MariFishFinal Report

Instructions are presented in Section 3. If you need more information and guidance on completion and submission of the report please contact the MariFishCall Secretariat (perm@fi.dk or John.Lock@defra.gsi.gov.uk).

Project Title (Acronym)
understandingREcruitmentPROcesses Using Coupled biophysical models of the pelagicEcosystem (REPROdUCE)

Project Duration:

Start date:	1 October 2009
End date:	31 September 2012 (extended: 31 March 2013)

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2. Executive Summary

Project title (acronym):REPROdUCE: understanding REcruitmentPROcesses Using Coupled biophysical models of the pelagic Ecosystem

Project objectives:REPROdUCEaimedtodevelop ecosystems models that incorporate human and ecological aspects in order to identify the main processes determining recruitment strength and population fluctuations of two key southern European pelagic species (sardine and anchovy), in two case studies, Bay of Biscay (sardine and anchovy) and the North Aegean Sea (anchovy). The main objectives were:

- To develop conceptual models of the different trophic levels of the pelagic ecosystem for the project case studies
- To develop and validate numerical, integrated ecosystem models of the full-life cycle of sardine and anchovy within the pelagic ecosystem
- To identify the main recruitment drivers and their relative importancefor small pelagic fish in the two case studies of the project
- To develop recruitment-based fishery indicators that allow to improve the short and medium-to-long term management of these stocks

Methods: A variety of approaches have been developed for the different case studies, all based on a modular approach (climate – hydrodynamics – lower trophic level – fish). In the different case studies, attention was paid to the main processes affecting the different fish life stages, developing sub-modules for eggs/larvae, juveniles and adults as required. The process of identifying recruitment drivers was based on an iterative two-fold approach; on one hand assumptions on the forcing functions affecting the different life stages were made in the conceptual phase, and then incorporated in the numerical models. These assumptions were tested and when possible validated against observations, and an iterative process of model refining was used. On the other hand, whenever possible validated models were used to analyse the relative effect of the different variables both in each life stage but also in the overall population variability.

Main results: For the Aegean Sea case study, the final model provides a full life cycle self-regenerating representation of anchovy in the area, with dynamic reproduction and movement included. The model therefore achieved the original goal. Within the duration of REPROdUCE, simulations were also done using the N. Aegean anchovy model on a subset of environmental and fishing scenarios and over short time periods. Further simulations and improvements on some of the modules are foreseen to be undertaken after REPROdUCE. The N. Aegean anchovy model provides a good representation of anchovy growth, distribution and dynamics in the area, and allows investigating factors affecting recruitment strength in a holistic way. This was the first time that synergetic complex effects on reproduction dynamics could be investigated through a simulation model. Results indicate that different sources of nutrient enrichment have different effects on anchovy dynamics and recruitment strength. Although both river inflow and inflow of water from the Black Sea have an important effect on the ecosystem productivity, the positive effect of the former is larger for the anchovy population. Increased Black Sea water inflow increases anchovy eggs and larvae transport to offshore unsuitable waters. These results improve our understanding of the mechanisms involved in anchovy population dynamics and could only be obtained with a dynamic ecosystem model such as the one developed through this project. In addition to this, the potential of the developed model for assisting into management decisions was tested, comparing the effect of two different management measures: changes in fishery closedseason and overall reduction of fishing effort. A change in the 3-months closed season from winter to autumn results in a reduced recruitment strength with time, while a large reduction of fishing mortalitydid not yield an increase in population as large as would be expected. Again these results benefited from the integrative, holistic view provided by the model developed within REPROdUCE.

For Bay of Biscay and Atlanto-Iberian anchovy and sardine the modelling of a full life cycle was achieved either by a sequence of separate submodels corresponding to different life stages or an integrated model but over one year only, from egg to spawning. For these case studies, no previous attempt of an integrated end-to-end model was available prior to REPROdUCE, and therefore a large effort on model development was required through the project, in particular on zooplankton compartment, active movement, bioenergetics and larval transport. In contrast to N. Aegean where adult anchovy stays sedentary in the productive coastal areas, anchovy and sardine in the Bay of Biscay undertake at adult stage seasonal migrations, which adds to the complexity of processes to be modelled and validated for achieving a full life cycle model. Notwithstanding the lack of full life representations, the models developed allowed to test a series of hypotheses on recruitment strength, in this case focusing on the early life stages alone. Changes in transport/retention of early life stages, caused by changes in the hydrodynamics and dynamic changes in egg buoyancy and larval vertical behavior were alone able to recreate to some extent recruitment estimates available from the assessment of anchovy in the Bay of Biscay. This provides an environmental recruitment index alternative to some other environmental indices that have been proposed for the species in the past, with the potential to be improved and refined as the different life stages are joint together into a full life cycle for the species. In addition, the models derived have allowed exploring the potential environment for the species in the area, using an innovative bioenergetics approach. For Atlanto-Iberian sardine, some results on transport/retention in relation to recruitment strength are also promising, although for this case study further tests should be carried out.

Developed models have also been tested against field observations, existing laboratory experiments and bibliographic data. Overall, validation of the different modules developed through the project has been satisfactory, with the models been able to reproduce the main characteristics of the different stages appropriately. Furthermore, the validation of the full life cycle model for the Aegean Sea, which includes validation of the interconnectivity of the different modules developed, has also been satisfactory.

In addition to the advances in understanding the population dynamics and recruitment strength of the target species, the models developed through REPROdUCE also allowed to have a better understanding of the dynamics of lower trophic levels, have provided improved habitat maps for the target species and allowed for an integrative description of the ecosystem of the Bay of Biscay, with the first application of the OSMOSE model in the area.

Further work will be however required to consolidate the hypotheseses suggested within this project and to incorporate the models and project results into fisheries management advice. On one hand, completed models such as the Aegean Sea anchovy model should be run over a larger variety of scenarios and over larger time periods. Model refinements such as improvements of movement rules are anticipated, but overall model structure is not expected to be largely modified. On the other hand, the potential of those models that do not complete the full life cycle to understand population dynamics and recruitment strength is expected to improve once the life cycle of the target species is closed. Although this will require further scientific research and model development, the advances made within REPROdUCE are large and the complete full life cycle models for those case studies is now considered to be achievable in a short to medium term.

3. REPROdUCEFinalReport

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Objectives of the project

REPROdUCEaimedto develop ecosystems models that incorporate human and ecological aspects in order to identify the main processes determining recruitment strength of two key southern European pelagic species (sardine and anchovy), in two case studies, Bay of Biscay (sardine and anchovy) and the North Aegean Sea (anchovy).

REPROdUCE focus on two case studies with large differences in their ecological characteristics and human exploitation patterns, the Bay of Biscay (Atlantic case study) and the North Aegean Sea (Mediterranean case study), and analyses the recruitment of small pelagic fish in relation to the state of the population (demography, structure and biomass – *internal mechanisms*) and the overall pelagic ecosystem, including human exploitation (habitat suitability, food availability and predation rates - *external mechanisms*). The project builds from available but scattered knowledge of processes and interactions working at different trophic levels of the pelagic ecosystem, integrating it into a full life cycle pelagic ecosystem model, centred on the role of small pelagic fish as key forage species of these ecosystems. Once developed, the ecosystem models will be used to tackle the main objectives of this project, by applying them to answer the following questions:

1- What are the main mechanisms driving recruitment (internal *vs* external mechanisms) and what are the links between those mechanisms?

2- Which of these mechanisms can be responsible for prolonged reduction of reproductive potential in sardines and anchovies, and what is the effect of the reduction in reproductive potential in population recovery rates?

3- Are the recruitment drivers identified coherent with current general ecological hypothesis on population expansion-contraction for small pelagic fish?

The project objectives were:

- To develop conceptual models of the different trophic levels of the pelagic ecosystem for the project case studies.
- To develop and validate numerical integrated ecosystem models of the full-life cycle of sardine and anchovy within the pelagic ecosystem
- To identify the main recruitment drivers and their relative influence for small pelagic fish in the two case studies of the project.
- To develop recruitment based fishery indicators that allow to improve the short and medium-to-long term management of these stocks

Summary by Case Study

North Aegean Sea case study

In the North Aegean Sea a 3-D full life cycle model for the anchovy stock was developed (Figure 1). The latter is two-way linked to a LTL model, i.e. a hydrodynamic-biogeochemical model implemented in the North Aegean Sea within the POSEIDON forecasting system (www.poseidon.hcmr.gr).

Description of the ecosystem, full life anchovy cycle model in the Aegean Sea

The anchovy life span is considered to last 3.5 years and was divided into seven life stages/age classes. Specifically, anchovy early life was divided into three stages (ELS) according to length: (a) embryonic (egg+yolk sac larvae) stage (< 3.5 mm, autotrophic stage), (b) early larval (3.5–11 mm) and (c) late larval (11–38 mm) stage. The first two stages (<11 mm, encompassing egg, yolk sac, preflexion and early postflexion larvae) have limited swimming capabilities and undeveloped vertical migration behaviour. They were considered to behave like passive particles and to feed on microzooplankton. Late larvae and subsequent stages were considered to have attained significant behavioural and swimming capabilities being able to respond effectively to water movements (currents). Vertical migration behaviour is fully developed in the late larval stage, in which a shift in feeding preferences from microzooplankton to mesozooplankton is taking place. The juvenile (>38 mm) and adult stage feed on mesozooplankton. Although length at 50% maturity of the North Aegean Sea anchovy is approximately 105 mm, it was more straightforward to adopt a reference date for the transition from the juvenile to the adult stage or from one adult age group to the next, given the extended spawning period of the species and the high variability of individual growth rates. We selected 1st of March as the appropriate date because it is the date of start of the annual fishing period in the Aegean Sea and matches closely the onset of gonadal maturation in spring.

Bioenergetics module

The Wisconsin bioenergetics framework has been adopted to simulate the anchovy growth in both the larval and juvenile/adult stages. The wet weight increment per unit weight of weight per day is calculated by the equation:

$$\frac{1}{W_{SI}} \cdot \frac{dW_{SI}}{dt} = [C - (R + EG + SDA + EX + E_{egg})] \cdot \frac{CAL_z}{CAL_f},$$

where W_{SI} =fish wet weight (g), t = time (days), C = consumption, R = respiration (or losses through metabolism), SDA= dynamic action (or losses because of energy costs of digesting food), EG=egestion (or losses because of faeces), EX=excretion (or losses of nitrogenous excretory wastes) and E_{egg}=the energy allocated to reproduction.

Population module

The super-individual (SI) approach was adopted for the representation of the anchovy population. The attributes that characterize the SIs are: life stage/age group, weight, length, age, and position (longitude, latitude, depth). The number of individuals within each anchovy super-individual (SI) is reduced with time as a result of natural and fishing mortality,

$$\frac{dN_{SI}}{dt} = -(M_{SI} + F_{SI})N_{SI},$$

whereN_{SI} is the daily number of individuals within the SI, $M_{SI}$is the assigned natural mortality rate and F_{SI} is the corresponding fishing mortality rate. Fishing mortality follows the separability assumption and is determined by the product of three components,

$$F_{SI} = F_m \cdot F_{season} \cdot F_{position},$$

where$F_m$is the mean annual fishing mortality for the age class, $F_{season}$is a proportional term that parameterizes the seasonality of fishing effort and $F_{position}$denotes a flag, taking values 0 or 1 toindicate if the current position of the SI is within or outside the known fishing grounds. For both the early and adult feeding stages, an empirically-defined starvation condition threshold is further imposed below which the SI vanishes.

Reproduction module

A dynamic egg production algorithm was developed based on current knowledge on anchovy reproductive biology (spawning rhythms, allocation of energy to reproduction, variability of reproductive parameters): Energy from consumption is prioritized and first channeled to maintenance.Any surplus energy is subsequently allocated to reproduction and growth. If fish length is higher than length at first maturity and sea surface temperature is >15^{o}C, this surplus energy is allocated to reproduction first (fixed daily amount). If energy from consumption is not sufficient for maintenance, energy already allocated to the so called reproductive buffer (first) and bodymass (secondly) is channeled back to maintenance (to meet daily maintenance costs). If the daily energy is enough for both maintenance and reproduction, the remainder is channeled to growth (increase in weight).

Movement module

Egg and early larval stages are considered as passive particles and are advected by the mean current in the upper water column (0-30m). The active life stages (late larvae, juveniles and adults) exhibit diurnal vertical migration and active horizontal movement behaviour in response to ambient environmental conditions. The horizontal movement module for the North Aegean Sea anchovy was based on theso called restricted area approach in the sense that this particular stock does not carry out broad-scale migrations but rather tends to remain position close to the favorable (productive) areas. At each position of the SI, the environmental, bathymetric and population characteristics of the surrounding cells are calculated to determine the fish movement direction that ultimately results from the combined effect of these factors. On the whole, fish movement is controlled by the velocity and direction of fish and the main agents that determine movement are the currents fields, per-capita food availability and bathymetry.

Coupling of the fish model with the hydrodynamic-biogeochemical model

The abiotic environment of anchovy (currents, temperature) is described with outputs from the 3-D hydrodynamic model. The latter is based on the Princeton Ocean Model (POM) and has been implemented in the Aegean Sea as part of the operational POSEIDON forecasting system. An ecological model, based on the European Regional Seas Ecosystem Model (ERSEM), is coupled to POM and provides zooplankton densities (microzooplankton and mesozooplankton) that serve as available energy through consumption for the anchovy model.

The coupling between the fish model and the lower trophic level model is dynamic, i.e. heterotrophic plankton biomass (microzooplankton, mesozooplankton) simulated by the biogeochemical model, is reduced due to the predation pressure exerted by the fish. Concurrently, at the same time step, fish energy losses are summed and fed back into the inorganic (nutrients) and organic (detritus) pools of the biogeochemical model.

Model validation and ad hoc surveys in the Aegean Sea

A particular effort was made in this project to assess the performance of the different modules of the coupled model at each step of its development. Outputs of the hydrodynamic-biogeochemical model were compared with available *in situ* and remotely sensed oceanographic data (e.g. Figure 2), whereas the various modules of the fish model were evaluated against archived somatic growth data (from past otolith studies), maps of distribution and abundance of eggs, larvae and adults, as well as egg production and biomass estimates from ichthyoplankton, egg production and acoustic surveys that had been carried out in the Aegean Sea. The yearly acoustic and ichthyoplankton surveys for the estimation of the biomass of the North Aegean Sea anchovy stock have been routinely performed in June, i.e. at the peak of the spawning period. No information existed regarding the distribution of anchovy and its spawn in other periods (months) of the reproductive season. For this reason, two *ad hoc* sampling cruises were carried out during the first year of the project to collect data on the spatial distribution of eggs and adult fish during an early (May) and a more advanced (July) phase of the reproductive period. The study area was the northeastern Aegean Sea, i.e. the main spawning area of stock. Results showed that major distribution patterns known from the peak spawning time do not change in other parts of the reproductive period.

Statistical habitat models and initial conditions

Data available on presence/absence of anchovy eggs and adult schools from all available ichthyoplankton and acoustic surveys in the North Aegean Sea that had been carried out from 2003 to 2010 (including the REPROdUCE*adhoc*cruises) were used to build statistical habitat models using *in situ* collected environmental parameters and parameters calculated from the hydrodynamic-biogeochemical model simulations (e.g. Figure 3). The statistical habitat models are very useful in defining areas with potential fish presence in relation to environmental conditions and were used here to define realistic initial conditions for IBMs, i.e. the positioning of fish super-individual in space in order to start the simulations of the numerical fish models. Furthermore, the statistical models built using parameters from the hydrodynamic-biogeochemical model (e.g. Figure 3) can be used in the future to hindcast/forecast the changes in the distribution of potential habitats. This will be particular useful in the context of rising temperatures and related investigations on associated alterations in species distributions.

Model implementation and scenario testing

The full life cycle model linked to the 3-D lower trophic level model was implemented and evaluated in the Aegean Sea over the period of 2003-2006when relevant field data were available to assess its performance. Initial conditions (number of individuals and horizontal distribution of super-individuals) were realistically defined based on statistical habitat models and field estimates of daily egg production and adult biomass from ichthyoplankton and acoustic surveys.

At a first stage, we ran simulations using the early-life-stages part of the model (eggs and larvae) to explored its use in defining areas important for recruitment (Figure 4), as well as testing potential recruitment indices, such as the number of individuals that survive through the early larval stage or the numbers of larvae that metamorphose to juveniles. We found, for example (Figure 5), that the numberof individuals at Age-1 from the acoustic surveys in June correlatedwell with the numbers of individuals that, according to the model results, changed from the early to late larvalstage or from larvae to juveniles in offshore (>200 m) waters during the previous year's spawning period. Survival of larval stages in offshore waters will therefore be further explored as a potential recruitment index.

With regard to the full life cycle model, its base run produced population levels (Figure 6) and distribution and abundance patterns (Figure 7 & 8) that were very similar to those from field measurements and/or habitat models. This is to our knowledge the first time that such a complex model (3-D, full life cycle, fish population model, coupled with a hydrodynamic-biogeochemical model) is implemented for a pelagic stock.

In a subsequent step of the analysis, we tested the sensitivity of the full life cycle model to factors considered important for recruitment and population variability of anchovy in the North Aegean Sea. Two parameters were considered as most crucial for the stock: (a) the input of nutrients from the major rivers in the area, and (b) the outflow of Black Sea waters (BSW) from the Dardanelles Strait. Model simulations highlighted that a reduction in river nutrientscould have a negative effect on the anchovy population (Figure 9). Unexpectedly, a similar increase in BSW outflow, although enhancing productivity in the area, has a negative effect on the anchovy stock (Figure 9). As the model highlighted, the increased BSW outflow causes an increasein the advection of eggs and larvae to unfavorable areas.

