PHYSICAL CONTROLS ON THE EVOLUTION OF ANCHOVY IN THE BAY OF BISCAY: A NUMERICAL APPROXIMATION


Abstract

In this paper, the preliminary results of the application of an Individual Based Model (IBM) are presented. This model is used for the study of the spatio-temporal physical evolution of anchovy Engraulis encrasicolus in the Bay of Biscay, from its earliest life stage to juvenile ages under four months. The hydrodynamics used as input data for the IBM have been derived from the TRIMODENA model, developed using the Finite Element Method. The IBM predictions at the end of the study periods are compared with juvenile density field data. Differences obtained between the model results and field data show that the physical component of the modelling is not enough to explain the anchovy behaviour in the Bay of Biscay. These differences are attributed to biological processes that must be incorporated into the modelling in order to get a closer approximation to the real situation.

Key words: Anchovy, Bay of Biscay, Eggs, Finite Element Method, Individual Based Model, Larvae, Recruitment, Sardine, TRIMODENA
1. Introduction

A wide variety of biological models, linked to physical models, have been developed over the last decade (Heath and Gallego, 1998; Brickman and Frank, 2000; Bartsch and Coombs, 2001; Huggett et al., 2003; Pedersen et al., 2003; North and Houde, 2004). These attempt to describe different parts of the complex network of the marine ecosystems. The models are characterised by the different selection of the variables and processes formulations used for describing the specific study phenomenon (algal bloom, fish recruitment, influence of the human activities, etc.). Here, the preliminary results of the application of an Individual Based Model (IBM), which consists of a Lagrangian particle tracking model and an associated biological module, are presented. This model is used for the study of the spatio-temporal physical evolution of anchovy *Engraulis encrasicholus* in the Bay of Biscay, from its earliest life stage (approximately in mid-May) to juvenile ages under four months (at the beginning of September). The IBM is prepared to operate with hydrodynamic data of both regular and irregular grids. In this case, the hydrodynamics used as input data for the IBM have been derived from the *TRIMODENA* model, developed using the Finite Element Method (FEM).

In the present development of the IBM, the behaviour of the early life stages of anchovy is analysed considering that their motion depends only on the current characteristics, being the model predictions at the end of the study periods compared with juvenile density field data. The model is also applied to analyse the behaviour of sardine (*Sardina pilchardus*) for the same hydrodynamic data and study periods. This is a species that coexists with anchovy in the Bay of Biscay. Following this methodology, we can get information on the role of the physical component of the modelling on the evolution of different species and, therefore, estimate the importance of the biological processes on the specific evolution of anchovy. The obtained information will be very useful for improving in the model the biological processes perspective for anchovy in order to predict future recruitments with guarantees of success. The organization of this paper is as follows. The experimental setup and the numerical models are described in sections 2 and 3, respectively. In section 4 the results of the study and their discussion are presented, to finally, summarise the conclusions in section 5.

2. Experimental setup

The Bay of Biscay is an arm of the Atlantic Ocean, limited by the northern and western coasts of Spain and France respectively, which covers approximately 250,000 km². Its hydroclimatic regime corresponds to that of a mid-
latitude temperate zone with a main primary production peak in spring and some secondary vernal blooms. The currents at the upper layers of the water column are directly related with the wind fields, being their effects more important than the ones caused by circulation systems of higher scales, which have more relevance in the outer zone of the continental shelf (González et al., 2002).

Nearshore, the coastline orientation together with the seasonal distribution of the prevailing winds explain the drift of the water mass in the Bay of Biscay. In autumn and winter, the winds blow predominantly from the Southwest originating marine currents that, on an average, cause drift toward the East and North. During the spring, the wind regime changes toward the North-Northwest, generating South and West-Southwest currents in the French and Spanish coasts respectively. The summer situation is similar to that of spring, although the weakness and great variability of the winds cause that the general drift direction of the currents remains uncertain.

