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A biophysical model for simulating early life stages of sardine in the Iberian Atlantic stock

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ABSTRACT

The Iberian sardine (*Sardina pilchardus*) is a traditional fishery in western Iberia that is economically important in Portugal and in Galicia (NW Spain). The International Council for the Exploration of the Seas (ICES) advice for the sardine in regions VIII and IXa in 2013 indicated that the biomass has decreased since 2006 and recruitment has been below the long term average since 2005. Recruitment is very variable, so it is important to understand the underlying processes driving this variation in order to manage the fishery effectively. In this study, a biophysical model was used to simulate the early life (egg and larval) stages of sardine. A high resolution hydrodynamic model for North and Northwest Iberia was used to force a Lagrangian Individually-Based Model (IBM) that simulated advection and dispersion (both horizontal and vertical) and included some biological behaviour. A Lower Trophic Level (LTL) model coupled to the hydrodynamic model was also used to get some insight on recruitment for years 2006–2007. Additionally, since in this area there are two different spawning grounds that could be associated with two eventually different populations, we have tried to show how the model can be used for giving insight on stock connectivity and therefore can contribute to stock delineation.

1. Introduction

Fisheries assessment and management requires environmental and ecosystem knowledge and information about the areas where stocks of economical importance are exploited. Understanding the variability of oceanographic and plankton conditions is important for the characterization of habitats of pelagic and demersal fishes. However, understanding the link between fisheries and environmental variability is a significant challenge and can impact on key stages including spawning, larval stages and recruitment, i.e. the appearance of a new generation of individuals in a fish stock. The use of Lagrangian models to simulate eggs and larvae as particles evolving in a 3D environment characterised by a biophysical model has become a established tool in the last decades (e.g. Hinckley et al., 1996; Werner et al., 1996; Mullon et al., 2003). Early life stages (ELS) models can serve as a tool for exploring recruitment as well as dispersal and migration pathways and, thus, connectivity of populations.

The Iberian sardine (*Sardina pilchardus*) is a target species for fisheries in western Iberia that is economically important in Portugal and, to a lesser extent, in Galicia (NW Spain) (Santos et al., 2011). The International Council for the Exploration of the Seas (ICES) treats sardine stock in the Atlantic waters of the Iberian Peninsula as a single stock for management purposes. The stock area includes ICES sub-areas VIIIc and IXa that range from the Gulf of Cadiz along western and northern Portugal to Galicia and the southern Bay of Biscay (Cantabrian Sea). Spawning of the Atlantic Iberian sardine occurs in two main areas: the Cantabrian Sea and the western Portuguese shelf between the Nazare Canyon and the Minho river. Spawning is restricted to the shelf and occurs at water temperatures between 12 and 17 °C (Bernal et al., 2007). The spawning season varies geographically: in the western Iberian coast it spans between September and May, peaking in November, whereas in the Cantabrian Sea, it takes place in spring, peaking in April. The landings in these areas show large interannual variability, with captures peaking in the periods 1941–1945, 1960–1967 and 1980–1985 (Carrera and Porteiro, 2003; ICES, 2014) and catches declining from 1985 to the lowest observed levels in recent years. Recruitment also varied significantly among years, but high recruitment in 2000 and 2004 has not lead to a recovery of the stock (ICES, 2014). Several studies have tried to link environmental variability with sardine abundance and recruitment, but no direct relationship to environmental parameters has been derived (see Santos et al., 2011 for a general review). Carrera and Porteiro (2003) put forth that the Iberian sardine is a single stock, although spawning

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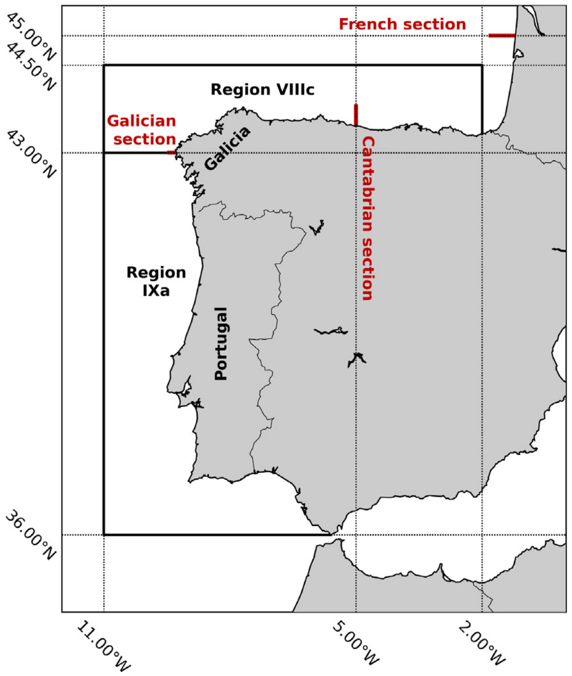

Fig. 1. ICES areas considered in the present study. The figure also presents three sections that have been used in the modelling experiments explained in Section 2.5.1.

occurs in two different locations. In this sense, the Iberian Atlantic sardine could be considered as metapopulation, regional group of local populations with asyncronous internal dynamics but linked with sufficient gene flow to establish demographic connectivity. This metapopulation hypothesis was used by Carrera and Porteiro (2003) to explain the collapse of the sardine fishery in the 1990s. Low recruitments in the 1990s caused the contraction of sardine populations to the spawning areas and restricted connectivity.