Finally, the full life cycle anchovy model was used to test specific fishing scenarios in order to exploreits merits as a forecasting tool for fisheries management. These initial simulations performedduring the project showed that a reduction in fishing mortality does not causeanynoticeabledecrease of anchovy biomass in the short term (Figure 10), but, the temporal shift of the existing closed period from winter (December-February) to autumn (October-December) would have a negative effect on the stock.

Both the environmental and fishing scenarios investigated during the project highlighted the value of ecosystem, full life cycle fish models under themore general framework of ecosystem approach to fisheries management and revealed their potentialto improve our understanding of the mechanisms of population changes.

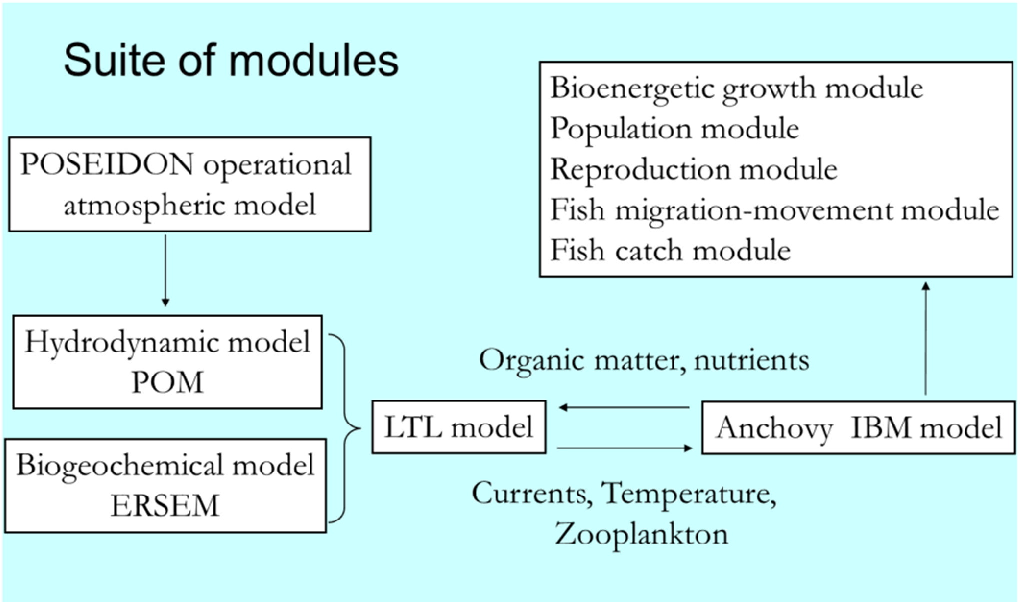

Figure 1. Schematic representation of the ecosystem, full life cycle model of anchovy in the North Aegean Sea.

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Figure 2. Model simulated near surface Chl-a (mg m^{-3}) against satellite data (MODIS) for March, June, September and December 2003.

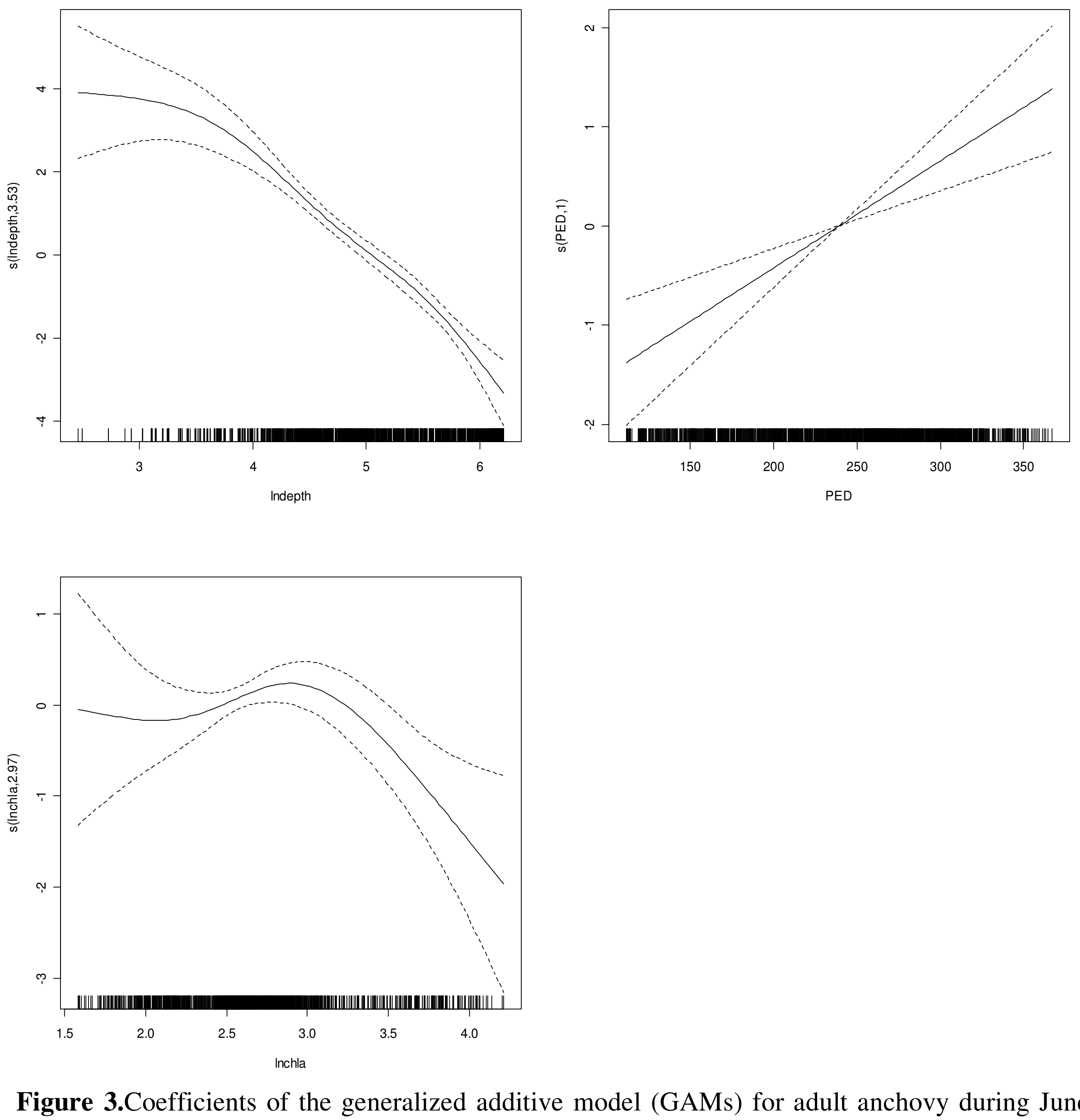


Figure 3. Coefficients of the generalized additive model (GAMs) for adult anchovy during June in the North East Aegean Sea against variables from hydrographic-oceanographic model (POM-ERSEM).lndepth, ln-transformed depth (m); PED, potential energy deficit (J); lnchla, ln-transformed integrated chlorophyll (mgC m^{-2}). Black thick lines indicate the value of GAMs coefficient, dotted lines represent the confidence intervals at P = 0.01. The rug under each variable effects plot indicates the density of points for different variable values.

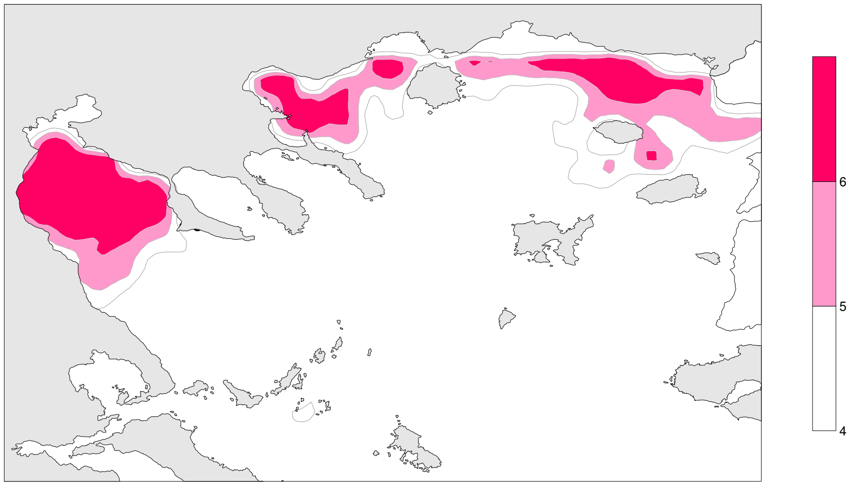


Figure 4. Early life stages runs: identification of areas that are important for recruitment:Areas with combined high values for early and late larval abundance, somatic growth and metamorphosis rate (principal component analysis).

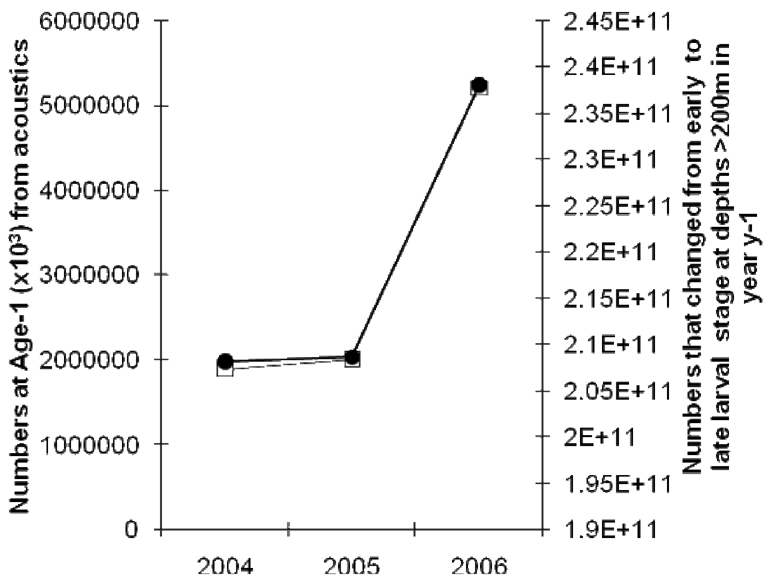


Figure 5. Early life stages runs: investigations on potential recruitment indices. Numbers at Age-1 from acoustics correlate with numbers of individuals that change from early to late larvae or from late larvae to juveniles the previous year in offshore (>200 m) waters (model).

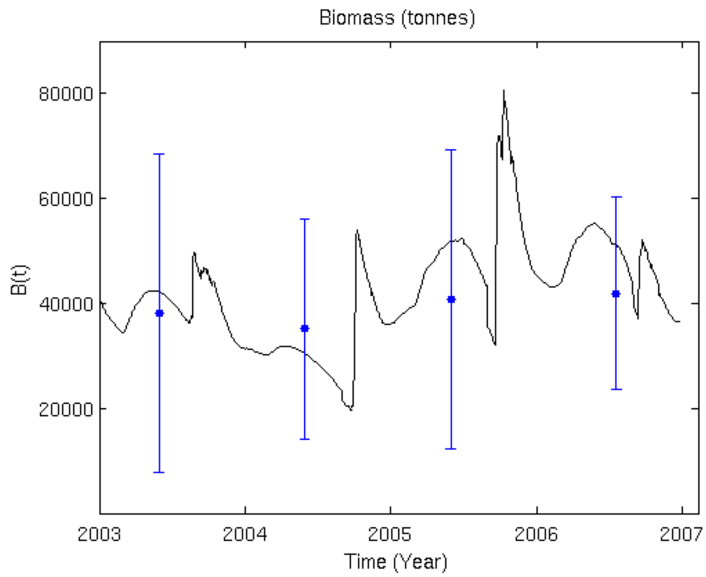
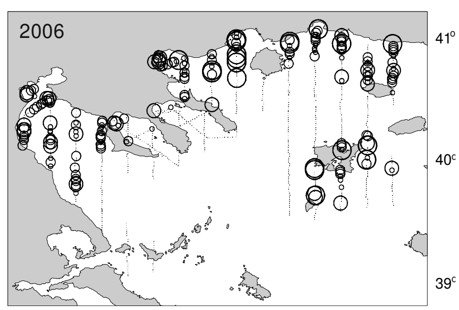


Figure 6. Full life cycle model base run. Model-derived anchovy biomass in 2003-2007. Biomass estimates from the June acoustic surveys are also given (blue dots). Bars indicate approximate 95% confidence intervals.



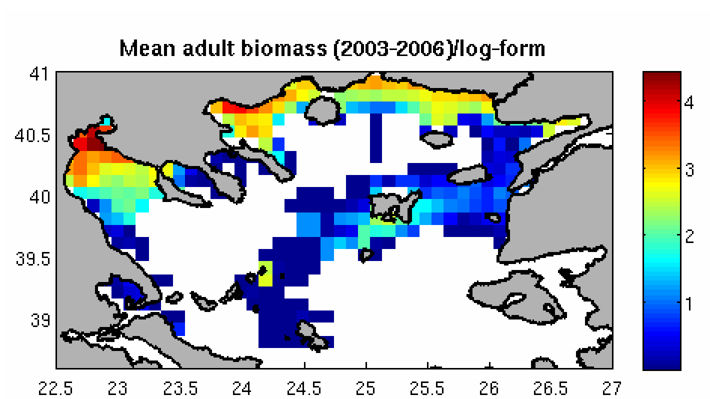


Figure 7. Full life cycle model base run.Comparison of distribution patterns of anchovy from the acoustic surveys of June (upper panel: June 2006) and the model (lower panel: mean adult biomass in June for the years 2003-2006, log-transformed).

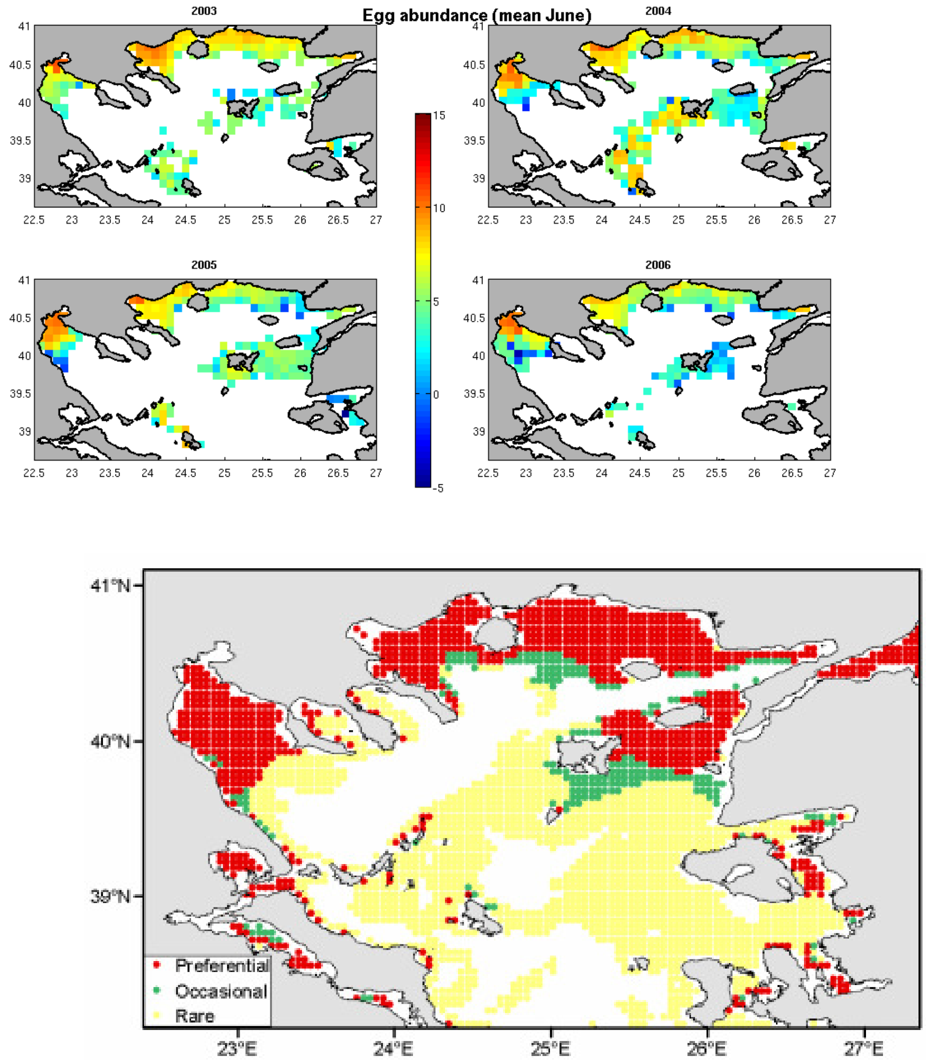


Figure 8. Full life cycle model base run.Comparison of distribution & abundance of eggs in June from model (upper panel) against potential spawning habitats from statistical habitat models (Lower panel: map of preferential, occasional & rare anchovy spawning habitat in June fromstatistical modeling).