In this environment, anchovy is a fish of high economic interest, being together with sardine one of the main small pelagic species. The spawning season of anchovy in the Bay of Biscay extends from March to July-August, although most of the reproductive effort is made in May-June (Motos et al., 1996; Uriarte et al., 1996; Petitgas et al., 2003). With respect to sardine, the spawning season is broad and varies from one zone to another. Peaks in the Bay of Biscay happen along the months of February and March. The most common spawning grounds for both species in the Bay of Biscay can be identified by means of the field data about the spatial distribution of relative egg abundance, RA, which is defined as

\[ RA(i, y) = \frac{N_{i,y}}{\sum_{i=1}^{j} N_{i,y}}, \]  

where \( N \) is the number of eggs, \( i \) is the station, \( y \) is the year, and \( j \) is the number of stations. The mean spatial distributions of \( RA \) obtained between the years 1999 and 2002 have been represented in Figure 1, where the main spawning areas have been defined (Sagarminaga et al., 2004).

For anchovy, the spawning areas are located close to the Gironde estuary and Adour river mouth on the French shelf. Nevertheless, there is also a noticeable spawning area in the mid-outer Armorican shelf (areas 1, 2 and 3, respectively). For sardine, the main spawning grounds are found over the Cantabrian shelf and close to the Adour discharge zone. On the northern part of the Bay, there is a spawning area over the shelf edge, and another one over the mid-inner Armorican shelf between the Gironde estuary and Loire river (areas 4, 5, 6 and 7, respectively). Both species have a spawning ground in the Aquitanian region (area 8), where there is also a significant egg production, but
lower than in the above mentioned areas. Where both species are present there is generally a dominance of one of them.

The information about the abundance and spatial distribution of anchovy and sardine eggs used in this work has been obtained from the cruises which AZTI Foundation carries out annually in May-June for the estimation of anchovy and sardine biomass. These cruises are in the frame of the DEPM project (Plan Nacional de Muestreo de Pesquerías) with financial support from the European Union. The individual density field data obtained in the years 1998, 1999 and 2003 are used in this study in order to analyse the behaviour of the IBM. With respect to the juvenile data, these have been obtained from the international JUVESU project (EC Fair CT97-3374, Experimental surveys for the assessment of juveniles) for the years 1998 and 1999, and from a specific cruise for the year 2003. The main distribution area in the Bay of Biscay of anchovy juveniles with ages under one year is located over or beyond the continental shelf edge of the Cantabrian sea in late summer and early autumn and in more northern regions. In the sardine case, the juveniles are concentrated in the proximity of the Gironde estuary. These areas are shown in Figure 2 for both species.

During the early life stages of anchovy and sardine, the eggs and larvae can be considered as passive particles which are drifted around close to the surface (upper 50 m of the water column) by the currents. In the IBM, this passive behaviour is assumed for individuals with ages under four months (i.e. no swimming ability is considered), which covers the life stages of interest in this study. Assuming this hypothesis, the differences between the real situation given by the juvenile density field data and the one predicted by the model from the physical point of view can be obtained. It seems evident that the physical transport processes can influence fish recruitment, both directly by advection of individuals and indirectly making possible to get favourable growth and survival conditions (suitable temperature, food availability, avoid competitors and predators, etc.). However, it also seems obvious that such physical processes, by themselves, should not be enough to explain the individual behaviour. This is due to the existence of a biological component which varies from one species to another. This component must be estimated for each species and incorporated into the modelling in order to explain the fish behaviour.

3. Numerical models

In this study, the abundance and spatial distribution of anchovy and sardine eggs obtained in the Bay of Biscay are used as input data in an Individual Based Model (IBM), which has been developed using Fortran language.
Fig. 1. Main spawning grounds for anchovy and sardine in the Bay of Biscay based on the mean spatial distributions of relative egg abundance.
consists of a Lagrangian particle tracking model and an associated biological module which can estimate the individual growth and mortality using different optional equations and generate spawning areas in function of the environment characteristics or field data. The IBM, which has been developed in a modular way, is prepared to operate with hydrodynamic data of both regular and irregular grids. Its Fortran codes have been implemented in Visual Basic in order to provide an user-friendly interface of the model with different options of graphic outputs. This type of models allows to know the life history of every individual, as opposed to Eulerian ones in which all the information is estimated on the fixed points of a grid.

