicolus L.) in relation to hydrodynamic and trophic environment in the Bay of Biscay. Journal of Plankton Research, 30: 467–481.

Fernandes, J. a., Irigoien, X., Goikoetxea, N., Lozano, J. a., Inza, I., Pérez, A., and Bode, A. 2010. Fish recruitment prediction, using robust supervised classification methods. Ecological Modelling, 221: 338–352.

Foote, K. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. International Council for the Exploration of the Sea. 81 pp.

Gerritsen, H. 2013. mapplots: Data visualisation on maps.

Gomis, D., Ruiz, S., and Pedder, M. 2001. Diagnostic analysis of the 3D ageostrophic circulation from a multivariate spatial interpolation of CTD and ADCP data. Deep Sea Research, 48: 269–295.

Hoare, D. J., Krause, J., Peuhkuri, N., and Godin, J.-G. J. 2000. Body size and shoaling in fish. Journal of Fish Biology, 57: 1351–1366.

Ibaibarriaga, L., Fernandez, C., Uriarte, A., Roel, B. a., Ibaibarriaga, L., and Ferna, C. 2008. A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES Journal of Marine Science, 65: 191.

ICES. 2009. Report of the Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES Areas VIII and IX (WGACEGG). ICES CM, LRC:20: 181.

ICES. 2015a. . Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA), 24–29 June 2015, Lisbon, Portugal.: 612 pp.

ICES. 2015b. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES CM, ACOM:16: 580.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008a. From egg to juvenile in the Bay of Biscay: spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Cotano, U., Boyra, G., Santos, M., Alvarez, P., Otheguy, P., Etxebeste, E., *et al.* 2008b. From egg to juvenile in the Bay of Biscay: Spatial patterns of anchovy (Engraulis encrasicolus) recruitment in a non-upwelling region. Fisheries Oceanography, 17: 446–462.

Irigoien, X., Fiksen, Ø., Cotano, U., Uriarte, A., Alvarez, P., Arrizabalaga, H., Boyra, G., *et al.* 2007. Could Biscay Bay Anchovy recruit through a spatial loophole ? Progress in Oceanography, 74: 132–148.

Kondrashev, S. L., Gnyubkina, V. P., and Zueva, L. V. 2012. Structure and spectral sensitivity of photoreceptors of two anchovy species: Engraulis japonicus and Engraulis encrasicolus. Vision Research, 68: 19–27. Elsevier Ltd.

Koutsikopoulos, C., and Le Cann, B. 1996. Physical processes and hydrological structures related to the Bay of Biscay anchovy. Scientia Marina, 60: 9–19.

Lawson, G. L., Barange, M., Freon, P., and Fre, P. 2001. Species identification of pelagic fish schools on the South African continental shelf using acoustic descriptors and ancillary information. ICES Journal of Marine Science, 58: 275–287.

Maclennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365.

Massé, J. 1996. Acoustic observations in the Bay of Biscay : Schooling , vertical distribution , species assemblages and behaviour *. Scientia Marina, 60: 227–234.

Motos, L., Uriarte, A., and Valencia, V. 1996a. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L.). Scientia Marina, 60: 117–140. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Motos, L., Uriarte, A., and Valencia, V. 1996b. The spawning environment of the Bay of Biscay anchovy (Engraulis encrasicolus L). Scientia Marina, 60: 117–140.

Novales Flamarique, I. 2011. Unique photoreceptor arrangements in a fish with polarized light discrimination. Journal of Comparative Neurology, 519: 714–737.

Ona, E. 2003. An expanded target-strength relationship for herring. ICES Journal of Marine Science, 60: 493–499.

Otamendi, E. B. 2012. Trophic ecology of small pelagic fish in the Bay of Biscay.

Petitgas, P., Reid, D. G. D., Planque, B., Nogueira, E., Hea, B. O., Cotano, U., and O'Hea, B. 2006. The entrainment hypothesis: an explanation for the persistence and innovation in spawning migrations and life cycle spatial patterns. ICES CM: 9pp.