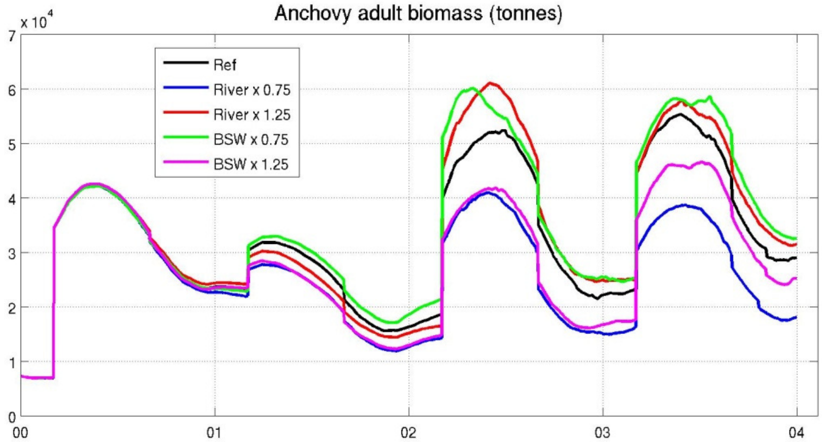


Figure 9: Model simulated total N. Aegean adult anchovy biomass (tones) for the reference simulation (black line) and simulations with decreased (-25%, blue line) and increased (+25%, red line) river nutrient inputs, and with decreased (-25%, green line) and increased (+25%, magenta line) Black Sea water (BSW) discharge.

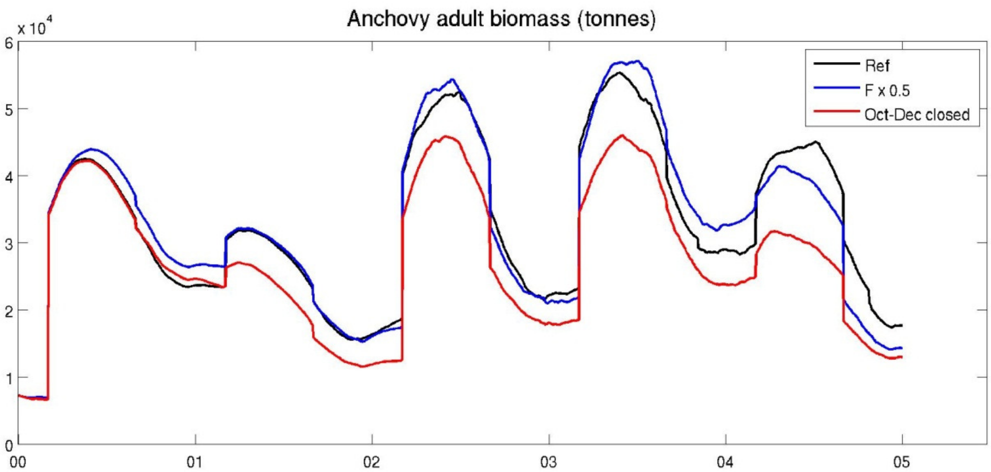


Figure 10. Model simulated total N. Aegean adult anchovy biomass (tones) for the reference simulation (black line) and the simulations with decreased fishing mortality (blue line), and shifted closed period (red line), from winter (December-February) to autumn (October-December).

Bay of Biscay anchovy case study

In the Bay of Biscay, an anchovy full life cycle model was developed (Fig.11). Validation effort was set on some of the modules with newly available data collected partly during the course of the project, while validation at the population scale over several years is still ongoing. Indicators of recruitment have been derived from the early life stage model only so far.

Model Configuration

The model is structured in a modular approach: a hydrodynamic model (MARS3D, www.previmer.org) and a biogeochemical (ECOMARS) module which constitutes the lower trophic level model, and a fish model (with several sub-modules). The hydrodynamic model provides the temporal and spatial three dimensional fields of physical variables (currents, turbulence, temperature). Prey is provided by a compilation and processing of size-structured zooplankton available over the bay (Fig 12). Combination of this dataset with the outputs of ECO-MARS model is under testing.

The coupled model is spatially explicit, with the IBM resolved in 3D for the early life stages, and in 2D for the juveniles and adults, and online coupled to the hydrodynamics. A single stage-specific bioenergetic module has been developed based on the DEB (Dynamic Energy Budget) approach, and is applied throughout the life cycle from early feeding larvae to adults. The drift module of early life stages was further developed, using strengthened information (i.e. on egg density and larval vertical distribution, see fig.13 and 14), and validated with newly available data on egg vertical distribution (Fig.15). For the movement of juveniles and adults we adopted a statistic implementation of the movement (Metropolis algorithm) to comply with seasonal fisheries acoustic surveys used as a climatology, thus not allowing any interannual variability to be simulated. Development of a more mechanistic movement module is ongoing.

Model base-run

The model base run is presented below for the year 2006, during peak spawning season, with 50,000 particles released according to spawning climatology in May (Fig.16), from eggs to mature adult at following spring. Each individual of the IBM has its own life history depending on spawning location, early life stage drift, and adult random movement following Metropolis algorithm. Fig.17 and 18 show distributions of the population at different time of the year together with examples of individual trajectories and growth.

Recruitment indicators

Larval dispersion was characterized by an index, which correlated with the abundance of recruits (age-1 fish the year after) as estimated by ICES (Fig. 19). Particles were released every week during the spawning season (4 months), on 5 potential spawning grounds. They were tracked for 50 days. The processes considered in the dispersal were 3d-currents, vertical behaviour, spawning sites and seasonal window. The simulations were hindcasted for the period 1996-2009. The weekly dispersal maps were characterized using a suite of indices including geostatistical indices to characterize drift, aggregation, spreading. The information was summarized using Principal Component Analysis, which led to a yearly global index of larval dispersion. That index correlated to the ICES recruitment series, meaning that dispersal as simulated was an important factor explaining recruitment.

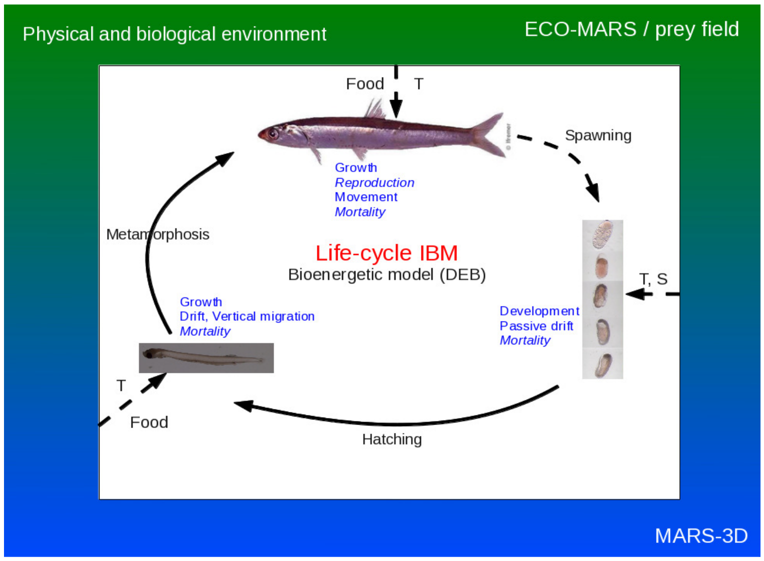


Figure 11. Structure of the full life cycle model of anchovy in the Bay of Biscay.

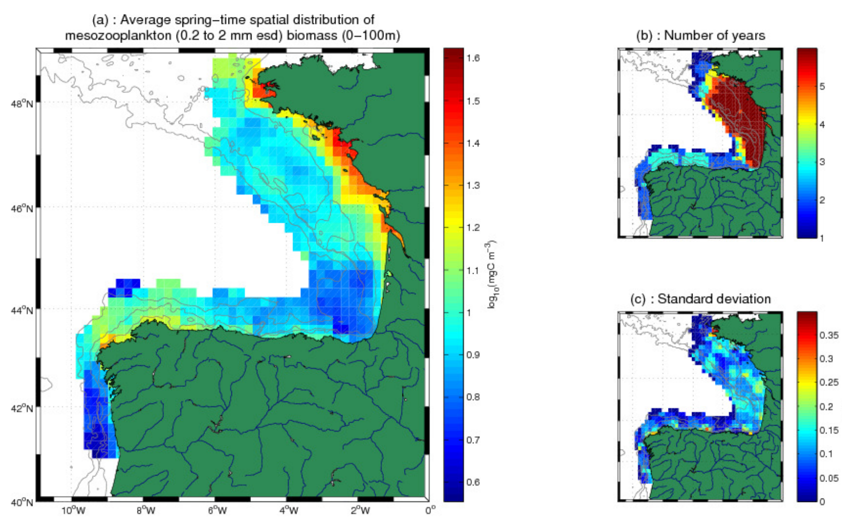


Figure 12: Spatial distribution of mesozooplankton (from 0.2 to 2 mm esd) biomasses (in log10mgC m/3) calculated as the integral of the NBSS estimated by the PLS (Partial Least Square) regression. A regular grid was generated each year and nodes were interpolated from available data within a radius of 30km and weighted by the square of their distance. (a) Shows the average distribution, (b) the total number of year used to calculate each points and (c) shows the standard deviation.

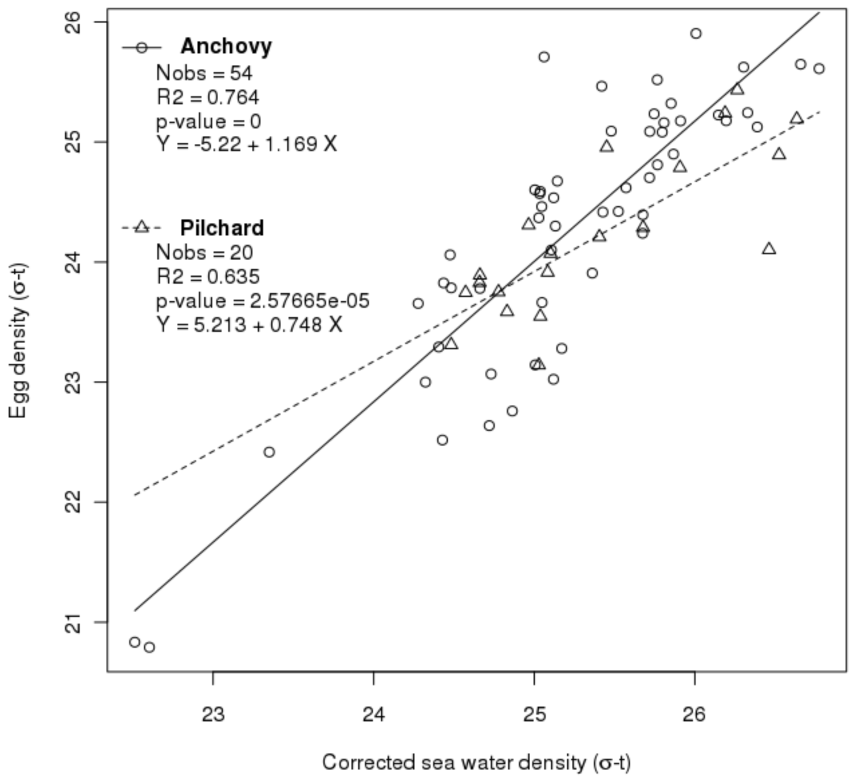


Figure 13. Regression of anchovy and sardine egg density on sea surface density. Surface densities are calculated with average CTD salinity values between the depths of 3 and 5 m, and temperature of the density gradient column for consistency with egg density measurements. Each point of the regression corresponds to the mean egg density at one station measured on ~50 eggs.

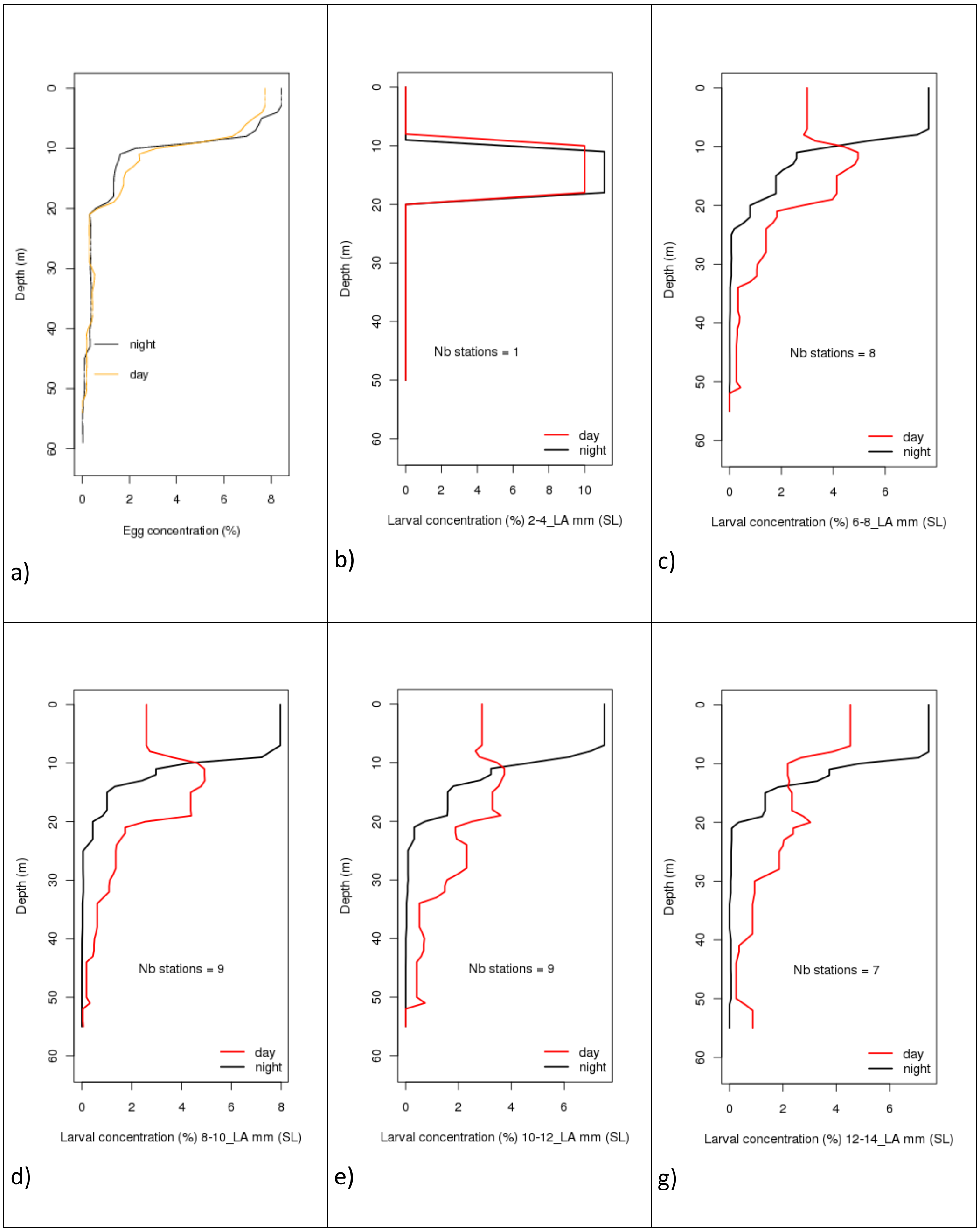


Figure 14. Average vertical distribution by day and night for anchovy eggs (a) and larvae (b-g) of different size ranges.

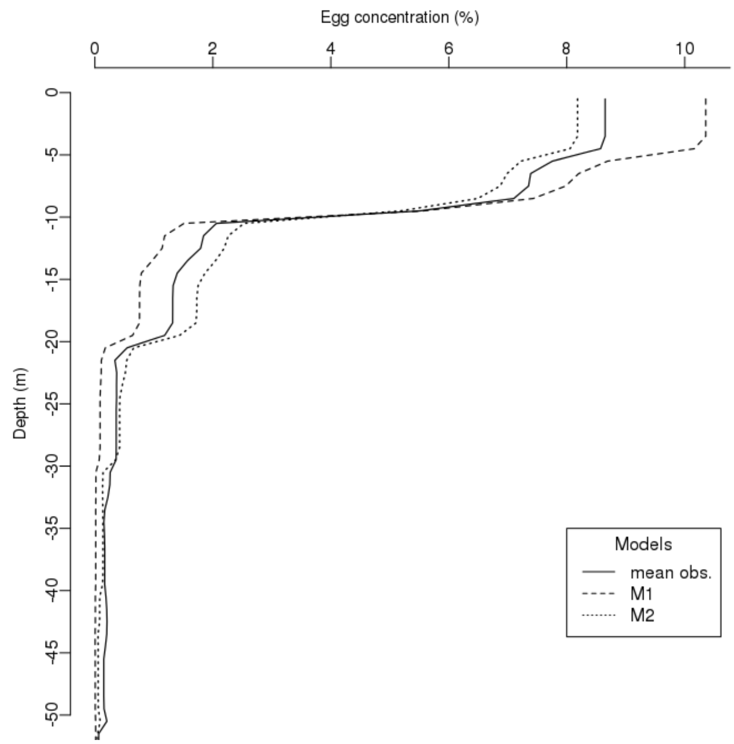


Fig. 15. Mean anchovy egg vertical distribution from observations (Multinet, 45 stations in different hydrology conditions), 1 dimension vertical (1DV) model estimation (M1). M2 is model results with density of eggs adjusted for best fit to data considering measurement errors (M2).