The IBM requires a hydrodynamic model capable of delivering current fields in three dimensions for the particle tracking model. The hydrodynamic model used in this work, called TRIMODENA, has been developed by LIM (Laboratori d'Enginyeria Marítima, Universidad Politécnica de Cataluña) and AZTI Foundation for engineering applications in small scale areas (Espino, 1994; González et al., 2001). In this case, the model has been applied to the Bay of Biscay after modifications in it in order to work in larger scale areas and provide current fields closer to the real situation (González et al., 1998). The hydrodynamic model is based on the Shallow Water Equations (SWE) which
are derived from the momentum conservation and continuity equations making the assumptions that the pressure distribution is hydrostatic and the terms referring to the vertical velocity are negligible. If the continuity equation is integrated vertically, considering that the velocity field depends on the \( z \) coordinate, the SWE may be written as follows:

\[
\frac{\partial \eta}{\partial t} + \partial_x[(\eta + h)U] + \partial_y[(\eta + h)V] = 0,
\]

\[
\partial_t u + u \partial_x u + v \partial_y u - f v = -g \frac{\rho_0}{\rho} \partial_z \eta - g \frac{1}{\rho} \partial_x \alpha + \partial_x[2K_H(\partial_x u)] + \partial_y[K_H(\partial_x v + \partial_y u)] + \partial_z[K_z(\partial_z u)],
\]

\[
\partial_t v + u \partial_x v + v \partial_y v + f u = -g \frac{\rho_0}{\rho} \partial_y \eta - g \frac{1}{\rho} \partial_y \alpha + \partial_x[2K_H(\partial_x v)] + \partial_y[K_H(\partial_y v)] + \partial_z[K_z(\partial_z v)],
\]

where \( \eta \) is the free surface height, \((u, v)\) and \((U, V)\) are the horizontal velocity components and their vertically integrated values respectively, \( h \) is the depth, \( f \) is the Coriolis parameter, \( \rho \) and \( \rho_0 \) are the density and its reference value at surface (1027.55 kg \cdot m\(^{-3}\)) respectively, \( g \) is the gravity acceleration, \( K_H \) and \( K_z \) are the horizontal and vertical eddy viscosity coefficients and \( \alpha \) is the integral of \( \rho \) between 0 and \( z \). These equations (continuity and momentum equations, Eq.[2] and Eqs.[3,4] respectively) are discretised by means of the Finite Element Method and solved using the Galerkin formulations (Zienkiewicz and Taylor, 1997).

The input data for the model are the bathymetry of the area of interest, the specific external forces of the study periods given by the density and wind fields, the astronomical tides, and the boundary conditions (González et al., 1998). The bathymetry for the area where the Bay of Biscay is located has been derived from the General Bathymetric Chart of the Oceans (GEBCO) provided by the British Oceanographic Data Centre (BODC). The wind fields have been obtained from the six-hour predictions provided by the National Oceanic and Atmospheric Administration (NOAA). In this case, the model does not take into account the currents due to density fields because we are interested in the currents at the upper layers of the water column. In these layers, the currents originated by wind fields have higher values than the ones due to density gradients. The hydrodynamic grid used to estimate the currents consists of 11,529 nodes and 11,284 elements, being the smallest ones nearshore in order to get a better resolution in shallow waters. The number of vertical degrees of freedom (number of base functions of the FEM) considered per node on this grid is five. The obtained current fields are interpolated by a linear triangulation method for their use in the particle tracking model of the IBM.
With respect to the biological module of the IBM, the option of generation of spawning areas (with the same spatial distribution and individual abundance as the first simulation day) is activated during the months of May and June with a time step of a week in order to reduce the number of particles in the model and, therefore, the computational calculation time. The initial number of particles in the model is 150,000 and each one represents a cluster of individuals with the same biophysical properties. The individual abundance in each particle has been calculated from the egg density field data registered for the specific study year. Although the generation of spawning areas is a biological process, this is used in order to put in the model new individuals and let them or the existing ones reach the zones where the field juveniles with ages under four months are located at the end of the study periods. The vertical and horizontal movements by means of the fish swimming ability are desactivated in the model, due to the assumption of passive behaviour of the individuals, as well as the mortality process.

4. Results and discussion

To evaluate how good our IBM is predicting the spatial density distribution of anchovy juveniles (with ages below four months) for a given initial egg population, and known current fields and spatio-temporal spawning areas, we have run the model for the years 1998, 1999 and 2003. The results for these years are presented from figure 3 to 8. In these figures, the density distributions of anchovy eggs (approximately in mid-May) based on cruises data are shown together with the ones predicted by the model for three dates (July and August, 1st, and September, 7th). The same information for the sardine case is presented in figures 9 and 10, but only for the year 2003.