In this study, a biophysical individual-based model (IBM) was developed for simulating ELS of sardine in divisions IXa and VIIIA (see Fig. 1). We have benefited from the availability of a physical model, which has been adapted by the modelling group of the Instituto Español de Oceanografía (IEO) to the Iberian Atlantic shelf and slope in the last years for simulating hydrodynamical variability at scales relevant for assessing the effect of the environment on early life stages. The model configuration focuses on high resolution shelf and slope processes (upwelling, river plumes, slope currents, etc.) and adequately accounts for the variability of these processes in response to wind events and tidal variability (Otero et al., 2008, 2013; Otero and Ruiz-Villarreal, 2008; Marta-Almeida et al., 2013). The model domain extends from Lisbon to the southern Bay of Biscay comprising the central north and north area of IXa and VIIIc. A Lagrangian model to simulate Early Life Stages (ELS) of sardine is presented in this manuscript. The ELS model is an *ad hoc* modified version of the Lagrangian software Ichthyop (Lett et al., 2008) which was coupled offline with our 3D hydrodynamic model. We have adapted the biological behavior in the ELS IBM model to describe ELS in sardine following the development performed by Ospina-Álvarez et al. (2012) and Catalán et al. (2013) for anchovy in the Mediterranean Sea. A simple coupling to a Lower Trophic Level (LTL) model was also included in order to impose food limitation to the growth of sardine late larval stages. The interaction between the ELS and the environment is simulated for a period ranging from autumn 2006 to autumn 2007, thus covering the spawning peaks of sardine both in the Iberian Atlantic coast and the Cantabrian Sea. The coupled ELS/biophysical model is used in this study with two main objectives:

1. Exploring the potential environmental mechanisms driving recruitment, focusing on the influence of the environment on the Atlanto Iberian sardine recruitment failure of year 2007 (see ICES WGHANSA 2012).
2. Discussing how the biophysical model can be used for studying dispersal and migration pathways and therefore for assessing the connectivity of sardine populations in the Ibero-Atlantic stock.

2. Materials and methods

2.1. The modelled ELS

The Lagrangian simulations used in this study focus on the egg and larvae ELS. In particular, larvae are followed until they reach a length of approximately 25 mm (around 40 days after spawning). According to Silva et al. (2014), from the age of 20–25 days after hatching, sardine larvae swimming capabilities start to develop and continue increasing with age and length. Around metamorphosis (especially from 45 days after hatching onwards), larvae spend most of the time swimming and are able to resist the mean current speeds. In this sense, we considered that 40 days after spawning (approximately 37 days after hatching) most sardine larvae would have improved the ability to swim and hence, to resist the mean currents, thus increasing their chances for survival. Therefore, we assumed that survival after 40 days can be a good indicator of recruitment.

Although late larvae, defined here as larvae whose length is larger than 25 mm, and early juveniles are not considered in the Lagrangian simulations, an analysis of the environmental conditions that would affect these stages is also included in the discussion. In summary, the ELS were divided in three periods (enumerated below) in order to analyze the suitability of the environmental conditions for survival according to existing recruitment hypothesis for the Atlanto-Iberian sardine in the literature:

1. Spawning period: eggs and yolk-sac larvae.
2. Early feeding larvae (from hatching to 25 mm length).
3. Late feeding larvae (larger than 25 mm) and first juveniles.

2.2. The superindividual approach

An Individual-Based model (IBM, DeAngelis and Mooij, 2005) was developed where each Lagrangian particle represented an early life stage of sardine which is characterized by its location (longitude, latitude and depth), stage (egg, yolk-sac larva or feeding larva), length and life status (alive or dead). The number of individuals that could be simulated is limited by computational power and it was not possible to simulate every egg, so individuals were grouped into one "superindividual" whose characteristics were kept homogeneous (Scheffer et al., 1995).

The physical and biological processes impacting superindividuals modelled were dependent on the development stage and size (see Table 1).

The mortality of ELS was done *a posteriori* during the post-processing of model outputs. This was because tracking of the number of individuals that each superindividual represents was not possible within Ichthyop.

2.3. Physical processes

Particle passive movement depends on the advective and dispersive processes that act on all stages. A full description of advection and dispersion in Ichthyop can be found in Lett et al. (2008) so are not described further here. Advection and dispersion were calculated from three dimensional horizontal and vertical