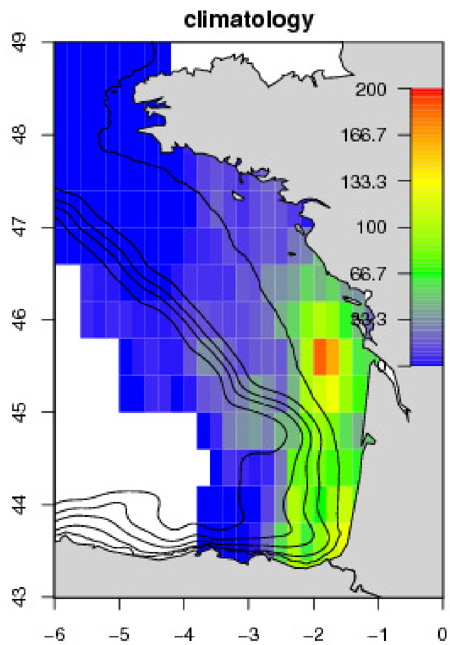
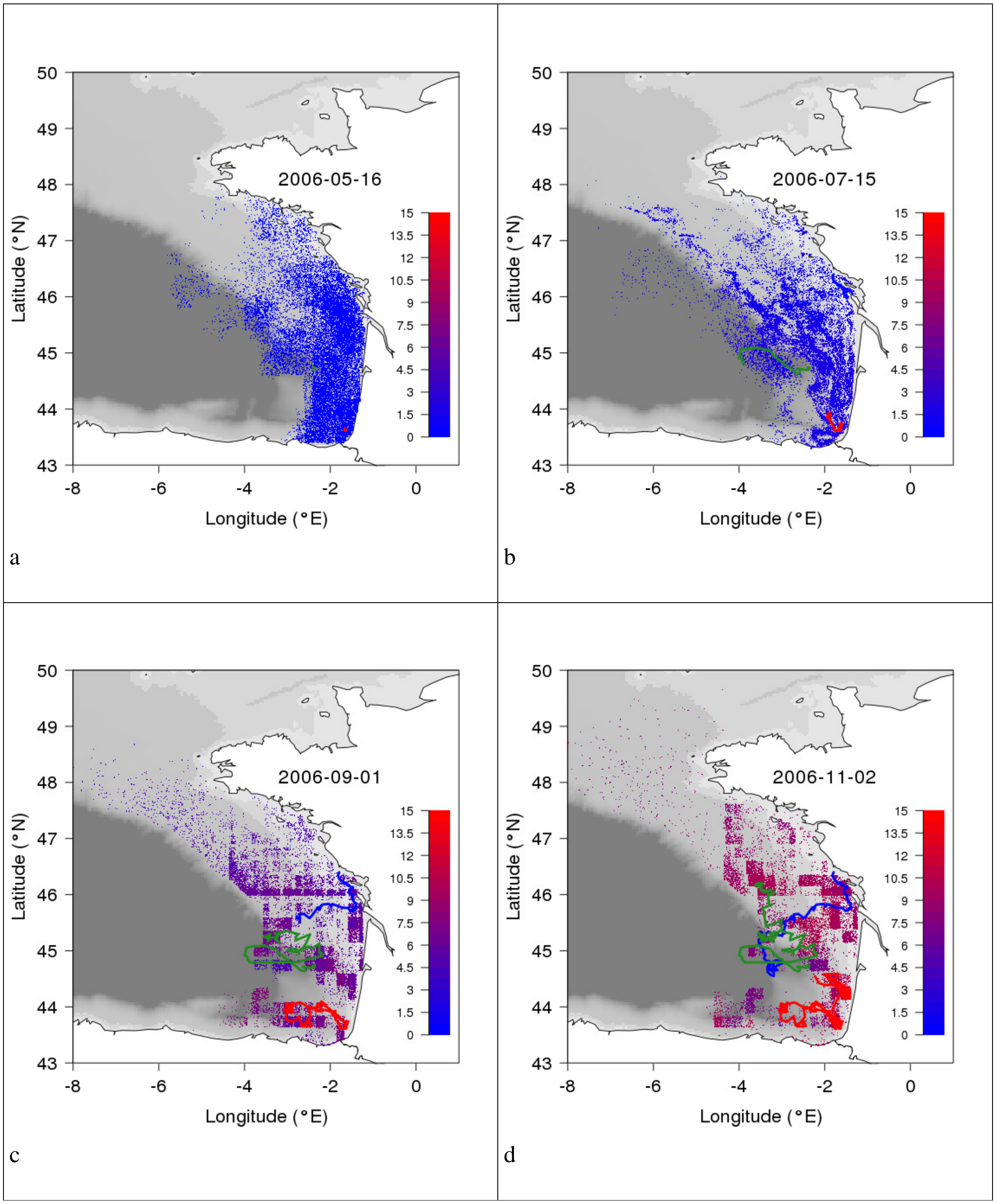


Figure 16. Distribution of anchovy spawning during Pelgas survey in Spring as a climatology over 2000-2012 (x10 eggs/m3).


2006-05-16
2006-07-15
2006-09-01
2006-11-02
Latitude (°N)
Longitude (°E)
50
49
48
47
46
45
44
43
-8
-6
-4
-2
0
15
13.5
12
10.5
9
7.5
6
4.5
3
1.5
0
a
b
c
d

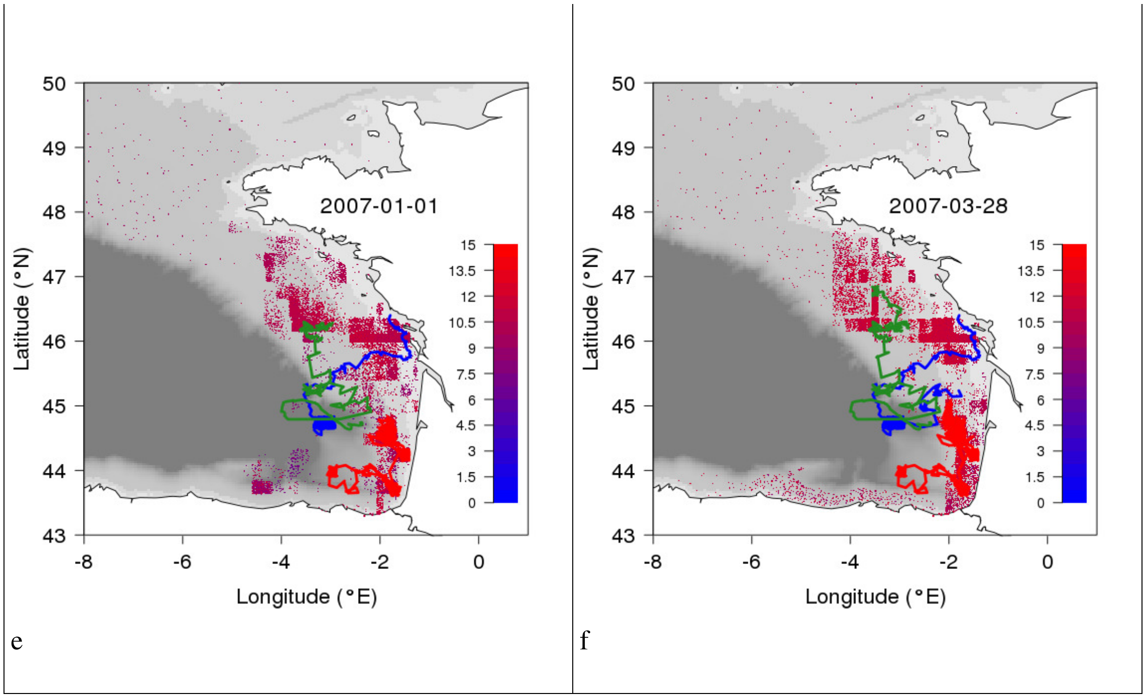


Fig.17. Distribution of the population based on IBM over one year (6 snapshots are presented) from spawning in mid-May 2006. Three trajectories from different spawning locations are also presented (blue, green and red colour trajectories) to illustrate individual trajectories. All points are individuals with color scale corresponding to fish size (SL, cm).

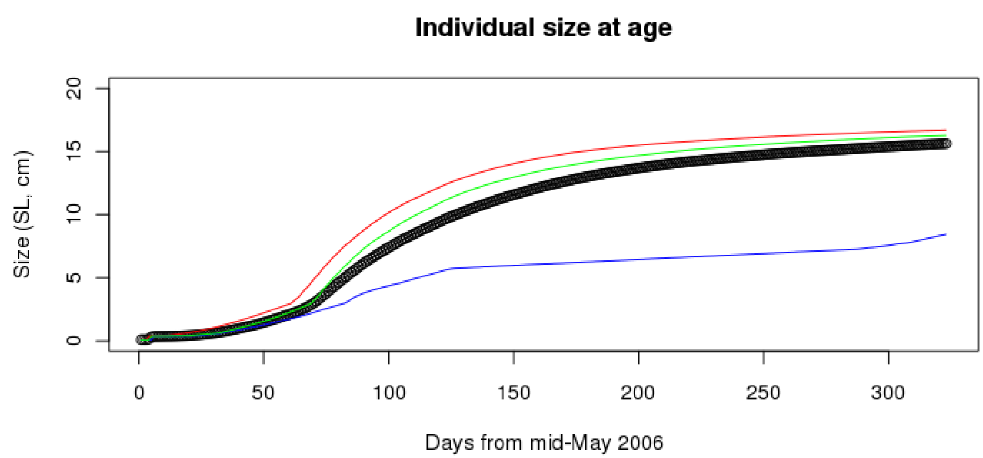


Fig.18. Individual growth aver a year from base-case simulation in 2006. Colours match with individual trajectories of fig.17, with blue and red the lowest and fastest growing trajectories, and black the mean population growth.

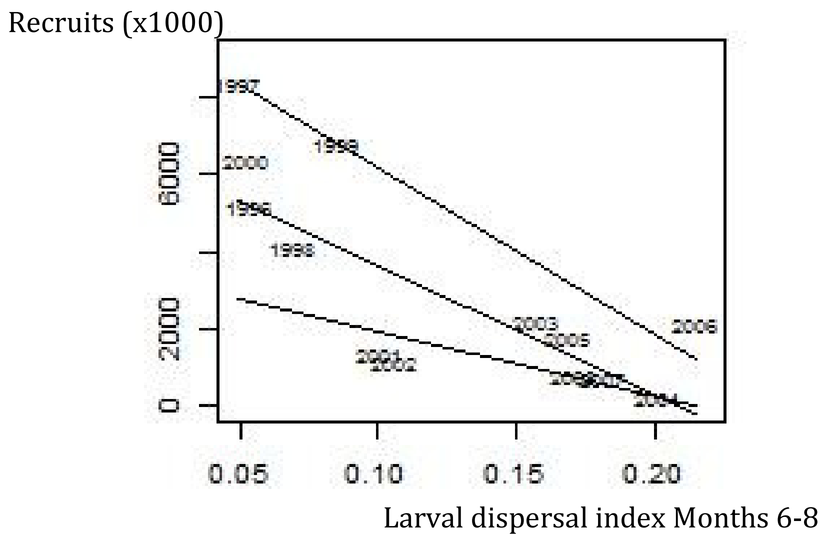


Fig.19. Relationship between Recruits as estimated by ICES and the larval dispersal index, 1996-2009. Lines are quantile regressions for different percentiles (0.9, 08, 0.7).

Atlanto Iberian Sardine case study

For the case study of Atlanto Iberian sardine, a coupled hydrodynamic – Lower Trophic Level (LTL) – fish Early Life Stages (ELS) model was implemented (Figure 20). The fish model includes passive vertical migration and hydrodynamic induced dispersion. Validation of the LTL model was done based on survey data, and the ELS model was used to test dispersion patters in relation to hydrodynamic conditions. A generic sardine/anchovy bioenergetics model with dynamic reproduction was also developed, as well as a probabilistic model for small pelagic fish, although both models were not coupled with the Hydrodynamics - LTL – ELS model.

Model configuration

Spawning of the Iberian sardine occurs in two main areas: the Cantabrian Sea and the western Portuguese shelf between Nazaré canyon and the Minho river. The spawning season is wide and shifts between areas depending on the moment when the suitable conditions, defined mostly in terms of temperature, are attained. In the western Iberian coast the spawning season spans between September and May, with a single peak in winter (November to January), whereas in the Cantabrian sea the spawning peak takes place in spring (April).

Especial attention has been given to the Early Life Stages (ELS), which are assumed to be largely responsible to determine the strength of sardine year class. Three stages have been distinguished: eggs, yolk-sac larvae (<4.5mm) and feeding larvae (> 4.5mm). Eggs and yolk-sac larvae are mostly considered to be passive particles, this is, they do not actively swim and their movement just depends on the transport by the currents. However, eggs were not strictly treated as passive in our models, since they are assigned variable buoyancy along development, meaning that they would change their position in the vertical along time. Self-feeding larvae obtain their food mainly from zooplankton, and they are characterized by a vertical displacement that varies with size. Although the literature is consistent with respect to sardine larvae diet (they mainly feed on calanoid stages), no agreement is observed with respect to the vertical migration patterns. Therefore, we have relied on the French Pelgas spring surveys, from where we adopted the following vertical behaviour:

- For larvae between 4.5mm and 6mm, the preferable depth at night is 12m and 13.5m during the day.
- For bigger larvae (> 6mm) they would be at 8m depths both at day and night.

When larvae reach a size of more than 120mm, they are considered to be juveniles. Juveniles are already able to swim, so they can move to find an environment that is more suitable for their survival.

The environmental conditions for sardine: a coupled hydrodynamic-LTL model.

As mentioned in the previous section, sardine ELS transport, spawning behaviour, egg and larvae development, mortality, etc. depends on the environmental conditions. Therefore, reproducing these conditions in a reliable manner constituted one of the main objectives of this project and the basis to go further in the development of a full life cycle model.

The physical/hydrodynamic configuration of the ROMS model for the area of West and North Iberia has been improved during Reproduce. Validations at different temporal and spatial scales have been done against observations of different nature (hourly data of currents from current buoys, snapshots of temperature and salinity profiles from the spring pelagic cruises that the IEO carries out each year, monthly data of temperature and salinity form the Spanish standard sections, daily/weekly averaged data of AVHRR SST, etc). The results confirmed that the hydrodynamic model presented good skills in reproducing the dynamics in the area (Figure 21)

Additionally, a LTL model has been coupled to the hydrodynamic model in order to simulate food fields for fish and larvae. The nitrogen based biogeochemical model of Fennel et al., 2006 has been selected. It comprises seven state variables: one group of phytoplankton, one group of zooplankton, two nutrients (nitrate and ammonium), two groups of detritus (small detritus and large detritus), and phytoplankton chlorophyll. We have decided to use parameters that are characteristic of plankton at the spring bloom. In particular, the parameters of *Chaetocerossocialis* have been considered for the unique phytoplankton class of the model for being the most abundant diatom at the beginning of the spring bloom in the area (Figure 22).

Comparison of the model results with daily maps of chlorophyll-a from the MODIS sensor processed with the OC3 algorithm lead to a reasonable agreement (results not shown). Monthly profiles of chlorophyll-a from the Spanish standard sections for years 2006 and 2007, as well as snapshots of chlorophyll-a and dry weight of zooplankton integrated in the first 100m of the water column measured during the IEO spring pelagic cruises Pelacus have also been used to validate the results of the LTL model, leading to satisfactory conclusions.

An Individual Based Model for sardine

The Lagrangian model Ichthyop(http://www.brest.ird.fr/ressources/ichthyop/index.php) has been used to simulate dispersion of sardines ELS. The hydrodynamic configuration of the ROMS model in the area provides the currents, mixing coefficients, temperature and salinity fields that drive the Lagrangian model.

Each particle of the IBM is considered to be a super-individual, representing a certain number of individuals whose average behaviour is the same. Horizontal and vertical advection and horizontal and vertical dispersion determine particle transport. All the biological processes in the IBM (egg development stage, egg mortality, larvae growth, etc) are functions of the temperature.

Although a LTL has been developed in parallel, it was not fully coupled to the IBM to simulate larvae growth. However, the concentration of chlorophyll-a along the trajectories of the Lagrangian particles has been analysed in order to estimate food availability for larvae and, hence survival for 2007 year class.

Figure 23 shows the modelled concentration of chlorophyll-a along the centre of gravity of the particles released at the Western Iberia spawning ground. It can be seen that if sardine larvae remain at the inner part of the shelf during the autumn-winter spawning peak, they are subjected to higher concentrations of chlorophyll-a, implying higher possibilities of survival. If eggs are released in spring, the concentration of chlorophyll is still high, even if they are transported offshore.

A bioenergetic model for sardine

The next steps to the development of a full life cycle require the coupling of the larvae growth function to the fields of zooplankton calculated in the LTL model in the IBM.

This has already been done in the case of adult growth modelling. In fact, a Wisconsin-type bio-energetic model applied to small pelagic fish (sardine and anchovy) has been under development during REPROdUCE at the IEO, giving special emphasis to the representation of the reproductive dynamics of these fish species as well as capturing their observed variability in reproductive potential. In this model, fish increases or decreases its weight depending on the energy gains or losses. Energy is gained by feeding, being this process previously modelled as temperature dependent, but already transformed into food dependent (phytoplankton and zooplankton fields obtained from a LTL model), whereas energy is lost during reproduction. Although this model has not been applied to our study area, it has been tested in the California Current System with promising results.