From the results obtained, it seems that the influence of the physical transport processes, taking into account the juvenile field data, is higher in the sardine case than in the anchovy one. Furthermore, there is a variability in the spatial density distribution from one year to another, which is logical due to the own variability of the wind fields and the different initial egg distribution patterns. Assuming that the mortality is negligible, the initial mid-May anchovy eggs and the ones generated later are advected by the model during the study periods to be concentrated nearshore at the beginning of September, when they are juveniles with ages under four months. This is against the results derived from the field data in which the juveniles are mainly located over or beyond the continental shelf edge of the Cantabrian sea and in more northern regions. In the sardine case, the juvenile distribution predicted by the model is closer to the one obtained in the field, which is located near the Gironde estuary. Nevertheless, the most part of individuals is concentrated over the mid-inner Armorican shelf between the Gironde estuary and Loire river. This is due to
the generation of spawning areas with the same spatial distribution and individual abundance as the first simulation day which is activated during the months of May and June. Although the peaks of the spawning season for sardine happen mainly along the months of February and March, the generation of new individuals is activated until July in order to have the same model conditions used for the anchovy case.

Assuming that there is no incorporation of new individuals in the Bay of Biscay from outer zones and the spatial egg distributions in the spawning areas generated by the IBM are the right ones, the way of explaining the aforementioned model results for anchovy is to make use of the swimming ability that the individuals acquired with their growth, which is a biological process. This swimming ability would be used by the individuals, which could go either against or with the currents in function of different variables (temperature, salinity, food, etc.), in order to get favourable conditions. For the sardine case, in which there is a better agreement between the real situation and the model predictions, the physical component of the modelling seems to have more importance than the biological one. This fact would mean that sardine takes more advantage of the current effects than anchovy, being reduced the required biological processes to get favourable growth and survival conditions.

If the mortality process due to natural reasons had been taken into account, this would have implied reduction of anchovy biomass and, therefore, that the individual density distribution would have depended on the characteristics of the areas where the fish has been and the individual abundances and life circumstances of anchovy competitors and predators. Nevertheless, this process would not change the individual positions which would carry on being far from the ones obtained in the field. Another reasons for the differences between the model results and anchovy field data could be the inaccuracies of many factors of the modelling. For example, the input data used for the hydrodynamic model (wind fields, boundary conditions, physical coefficients, etc.) or the mathematical formulations and numerical schemes used for modelling the currents and the individual dispersion which could be inappropriate in this case.

The conclusion we can draw from the IBM results is that the biological processes must add to the physical ones if we want to get a complete explanation of the behaviour of either anchovy or another fish of interest in a specific region. Both components must be estimated by means of mathematical formulations which are based on field data with both physical and biological information. For this reason, it is important to have a wide biophysical database in order to make an accurate estimation of the current fields and individual dispersion patterns (taking into account the fish swimming ability) which let us get a closer approximation to the real situation in the sea.
Fig. 3. Density distribution of anchovy individuals in mid-May based on cruise data and the one predicted by the model at the beginning of July for the year 1998.
Fig. 4. Density distributions of anchovy individuals predicted by the model at the beginning of August and September for the year 1998.
Fig. 5. Density distribution of anchovy individuals in mid-May based on cruise data and the one predicted by the model at the beginning of July for the year 1999.
Fig. 6. Density distributions of anchovy individuals predicted by the model at the beginning of August and September for the year 1999.
Fig. 7. Density distribution of anchovy individuals in mid-May based on cruise data and the one predicted by the model at the beginning of July for the year 2003.
Fig. 8. Density distributions of anchovy individuals predicted by the model at the beginning of August and September for the year 2003.
Fig. 9. Density distribution of sardine individuals in mid-May based on cruise data and the one predicted by the model at the beginning of July for the year 2003.
Fig. 10. Density distributions of sardine individuals predicted by the model at the beginning of August and September for the year 2003.
5. Conclusions

Differences obtained between the field data and the predictions of an Individual Based Model for anchovy in the Bay of Biscay imply the existence of a biological component in its behaviour which seems to have a higher influence than in the sardine case. This component must be incorporated into the modelling in order to get a closer approximation to the real situation. These conclusions imply the necessity of evaluating carefully the biological and physical components of the modelling for each species. This is not an easy task due to the nonlinear interaction which could exist between the biological and physical components. Besides, the lack of accurate measurements that could substantiate how the biological component works in function of the environment conditions and the behaviour of another species, makes this task more difficult to get.

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