Petitgas, P., Secor, D. H., McQuinn, I., Huse, G., and Lo, N. 2010. Stock collapses and their recovery: mechanisms that establish and maintain life-cycle closure in space and time. ICES Journal of Marine Science, 67: 1841–1848.

Pingree, R. ., and Le Cann, B. 1992. Three anticyclonic slope water oceanic eDDIES (SWODDIES) in the Southern Bay of Biscay in 1990. Deep Sea Research Part A. Oceanographic Research Papers.

Pingree, R. D., and Le Cann, B. 1990. Structure, strength and seasonality of the slope currents in the bay of Biscay region. J. Mar. Biol. Ass. U.K.

Pitcher, T. J., and Parrish, J. K. 1993. The functions of shoaling behaviour. *In* The behaviour of teleost fishes, 2nd ed., pp. 363–439. Ed. by T. J. Pitcher. Chapman and Hall, London.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raab, K., Llope, M., Nagelkerke, L. a J., Rijnsdorp, A. D., Teal, L. R., Licandro, P., Ruardij, P., *et al.* 2013. Influence of temperature and food availability on juvenile European anchovy Engraulis encrasicolus at its northern boundary. Marine Ecology Progress Series, 488: 233–245.

Simmonds, J. E., and Maclennan, D. N. 2005a. Fisheries Acoustics Theory and Practice. Second Edition. Chapman & Hall, New York: 472pp.

Simmonds, J. E., and Maclennan, D. N. 2005b. Fisheries acoustics - Theory and practice. Blackwell Publishing. 437 pp.

Sinclair, M. 1988. Marine populations. An assay on population regulation and speciation. 251 pp.

Solabarrieta, L., Rubio, A., Castanedo, S., Medina, R., Charria, G., and Hernández, C. 2014. Surface water circulation patterns in the southeastern Bay of Biscay: New evidences from HF radar data. Continental Shelf Research, 74: 60–76.

Takasuka, A., and Aoki, I. 2006. Environmental determinants of growth rates for larval Japanese anchovy Engraulis japonicus in different waters. Fisheries Oceanography, 15: 139–149.

Uriarte, A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Scientia Marina, 60: 237–255. THE INSTITUT DE CIENCIES DEL MAR DE BARCELONA.

Uriarte, A., Rico, I., Villamor, B., Duhamel, E., Dueñas, C., Aldanondo, N., and Cotano, U. 2016. Validation of age determination in European anchovy. Journal of Marine and Freshwater Research, in press.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Cermeño, P., De Miguel, E., Gómez Sánchez, J., *et al.* 2001a. Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning: do they form part of the plankton. ICES CM, W:20.

Uriarte, A., Sagarminaga, Y., Scalabrin, C., Valencia, V., Miguel, E. De, Sanchez, J. A. G., Jimenez, M., *et al.* 2001b. 2001 ICES Annual Science Conference ICES CM 2001 / W : 20 Ecology of anchovy juveniles in the Bay of Biscay 4 months after peak spawning : Do they form part of the plankton ? ICES CM, 20.

Van Der Lingen, C., Hutchings, L., and Field, J. 2006. Comparative trophodynamics of anchovy Engraulis encrasicolus and sardine Sardinops sagax in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated. African Journal of Marine Science, 28: 465–477. Taylor \& Francis.

Wickham, H. 2009. ggplot2: elegant graphics for data analysis. Springer New York.

Woillez, M., Poulard, J., Rivoirard, J., Petitgas, P., and Bez, N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. ICES Journal of Marine Science, 64: 537–550.

Zhao, X., Wang, Y., and Dai, F. 2008. Depth-dependent target strength of anchovy (Engraulis japonicus) measured in situ. ICES Journal of Marine Science, 65: 882–888.

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