Recruitment indicators

The effect of hydrodynamics on ELS dispersion was tested as a potential indicator of recruitment strength. However, only two years (2006 and 2007) were analysed during REPROdUCE, therefore the results are only considered preliminary. ELS dispersion was found to be very different between periods, with a variable percentage of particles being retained in the shelf (Figures 24 and 26). Also, retention was very different in the Cantabric Sea and in the Portuguese coast, with a larger retention in the Northern Portuguese coast than in the rest of the model domain area. Results also indicate different level of Chlorophyll concentration for the areas were particles are found at hatching (Figures 25 and 27), which will have an impact on the survival probability for those larvae.

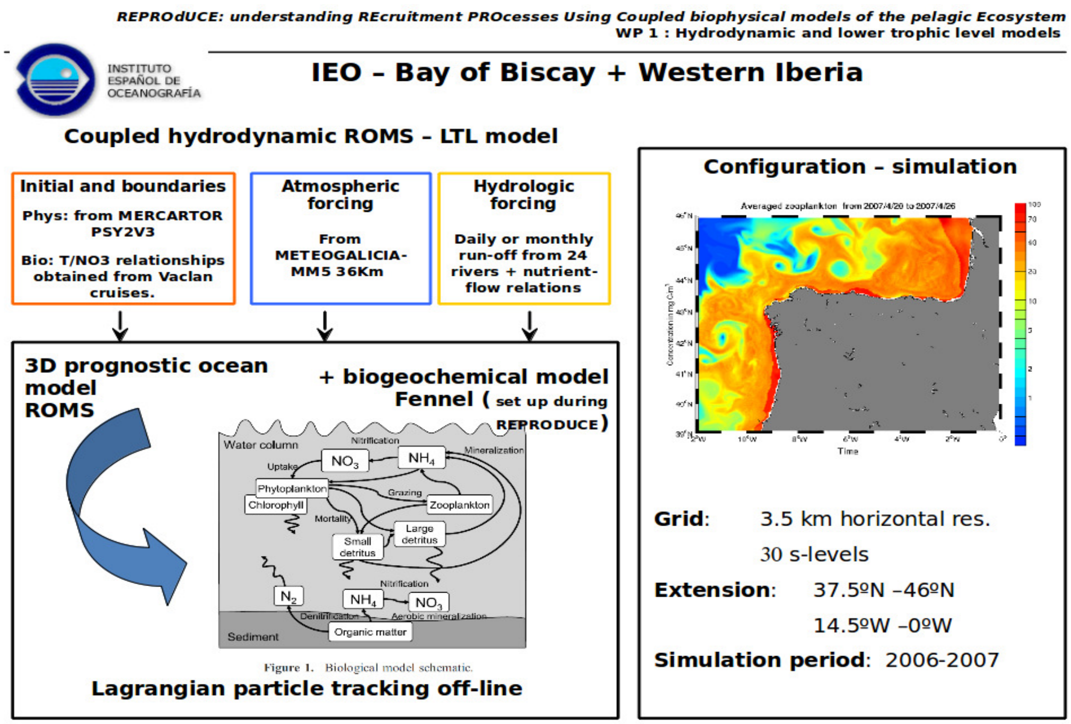


Figure 20, Atlanto-Iberian sardine case study: Model conceptual approach.

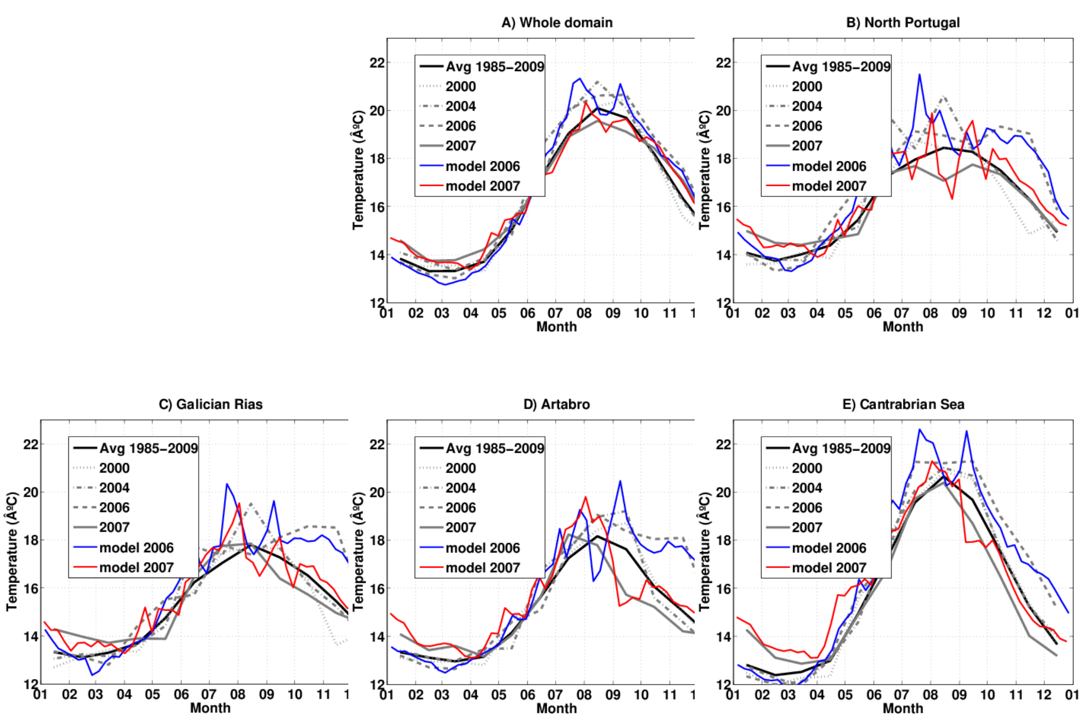


Figure 21, Atlanto-Iberian sardine case study: Monthly averages of AVHRR SST and weekly averages of modeled SST for 2006 and 2007 in different areas of the model domain.

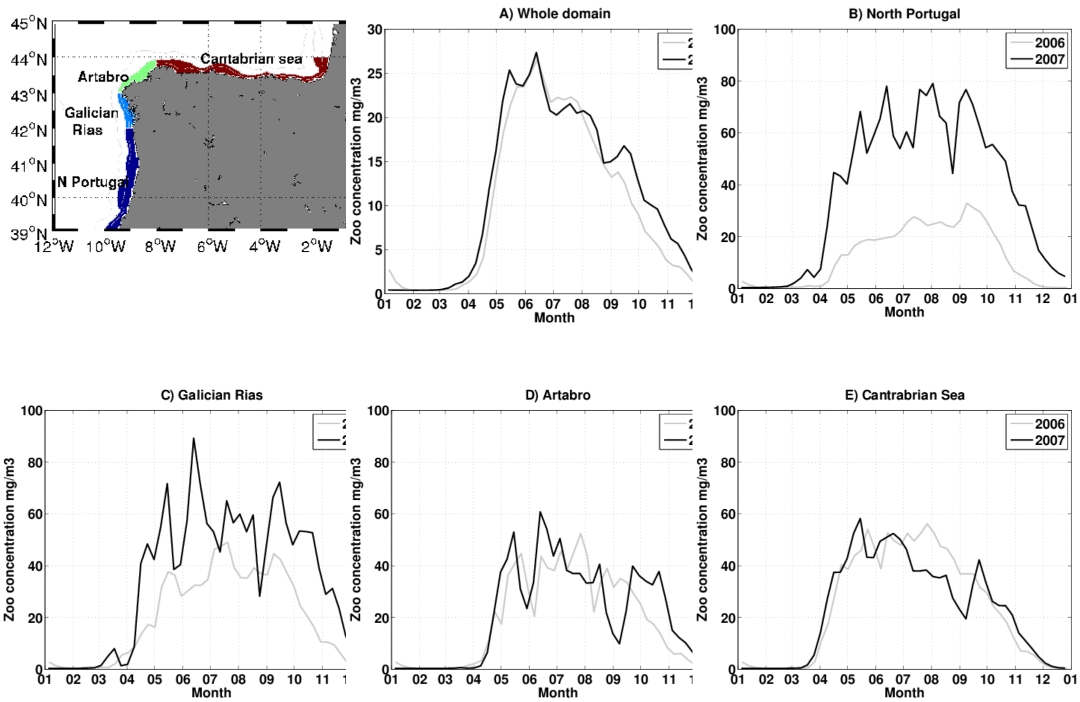


Figure 22, Atlanto-Iberian sardine case study: Weekly averages zooplankton concentration per area during 2006 and 2007.

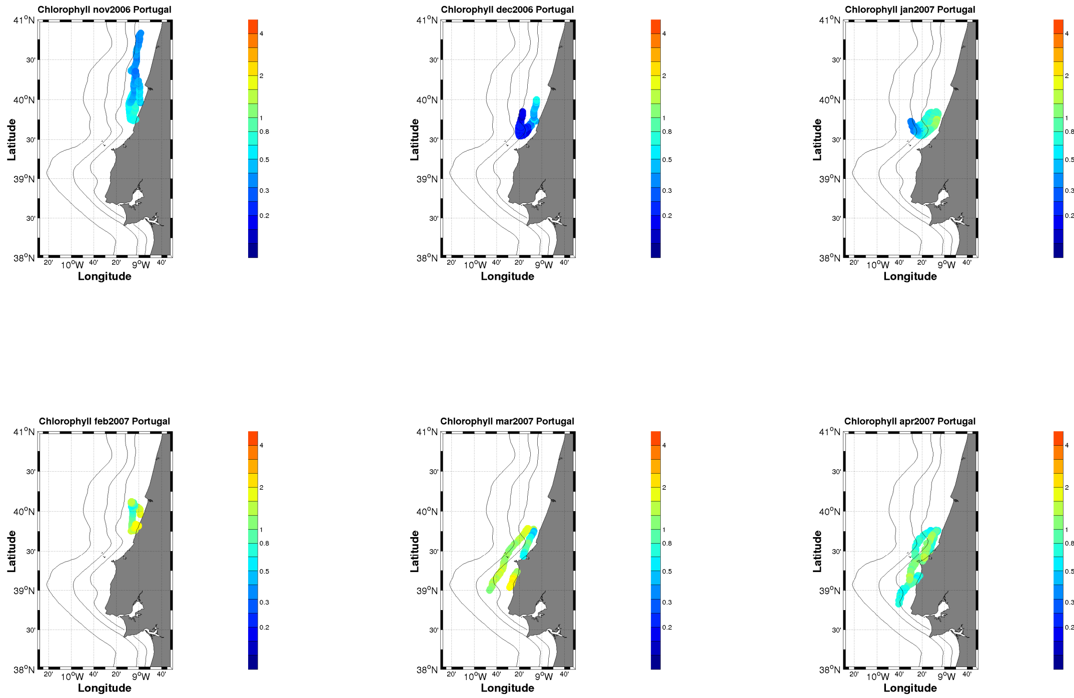


Figure 23, Atlanto-Iberian sardine case study: Concentration of chlorophyll-a along the center of mass of the particle trajectories released at the Western Iberia spawning grounds.

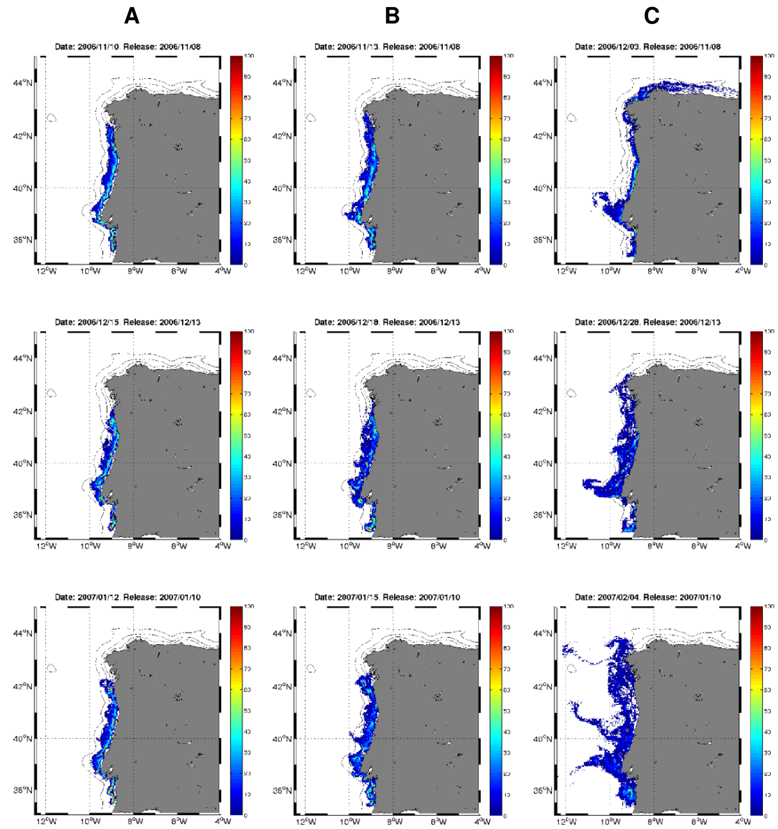


Figure 24, Atlanto-Iberian sardine case study: Maps showing snapshots of the density distribution of particles released at the Portuguese coast at the dates indicated in each figure. Column A shows the distribution after 2 days of spawning (egg stage), column B the distribution after 5 days of spawning (early larvae) and column C focuses on the late larvae.

A **B** **C**

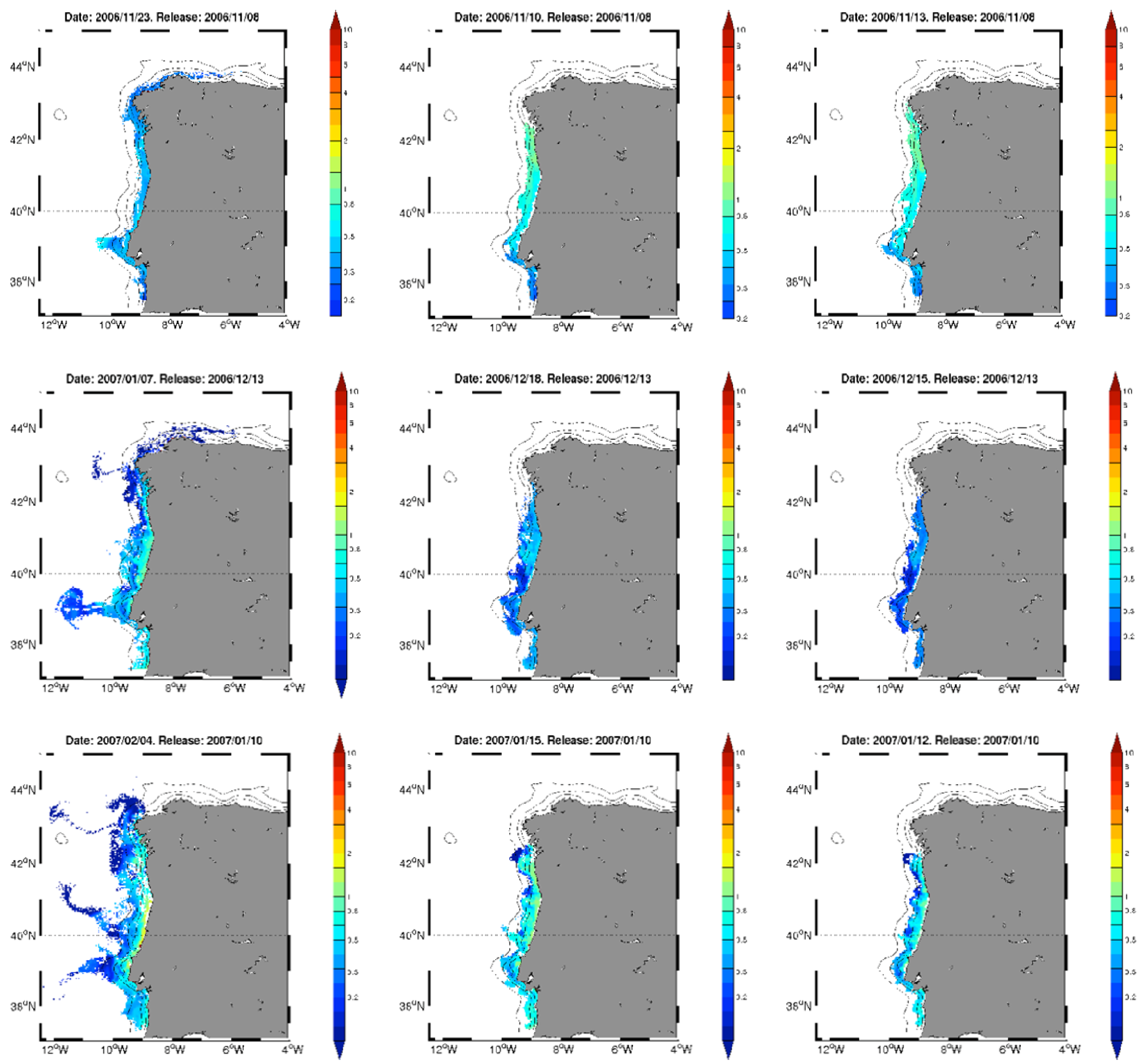


Figure 25, Atlanto-Iberian sardine case study: Maps showing snapshots of the chlorophyll distribution at the particle positions that are obtained after being released at the Portuguese coast at the dates indicated in each figure. Column A shows the distribution after 2 days of spawning (egg stage), column B the distribution after 5 days of spawning (early larvae) and column C focuses on the late larvae.

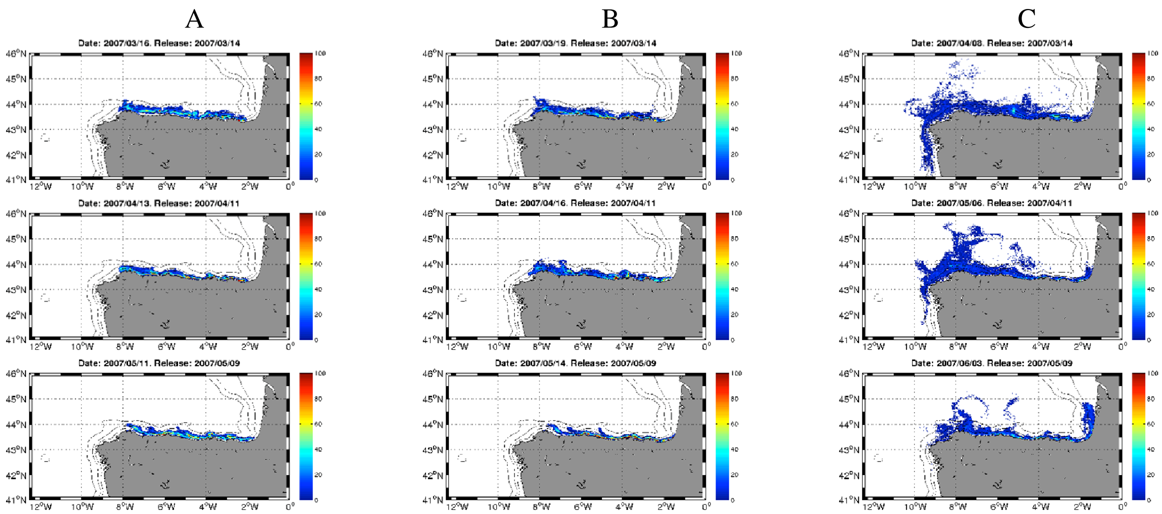


Figure 26, Atlanto-Iberian sardine case study: Maps showing snapshots of the density distribution of particles released at the Cantabrian coast at the dates indicated in each figure. Column A shows the distribution after 2 days of spawning (egg stage), column B the distribution after 5 days of spawning (early larvae) and column C focuses on the late larvae.

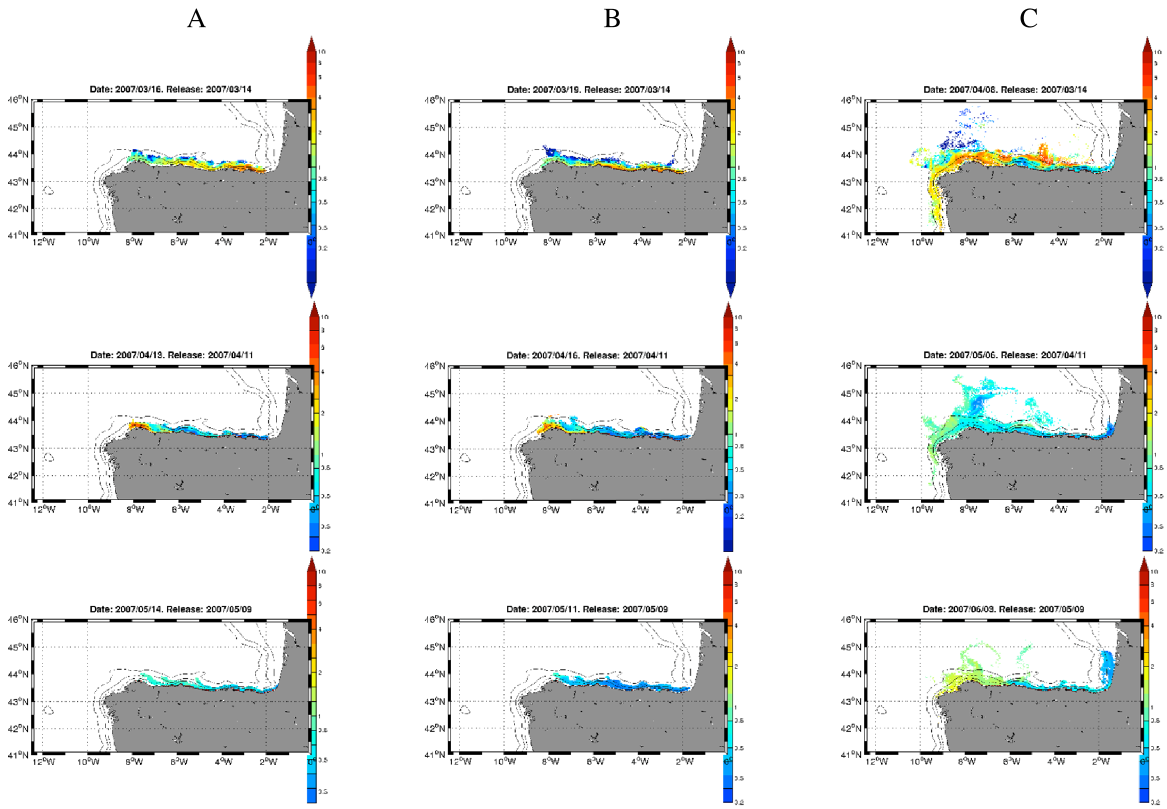


Figure 27, Atlanto-Iberian sardine case study: Maps showing snapshots of the chlorophyll distribution at the particle positions that are obtained after being released at the Cantabrian coast at the dates indicated in each figure. Column A shows the distribution after 2 days of spawning (egg stage), column B the distribution after 5 days of spawning (early larvae) and column C focuses on the late larvae.

An alternative approach: Bay of Biscay anchovy and sardine studies using an end-to-end model

Model Configuration

In the Bay of Biscay, an end-to-end model has been developed (Fig.28), using the LTL model ROMS-$N_2P_2Z_2D_2$ coupled to the HTL model OSMOSE.

Lower trophic level model ROMS-$N_2P_2Z_2D_2$
The high resolution 3D prognostic ocean model ROMS (Regional Ocean Model System,http://www.myroms.org/), forced by detailed atmospheric, hydrologic and oceanic forcing, has been used. The model domain covers the entire Bay of Biscay, extending from the French and Spanish coasts (40.5 ^{o}N) to the South of United Kingdom (52.5^{o}N) and to 13^{o}W (Fig. 1). In the present configuration for the Bay of Biscay, an extension of a configuration is limited to the South Bay of Biscay. The bathymetry has been obtained by interpolation of the ETOPO2 (2 minute digital Elevation TOPOgraphic model), GEBCO (General Bathymetric Chart of the Oceans), and IBCM (International Bathymetric Chart of the Mediterranean) data sets. ROMS for Bay of Biscay computes the primitive equations on a 6.6-km grid in the horizontal and 32 no-equally distributed σ-levels grid in the vertical.

The rivers runoff data are prescribed as boundary conditions on momentum, salinity, temperature and nitrate. Daily flow data are used from observations in the 20 most important rivers on the French and Spanish coasts. The temperature and nitrate concentrations of these rivers are prescribed from observations when available and using monthly means.

ROMS is coupled to a $N_2P_2Z_2D_2$ biogeochemical model, taking into account ammonium, nitrate, 2 classes of phytoplankton, 2 classes of zooplankton and 2 classes of detritus.

Higher trophic level OSMOSE

The higher trophic level model applied to the Bay of Biscay is the OSMOSE (Object-oriented Simulator of Marine ecOSystems Exploitation) model. Details of the system were provided in the EU project MEECE deliverable D2.3 (*"Sub-model OSMOSE, Functional coupling with plankton models"*) (http://www.meece.eu/). OSMOSE is a 2D, multispecies and Individual-Based Model (IBM) which focuses on fish species. It models processes of growth, predation, reproduction, natural and starvation mortalities, and uses the ouputs of the LTL model ROMS-$N_2P_2Z_2D_2$ as prey fields (Fig. 28). A total of 8 fish species are included, from small pelagic to top predators: *Engraulisencrasicolus, Sardinapilchardus, Trachurustrachurus, Scomberscomber, Merlucciusmerluccius, Micromesistiuspoutassou, Thunnusthynnus*, and *Thunnusalalunga*(Fig. 28). OSMOSE has been implemented in the Bay of Biscay, between 43-48^{o} N and 1-9^{o} W, with a spatial resolution of 0.15^{o} x 0.15^{o}. Temporal resolution is of 15 days. Detailed information of species distribution in terms of presence/absence data by age and time step has been extracted from literature. The implementation and calibration of the OSMOSE model in the Bay of Biscay have been undertaken by AZTI with the collaboration of Yunne Shin and Philippe Verley (IRD, France). A genetic algorithm has been used to calibrate OSMOSE model (collaboration with Philippe Verley, IRD, France) allowing to calculate larval additional mortalities and plankton accessibilities.

Reference Hindcast simulation
A 13-year simulation has been performed using ROMS-$N_2P_2Z_2D_2$, from 1997 to 2009, using the 6-hours NCEP re-analysis as atmospheric forcing: air temperature, winds, pressure and humidity and short-wave radiation. The initial and boundaries conditions for currents, temperature and salinity are interpolated on the grid from the World Ocean Atlas 2005 (WOA05) developed by the National Oceanographic Data Center (NODC) of the NOAA. The water level is specified for initial condition and also at each time step along the open boundaries, using the OSU TOPEX/Poseidon Global Inverse Solution version 5.0 (TPXO.5, global model of ocean tides). After a 1-year spin-up (year 1997) to reach equilibrium, the simulation covers the period 1998-2009, with 1 year of spin-up and a time step of 15 min.

The runoff data of the 20 most important rivers in the Bay of Biscay are prescribed as boundary conditions on momentum, salinity, temperature and nitrate. The daily flow observations have been extracted from databases: HYDRO II (France), and databases of "DiputaciónForal de Gipuzkoa" and "DiputaciónForal de Vizcaya" (Spain). Moreover, monthly climatologies of temperature and nitrate have been calculated using the *in situ* observations from the same databases, and prescribed in the simulation as boundary conditions at river points.

The hindcast reference simulation for the HTL model has been undertaken using the prey fields from the 1998-2009 hindcast ROMS-$N_2P_2Z_2D_2$ simulation: small and large phytoplankton and zooplankton. A climatologic year has been repeated during 50 years to reach equilibrium (Fig. 29). Since the OSMOSE model presents stochastic parameterization, 10 replicates of the 50 years reference simulation are computed at the same time. Thus, each resulted variable (e.g. fish biomass and abundance, and fish diet) is the mean of the 10 replicates. The equilibrium is reached after 25 years of spin-up (Fig. 29). That is to say that after 25 years of spin-up, the time evolution for each species is stable and only present the seasonal cycle. Since the 50 years simulation with OSMOSE does not represent a time evolution but the repetition of the same climatologic year (50 times), this climatologic year is calculated using the last 25 years of the simulation (from 26th to 50th years).

Results

Environmental conditions
In terms of hydrology, the 12-years monthly mean simulated SST has been compared to monthly climatology from AVHRR, using Taylor diagram and P*bias* (Fig. 30). The Taylor diagram between simulated monthly mean SST and AVHRR monthly climatology shows a correlation between 0.8 (July-August) and 0.9, and a normalized standard deviation between 0.75 and 1.25. Therefore, the model reproduces the overall seasonal cycle of SST in the Bay of Biscay. At spatial basis, the model fits also well the local processes: cold band water along the Atlantic French coast in winter, warming and north-south gradient in spring, Galician upwelling, Ouessant front and cold slope band in summer, and rivers plumes.

The model reproduces the main circulation patterns in the Bay of Biscay, and meso-scale processes (Fig. 31): a strong poleward slope current in autumn-winter, a slow circulation over the shelf, eddies formation from the slope towards the plain, the Galician upwelling west of Spanish coast in summer, and a strong jet coastal current along the coast in autumn (September to October) observed by Lazure et al. (2008). Moreover, the comparison of simulated surface circulation to RADAR observations during spring 2008 and 2009 shows a strong interannual variability of the slope current. The model reproduces the main shift in the circulation.

Lower Trophic Level

The hindcast validation of the lower trophic level (LTL) encompasses times series of nutrients, phyto- and zooplankton concentrations. The domain-averaged time series of integrated nitrate concentration, primary production, phytoplankton and zooplankton biomass present an important interannual variability (Fig. 32a,b,c). The model produces a mean seasonal cycle of phytoplankton biomass and nitrate concentration coherent with the observations in the region. A strong interannual variability in the timing and the duration of the bloom, and especially in the maximum value of chl*a* biomass (*e.g.* phytoplankton biomass) is simulated: strong and early bloom in 1998, 2005, 2006 and 2009, associated to high values of integrated nitrate concentrations; some years as 2000 and 2008 present two peaks of chl*a*. The comparison of the simulated surface chl*a* to SeaWiFS and MODIS observations, from 2001 to 2009, indicates a well captured interannual variability by the model, although a too early (about 1 month) simulated spring bloom (Fig. 32d). As an example, the strong spring blooms in 2005 and 2009 were reproduced by the model and also the earlier onset in 2005. Moreover, no validation has been undertaken for the nitrate concentration because of lack of available data in the region.

Higher Trophic Level

Time evolution

The seasonal evolution of the biomass shows higher values in spring-summer than in winter (Fig. 33). Simulated sardine and Atlantic mackerel represent the higher stocks in the Bay of Biscay. The mean anchovy biomass varies between 70000-8000 in autumn-winter and 140000-150000 tons at its maximum in May-June. Thus, the seasonal oscillation of anchovy biomass is *ca*. 70000 tons (50%). The mean sardine biomass varies between 300000-350000 in January-February and 500000-520000 tons at its maximum in June-July. The seasonal oscillation of sardine biomass represents about 40% (200000 tons) of its total biomass.

Seasonal distribution

The mean seasonal distributions of biomass for anchovy and sardine are shown on Figures 34 and 35. Simulated anchovy and sardine stock are present on the shelf, what is usually observed in the Bay of Biscay.

In winter, the anchovy stock is present everywhere on the shelf. In spring, the anchovy biomass increases with local maximums of 800-1000 tons, and is more extended to the shelf and the shelf break and southern in the Bay. This distribution corresponds to the spawning one. In summer, the anchovy biomass is northern along the French coast, and presents local patterns along the Spanish coast. In autumn, the biomass is low, with local maximums of about 500 tons.

The sardine stock is present on the shelf, and the values of biomass are higher than which of anchovy. In spring, the sardine stock is developed on the shelf break. In summer, the biomass increases with maximums of about 1800 tons.

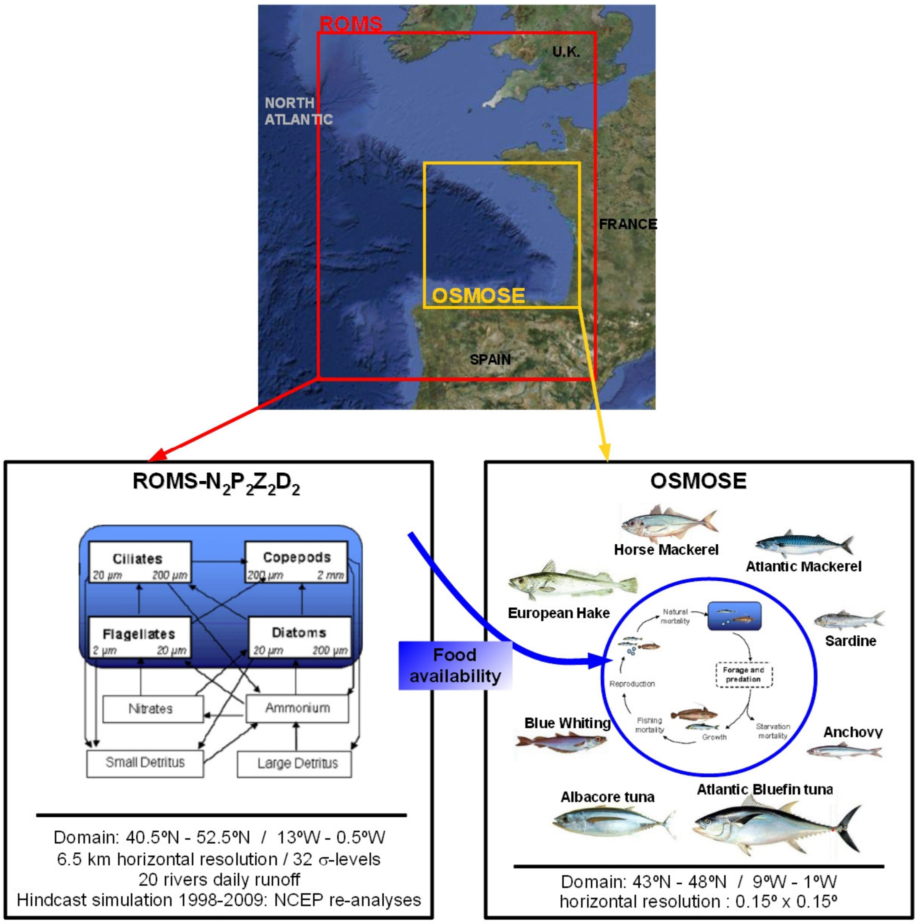


Figure 28: Synthesis scheme of the end-to-end model implemented in the Bay of Biscay: ROMS-$N_2P_2Z_2D_2$ and OSMOSE domains and specificities. 6 biogeochemical variables are included in the NPZD model, and 8 species in the OSMOSE model. The ROMS-$N_2P_2Z_2D_2$ provide the prey fields to the OSMOSE model.

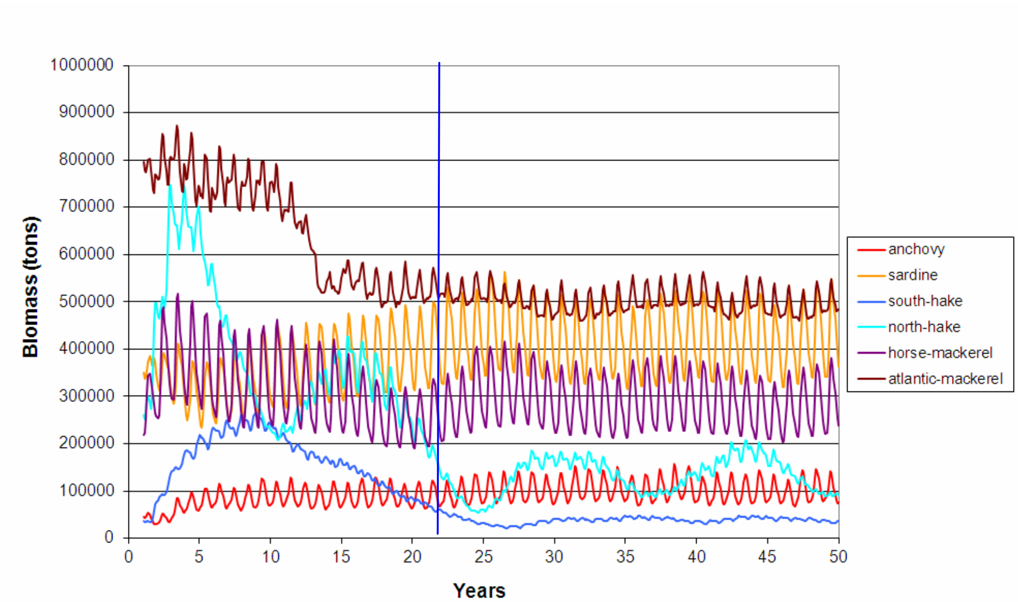


Figure 29: Evolution of fish biomasses over 50 years simulation – spin-up of 25 years.

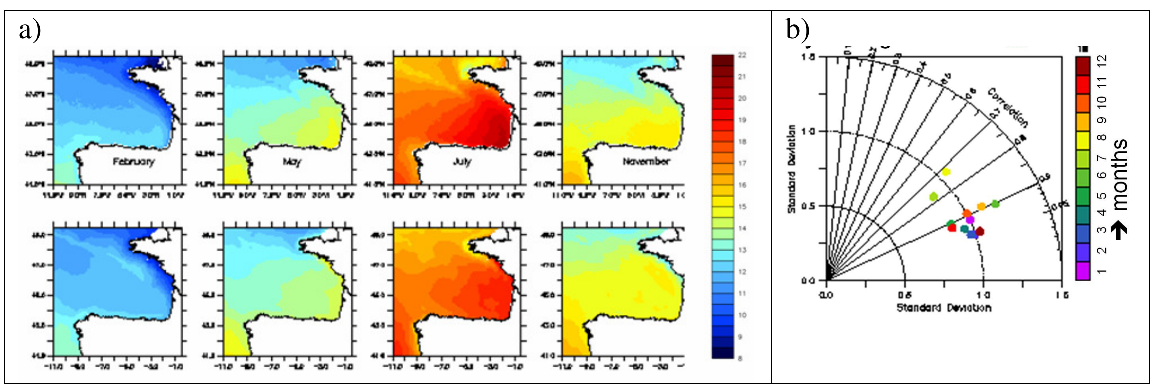


Figure 30: Sea Surface temperature: assessment of the model simulation quality against the 1998-2008 AVHRR observations: a) maps of SST from AVHRR (upper panels) and ROMS (lower panels) for February, May, July and November; b) Taylor diagram per month.

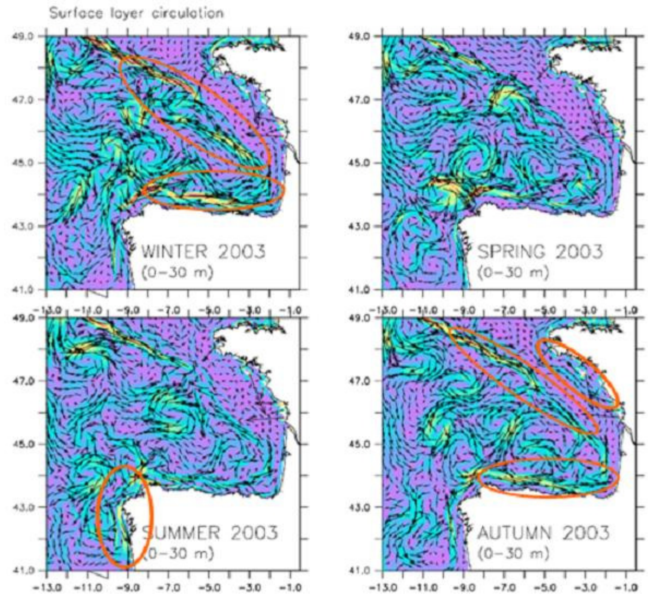
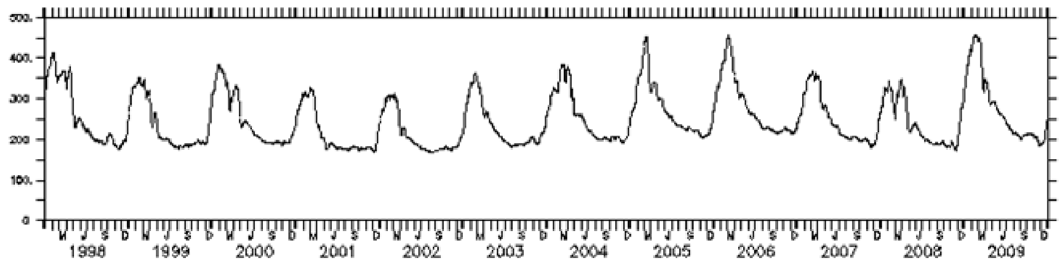
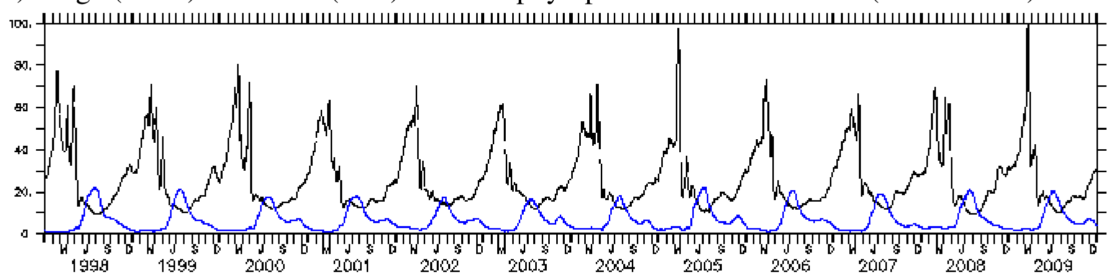


Figure 31: Simulated surface global circulation in the Bay of Biscay for the four seasons. The main circulation patterns are enclosed in red lines.

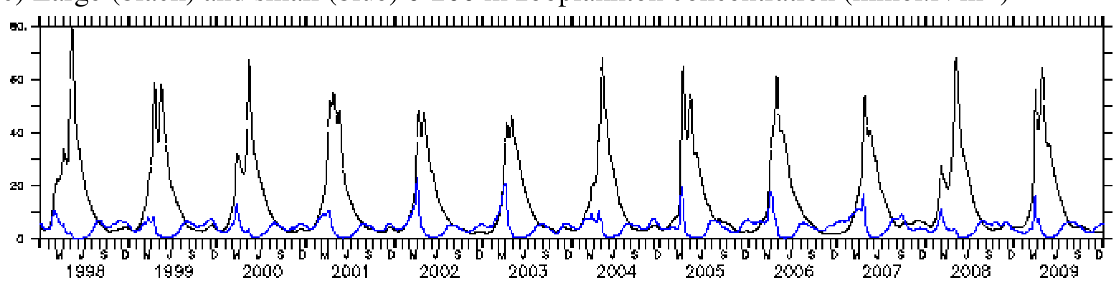
a) Nitrate 0-200 m concentration (mmol.N m^{-2})



b) Large (black) and small (blue) 0-200 m phytoplankton concentration (mmol.N m^{-2})



c) Large (black) and small (blue) 0-200 m zooplankton concentration (mmol.N m^{-2})



d) Comparison of monthly mean surface chlorophyll-*a*, horizontally domain-averaged: simulated by ROMS (black line), and observed with SeaWiFS (blue line) and MODIS (red line) sensors.

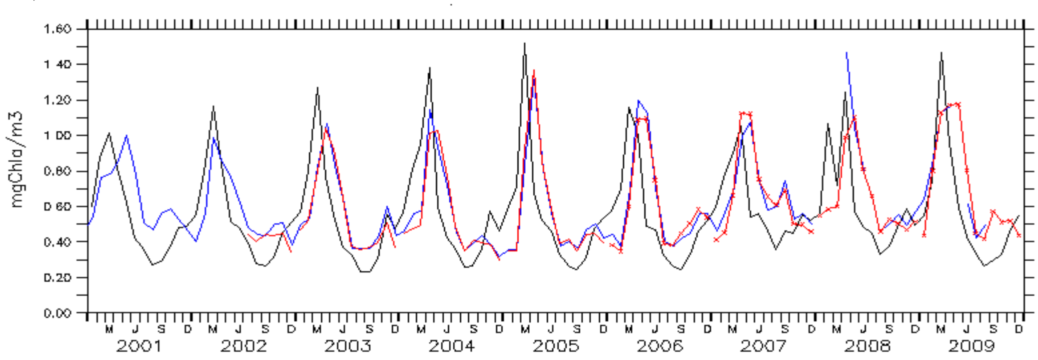


Figure 32: Times-series and horizontally domain-averaged (0.5-10.5 ^{0}W / 42-49 ^{0}N) of: a) simulated integrated nitrate concentration; b) simulated integrated phytoplankton concentration; c) simulated integrated zooplankton concentration; d) Comparison of monthly mean surface chlorophyll-a, horizontally domain-averaged: simulated by ROMS (black line), and observed with SeaWiFS (blue line) and MODIS (red line) sensors.

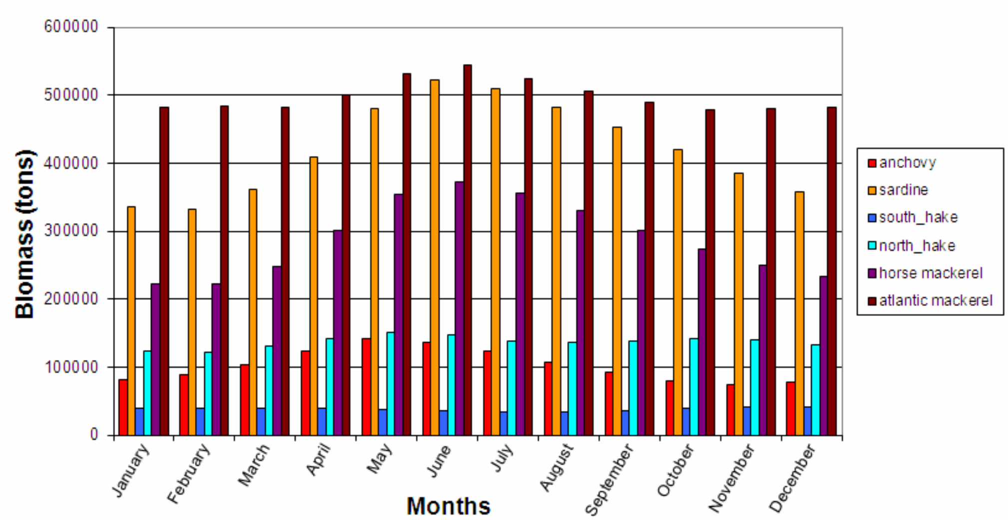


Figure 33: Seasonal evolution of fish biomass simulated by OSMOSE. Results are shown for the climatologic year corresponding to the hindcast 1998-2009.

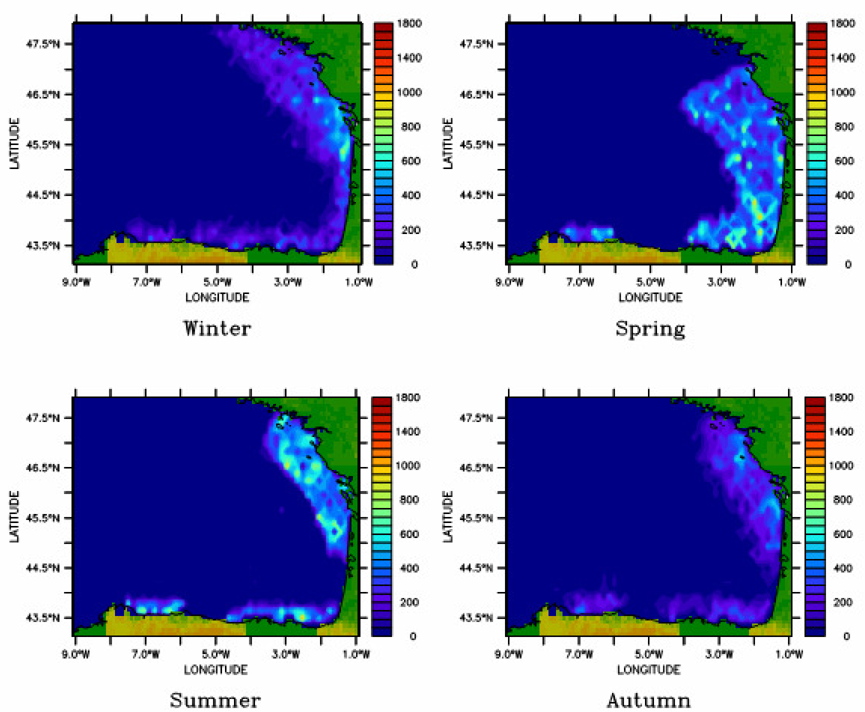


Figure 34: Mean seasonal distribution of anchovy biomass. Values are in tons.

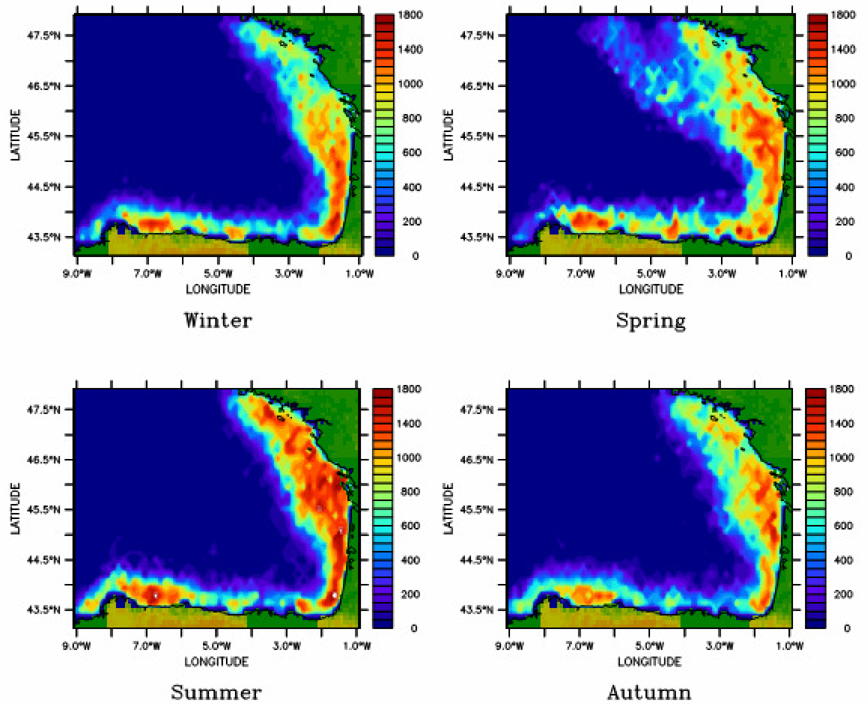


Figure 35: Mean seasonal distribution of sardine biomass. Values are in tons.

Main conclusions

REPROdUCE has allowed setting a number of ecosystem models for small pelagics in two different areas, the Bay of Biscay and the Aegean Sea. These models range in their degree of completeness in relation to the original plan of achieving self-regenerating full life cycle models of the target species.

For the Aegean Sea case study, the final model provides a full self-regenerating life cycle representation of anchovy in the area, with dynamic reproduction and movement included. The model therefore achieves the original model plan. Within the duration of REPROdUCE, first simulations were also done on a subset of environmental and fishing scenarios over short time periods. Further simulations and some improvements on some of the modules are foreseen to be undertaken after REPROdUCE. The N. Aegean anchovy model provides a good representation of anchovy growth, distribution and dynamics in the area, and allows investigating factors affecting recruitment strength in a holistic way. This was the first time that synergetic complex effects on reproduction dynamics could be investigated through a simulation model. Results indicate that different sources of nutrient enrichment have different effects on anchovy dynamics and recruitment strength. Although both river inflow and inflow of water from the Black Sea have an important effect in the ecosystem productivity, the positive effect of the former is larger for the anchovy population. The increased inflow of Black Sea water into the Aegean Sea increases anchovy eggs and larvae transport to offshore unsuitable waters. These results improved understanding of anchovy population variability in the Aegean Sea and could only be obtained with a dynamic ecosystem model such as the one developed through this project. In addition to this, the potential of the developed model for assisting into management decisions was tested, comparing the effect of two different management measures: changes in the fishery closed season and overall reduction of fishing effort. A change in the 3-months closed season from winter to autumn results in a reduced recruitment strength with time, while a large reduction of fishing mortality did not yield an increase in population as large as would be expected. Again these results benefited from the integrative, holistic view provided by the full life cycle model developed within REPROdUCE.

For Bay of Biscay and Atlanto-Iberian anchovy and sardine the modelling of a full life cycle was achieved either by a sequence of separate submodels corresponding to different life stages or an integrated model but over one year only, from egg to spawning. For these case studies, no previous attempt of an integrated end-to-end model was available prior to REPROdUCE, and therefore a large effort on model development was required through the project, in particular on zooplankton compartment, active movement, bioenergetics and larval transport.Notwithstanding the lack of full life representations, the models developed allowed to test a series of hypothesis on recruitment strength, in this case focusing on the early life stages alone. Changes in transport/retention rates of early life stages, caused by changes in the hydrodynamics and dynamic changes in egg buoyancy and larval vertical behavior were alone able to recreate to some extent recruitment estimates available from the assessment of anchovy in the Bay of Biscay. This provides an environmental recruitment index alternative to some other environmental indices that have been proposed for this species in the past, with the potential to be improved and refined as the different life stages are joint together into a full life cycle for the species. In addition, the models derived have allowed exploring the potential environmental influence on the species in the area, using an innovative bioenergetics approach. For Atlanto-Iberian sardine, some results on transport/retention in relation to recruitment strength are also promising, although for this case study further tests should be carried out.

Developed models have also been tested against field observations, existing laboratory experiments and bibliographic data. Overall, validation of the different modules developed through the project has been satisfactory, with the models being able to reproduce the main characteristics of the different stages appropriately. Furthermore, the validation of the full life cycle model for the Aegean Sea, which includes validation of the interconnectivity of the different modules developed, has also been satisfactory.

In addition to the advances in understanding the population dynamics and recruitment strength of the target species, the models developed through REPROdUCE also allowed to have a better understanding of the dynamics of lower trophic levels, have provided improved habitat maps for the target species and allowed for an integrative description of the ecosystem of the Bay of Biscay, with the first application of the OSMOSE model in the area.

Further work will be however required to consolidate the hypotheses suggested within this project and to incorporate the models and project results into fisheries management advice. On one hand, completed models such as the Aegean Sea anchovy model should be run over a larger variety of scenarios and over larger time periods. Model refinements such as improvements of movement rules are anticipated, but overall model structure is not expected to be largely modified. On the other hand, the potential of those models that do not complete the full life cycle to understand population dynamics and recruitment strength is expected to improve once the life cycle of the target species is closed. Although this will require further scientific research and model development, the advances made within REPROdUCE are large and the complete full life cycle model for those case studies is now considered to be achievable in a short to medium term.

Appendix A: Project Outcomes

1. MSc and PhD thesis

- Patricio Smith. 2011. A Comparative Analysis of European Anchovy (Engraulis encrasicolus L.) Growth Across Stocks and Areas (MSc thesis directed by M. Bernal and I. Palomera)
- Tsoukali, S. (2011). Characterization of the spawning habitat of European anchovy (Engraulisencrasicolus) in the North Aegean Sea using statistical models. MSc thesis, University of Crete, Department of Biology.

2. Papers

- Huret M., Petitgas P., Struski C., Léger F., Sourisseau M., Struski C., Léger F., and Lazure P. 2010 A 37 years hindcast of a coupled physical-biogeochemical model and its use for fisheries oceanography in the Bay of Biscay. ICES-CM2010/A06.
- Petitgas, P. (Ed.) 2010. Life cycle patterns of small pelagic fish in the Northeast Atlantic. ICES Cooperative Research Report, 306: pp.94. Chapter 8: Bay of Biscay anchovy, Chapter 9: Atlanto-Iberian sardine
- Petitgas, P., Huret, M., and Léger, F. 2011. Identifyingandmonitoringlimitingfactorsofrecruitment: anchovy in the Bay ofBiscay.ICES CM 2011/H:11, 33: 1-14. (ICES CM 2011/H:11)
- Petitgas, P., Doray, M., Masse, J., Grellier, P., 2011. Spatially explicit estimation of fish length histograms, with application to anchovy habitats in the Bay of Biscay. ICES J. Mar. Sci. 68, 2086–2095.
- Huret Martin, Vandromme Pieter, Petitgas Pierre, Pecquerie Laure (2012). Connectivity patternsofanchovylarvae in the Bay ofBiscayfrom a coupled transport-bioenergeticmodelforcedbysize-structuredzooplankton. ICES-CIEM Annual Science Conference, Bergen
- Huret Martin, Sourisseau Marc, Petitgas Pierre, Struski Caroline, Leger Fabien, Lazure Pascal (2013). A multi-decadalhindcastof a physical–biogeochemicalmodelandderivedoceanographicindices in the Bay ofBiscay. Journal Of Marine Systems, 109, S77-S94. Open Access version :http://archimer.ifremer.fr/doc/00114/22538/
- Petitgas, P., Alheit, J., Peck, M., Raab, K., Irigoien, X., Huret, M., van der Kooij, J., Pohlmann, T., Wagner, C., Zarraonaindia, I. and Dickey-Collas, M. 2012. Anchovy population expansion in the North Sea. Marine Ecology Progress Series, 444: 1-13.
- Petitgas, P., Grellier, P., Duhamel, E., Massé, J. and Doray, M. 2012. Variabilityandcontrolsofotolithgrowth in theanchovyofthe Bay ofBiscay. ICES CM 2012/J:18, ASC, Bergen.
- Schismenou E., Tsiaras K., Kourepini M.I., Lefkaditou E., Triantafyllou G., Somarakis S. (2013). Seasonalchanges in growthandconditionofanchovylatelarvaeexplainedwith a hydrodynamic –biogeochemicalmodelsimulation. Marine Ecology Progress Series 78: 197–209.

3. Oral Presentations and Posters at Scientific Conferences

ICES PICES Symposium on the Effects of Climate Change on Fish and Fisheries Sendai, Japan, 26-29April 2010

- Kate Hedstrom, Jerome Fiechter, Kenneth A. Rose, Enrique N. Curchitser, Miguel Bernal, Shin-Ichi Ito, and Bernard A. Megrey. Development of a climate-to-fish-to-fishers model: data structures and domain decomposition
- Kenneth A. Rose, Enrique N. Curchitser, Kate Hedstrom, Jerome Fiechter, Miguel Bernal, Shin-ichi Ito, Salvador Lluch-Cota, Bernard A. Megrey, Chris Edwards, Dave Checkley, Alec MacCall, Tony Koslow, Sam McClatchie, Ken Denman, and Francisco Werner. Development of a climate-to-fish-to-fishers model: proof-of-principle using long-term population dynamics of anchovies and sardines in the California Current
- Triantafyllou G., Tsiaras K., Petihakis G., Politikos D., Somarakis S., Ito S.-I., Megrey B.A., Pollani A. Development and implementation of a 3D-IBM in the north Aegean Sea (eastern Mediterranean) that describes the full life cycle of anchovy, p. 216.

ISOBAY 2010 Brest, France, May 2010

- Hernández, C., Villamor, B., and Gonzalez, C. 2010. Impact of environmental factors on survivalof juvenile European anchovy (EngraulisEngraulisencrasicolusencrasicolus) in the Bay ofBiscay : implicationsforrecruitment.
- Hernández, C., Villamor, B., Abaunza, P., Landa, J., Cendrero, O., Dueñas, C., Navarro, M. R., et al. 2010. Growth variabilityof European anchovy (Engraulisencrasicolus) in the Bay ofBiscay (NE Atlantic), 1994-2008.
- Huret, M., Petitgas, P., Sourisseau, M., Struski, C., Fabien, L., and Lazure, P. 2010. A 38 yearshindcastof a coupledphysical-biogeochemicalmodelandderivedindicesforfisheriesoceanography.

ICES Annual Science Conference ASC2010 Nantes, France, 20-24 September 2010

- Huret M., Petitgas P. and Struski C. (2010). Integrated modelsforanchovyresponseto environmental drivers in the Bay ofBiscay (ICES CM 2010/L:07)
- Huret M., Petitgas P., Struski C., Léger F., Sourisseau M., Struski C., Léger F., and Lazure P. A 37 years hindcast of a coupled physical-biogeochemical model and its use for fisheries oceanography in the Bay of Biscay. .
- Triantafyllou G., Tsiaras K., Petihakis G., Politikos D., Somarakis S., Ito S.-I., Megrey B.A., Pollani A. Implementation and data assimilation on the 3D-IBM for the European anchovy (Engraulisencrasicolus) in the north Aegean Sea (eastern Mediterranean).

ICES Decadal Symposium , Santander, Spain, May 2011

- Preciado, I., Velasco, F., Villamor, B., Nogueira, E., Iglesias, M., and Olaso, I. 2010. Effectofanchovyfluctuations on demersalfishpredators in the southern Bay ofBiscay Small pelagic.
- Villamor, B., Hernandez, C., Landa, J., and Gonzalez, C. 2011. Biological variabilityofthe European Anchovy (Engraulisencrasicolus) yearclassesduring 2000 -2009 in the Bay ofBiscay.
- Villamor, B., Costas, G., Gonzalez-Pola, C., Lago de Lanzós, A., Pérez, J. R., Franco, C., Garabana, D., et al. 2011. Temporal variabilityofthespawningseasonforthe southern componentoftheNortheastAtlanticMackerel (Scomberscombrus).
- Ruiz-Villarreal, M., García-García, L., Otero, P., Cobas, M., and Bernal, M. 2010. Modellingoceanographicconditions in the western and northern Iberianshelfandslopeaffectingearlystagesofpelagicfishduringthe 2000s.

4th International Conference on Hydrobiology and Fisheries, Volos, Greece, 9-11 June 2011.

- Tsoukali S., Somarakis S. (2011) Distribution of eggs and larvae of anchovy in the NE Aegean Sea during the beginning (May 2010) and the middle (July 2010) of its spawning period.

AMEMR 2011, Plymouth, UK, 27-30 June 2011

- García-García, L., Ruiz-Villarreal, M., Otero, P., Cobas, M., and Bernal, M. 2011. Towards an end2end modelfor W and N Iberianshelfandslope: modellingtheoceanographicconditionsaffectingthespawningandrecruitmentofpelagicfishduring spring 2007.
- Huret, M., Petitgas, P., Bourriau, P., and Grellier, P. 2011. An Individual Based Model ofanchovyearlylifestages in the Bay ofBiscay : validationofverticaldistributionandgrowth.
- Tsiaras K., Triantafyllou G., Politikos D., Somarakis S., Petihakis G., Pollani A. 2011 Development of a 3D-IBM for the European anchovy (Engraulisencrasicolus) in the Mediterranean Sea.

ICES Annual Science Conference. Gdansk, Poland. 19-23 September 2011

- Politikos D.V., Triantafyllou G., Tsiaras K., Giannoulaki M., Machias A., Somarakis S. The application of a biophysical model to the north Aegean anchovy fishery: Its implication for spatial management.
- Petitgas P., Huret M., and Léger F. Identifying and monitoring limiting factors of recruitment: anchovy in the Bay of Biscay. ICES CM 2011/H:11
- Vandrome, P., Nogueira, E., Huret, M., López-Urrutia, A., González-Nuevo, G., Petitgas, P. and Sourisseau, M. 2011. Results from zooplankton size structure surveys in the Bay of Biscay during the last decade. ICES CM 2011/K:12

ISOBAY 2012, Colloquium of the Bay of Biscay, Santander, Spain, April 2012

- García-García, L., Ruiz-Villarreal, M., Otero, P., Cobas, M., and Bernal, M. Investigating the processes that affect sardine recruitment in the W and N Iberian shelf and slope.
- Petitgas, P., Villamor, B., Preciado, I., Sptiz, J., Dorémus, G., Santos, B., Punzón, A., Rodriguez-Marin, E., Iglesias, M. and Massé, J. 2012. Maps of potential predation on the different life stages of anchovy in the Bay of Biscay.
- Vandromme P., Nogueira E., Huret M., González-Nuevo G., López-Urrutia A., Petitgas P. and Sourisseau M. Spatial and vertical distribution of springtime zooplankton size-spectra. Results from survey (Pelacus – Pelgas) in the Bay of Biscay using L-OPC and nets/ZooScan datasets.

ICES/PICES Symposium on forage fish interactions, November 12-14, 2012, Nantes, France.

- Nikolioudakis N., Isari S., Pitta P., Somarakis S. (2012) Sardine and anchovy trophic ecology in the eastern Mediterranean pelagic food web.

ICES Annual Science Conference. September 2012, Bergen

- Huret, M., Vandromme, P., Petitgas, P., Pecquerie, L., Connectivity patterns of anchovy larvae in the Bay of Biscay from a coupled transport-bioenergetic model forced by size-structured zooplankton

4. Dissemination

- Two page summary for Marifish ERANET webpage

5. Presentation of Reproduce at ICES scientific workshops and working groups, including special sessions

ICES – FRESH Joint Workshop on Egg Production Methods for Estimating Fish Biomass (WKEPM). Athens, 10–13 March 2010.

Bernal et al. Beyondthe egg productionmethods: usingreproductiveparametersfrom egg productionsurveystoestimatereproductiveexpensesof (pelagic) fish

Workshop on understanding and quantifying mortality in pelagic, early life stages of marine organisms: experiments, observations and models (WKMOR), Aberdeen, March 2010

Petitgas P., Huret M., and Léger F. Identifying the limiting factors of recruitment.

MARIFISH-ICES Joint Workshop on Integrated ecosystem modelling; building our capacity to understand and manage marine ecosystems in a changing world (WKIEM). Barcelona, 15 - 19 November 2010

Several presentations of Reproduce advances (see program)

- Ruiz-Villarreal, M., García-García, L., Cobas, M., Otero, P. and M. Bernal Modelling oceanographic conditions influencing early stages of small pelagic fish

ICES Working Group on Modelling of Physical/Biological Interactions,

Reproduce results presented at 2011 (Pasaia, Spain) annual meeting

- Huret M., Bourriau P. and Petitgas P. Vertical distribution of early life stages of anchovy and sardine in the Bay of Biscay. Observation and modelling.
- García-García, L., Ruiz-Villarreal, M., Otero, P. and M. Bernal, Impacts of circulation patterns on the early stages of small pelagic fish in North and Northwest Iberia.

ICES WGOOFE Working Group on Operational Oceanographic Products for Fisheries and Environment

Reproduce results presented at 2011 (Exeter, UK), 2012 (Brussels, Belgium) annual meetings

ICES WGACEGG Working Group on Acoustic and Egg Surveys for Sardine and Anchovy in ICES areas VIII and IX.

- Bernal et al. Pelagicfishmultispecieshabitatmodels

ICES WGIPEM Working Group on Integrative, Physical-biological and Ecosystem Modelling.

- Several presentations at 2012 annual meeting in Copenhaguen, Denmark:

- Mahévas, S., Huret, M., Travers, M., Macher, C., Villanueva, M.C., P. Marchal, P., Vermard, Y., Guyader, O and Dumas F. Towards an end-to-end model of marine ecosystems as support decision-making tool for fisheries management. WGIPEM, March 2012 Copenhagen, Denmark.

- Huret, M., Vandromme, P., Gatti, P. and Petitgas, P. An Individual-Based Model of anchovy life cycle in the Bay of Biscay under environmental forcing. WGIPEM, February 2013, Paris, France.

- Special Reproduce session at the 2013 annual meeting in Paris, France

- Lagrangian modelling of sardine early life stages in the Bay of Biscay (Luz MaríaGarcíaGarcía)

- Lower trophic level modelling in the Northern Iberian Shelf (Manuel Ruiz Villareal)

- Anchovy life cycle model developments for the Bay of Biscay (Martin Huret)

- Constructing simple indicators from complex model output (Pierre Petitgas)

- Modelling the foraging and growth of anchovy larvae using prey size-spectra (AgurtzaneUrtizberea)

- Movements of anchovy in a full life-cycle model coupled to a 3-D biophysical, lower trophic level model (George Triantafyllou)

ICES WKPELA Benchmark Workshop on Pelagic Stocks (WKPELA 2013)

Petitgas, P. 2013. Coherence between Egg and Acoustic survey estimates (Bay of Biscay anchovy) Working document 4 to WKPELA, 4-8 February 2013, Copenhagen, ICES CM 2013/ACOM: 46, pp.297-301

6. Presentation of Reproduce at meetings and workshops of other projects

- Lotofpel, Long-term variability of small-pelagic fishes at the North Iberian shelf Ecosystem. PI: R. González-Quirós. financed by the Spanish Ministery MICINN. (2011-2013). Reproduce modelling advances were presented at annual meetings 2011 and 2012
- REIMAGE RESPUESTA DE LOS ECOSISTEMAS COSTEROS A LOS APORTES ALÓCTONOS DE MATERIA EN EL CONTEXTO DEL CAMBIO AMBIENTAL GLOBAL ANTROPOGÉNICO, financed by the Spanish Ministery CTM2011-30155-C03. Reproduce modelling advances were presented at a workshop in Aveiro (28 June 2012)

REPROdUCE

Understanding REcruitmentPROcesses Using Coupled biophysical models of the pelagic Ecosystem

Appendix B: Project Deliverables

This appendix is provided as a different document due to its length and document size.