SARDINE LARVAE VERTICAL MIGRATION AND HORIZONTAL DISPERSION PATTERNS RELATED TO LIGHT INTENSITY IN THE DYNAMIC WESTERN PORTUGUESE COAST: A NUMERICAL STUDY

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CHAPTER SYNOPSIS

Background

Sardine is an important traditional fishery in Portugal which recruitment could be affected, among other factors, by oceanographic and atmospheric conditions. Their annual spawning period generally extends between November and April, coinciding with the period when the upwelling episodes are less intense. The sardine larvae present vertical migration strategies that could generally be explained by predatory and survival behaviour. In this work, larvae vertical migration was parameterized using a relation with light availability and implemented into a lagrangian tracers model. A parameterization for sardine was modelled in the Western Portuguese coast using the 3D PCOMS model results to determine the different horizontal dispersion scenarios.

Results

The lagrangian model was applied in two realistic upwelling and downwelling simulations, obtaining the continental shelf retention index with and without vertical migration activation. Modelling results showed that vertical migration increased larvae retention in both scenarios. Thus, indicating a relationship between the spawning period and the typical oceanographic scenarios associated to the dominant atmospheric regimes in this coastal area.

Conclusions

Vertical migration strategies are important for the sardine larvae survival in the Portuguese continental coast, not only because of food abundance or protection from predators, but also because it increases their retention in coastal areas. Modelling tools could contribute on the study of fish larvae mechanistic behavioural providing aid to fisheries management and larvae sampling campaigns design.

1 INTRODUCTION

The significant European sardine *Sardina pilchardus* (hereafter referred only as sardine) recruitment decrease off the Portuguese coast during the 90's [1] led to several studies trying to determine the possible causes. In addition to the overfishing, some oceanographic phenomena were pointed out to explain the problem [2-4]. Ekman offshore transport caused by unusual winter upwelling events, showed an inverse correlation with the sardine and horse mackerel recruitment in the Portuguese Atlantic coast [2], but the interaction between costal currents and river plumes could also provide a vertical retention mechanism responsible for some of the recruitment variability [3]. A numerical study analysing the sardine larvae survival off the Atlantic Portuguese coast pointed out that the intense upwelling conditions during the winter of 1994 could lead to a recruitment decrease [4]. This study suggested that the transport to oligotrophic zones could not only be the reason for the recruitment decrease as changes on temperature patterns could infer some of this variability.

The larva transport along its growth is naturally affected by its own capacity of movement. These movements come from the development of their capacity of horizontal swimming or from its capacity of vertical movements due to the inflation and deflation of the swim bladder.

The locations where the propagules are found at the end of the larval phase are determinant for the juvenile recruitment success [5]. For this reason, it is extremely important that both the hydrodynamic model and the larvae model employed are as realistic as possible [6]. The knowledge about larvae movement is scarce and in most species is limited to the vertical migration movements, justifying its inclusion in most IBMs (Individual Based Models). Vertical migration parameterisation in numerical models has been an important research topic in recent years [7-15].

The sardine spawning season in the Western Portuguese coast usually takes place between November and April [16]. In general during this period, wind predominantly blows from the South inducing downwelling conditions whereas in summer months wind usually blows from the Northeast and coastal circulation is dominated by an upwelling regime. The early phases, eggs and yolk-sac, of the Pacific Sardine *Sardinops sagax* life are around 5.6 days long being followed by the early and late larvae phases that in the sardine case take approximately 11 and 35 days respectively [17]. Prior to the swim bladder activation the sardine larvae could be regarded as part of the planktonic life, and its dispersion is dominated by the oceanic currents.

A functional swim bladder allows active depth selection in the water column in order to find particular physical conditions, high prey density and to protect of eventual predators [18]. Diel swim bladder inflation/deflation rhythm initiates in sardine around age 17 days [19]. This diel migration could be related to phototropism phenomena as the bladders are generally found full of gas during the night period and empty at daytime. The filling process takes place during the twilight by atmospheric air intake [20]. During a research cruise in May 2002, the sardine vertical migration strategy was observed and correlated with daytime and night-time [21].

Due to the vertical migration importance and bearing in mind that the determining factor of these vertical movements is light-related, in this work an atmospheric model was coupled providing instant light intensities to the lagrangian model along the water column. In this approach, during dense cloud cover conditions, larvae could remain for longer at surface after dawn. This hypothesis agrees with the suggestion pointed out by Vikebø et al. [15], where the fish larvae has information related to growth and mortality conditions in the water column. The incorporation of realistic atmospheric values could provide a closer approximation to reality in fish larvae dispersion studies, in particular in the present study to the sardine larvae off the Portuguese coast.

The present work objectives include: to integrate a vertical migration model, based on the light availability computed by an atmospheric model, into a lagrangian model; to verify the influence of the vertical migration in the sardine larvae horizontal dispersion patterns and to associate the sardine vertical migration to their seasonal spawning strategy.

2 METHODS

2.1 PCOMS circulation model

The PCOMS (Portuguese Coast Operational Modelling System) model consists on a fully 3D baroclinic circulation model covering the Iberian Western Atlantic region (Figure 1) that runs the Mohid model (http://www.mohid.com) with a horizontal resolution of 5.6 km and with 50 vertical layers, 43 in Cartesian coordinates and the top 7 in sigma coordinates, with a resolution of down to 1 m near the surface. The PCOMS model is a downscaling of the Mercator-Océan PSY2V4 [22] and its water levels are obtained from the global tide model FES2004 [23].

The MOHID Water is an open source numerical model included in MOHID Water Modelling System [24] developed since 1985 mainly at the Instituto Superior Técnico (IST) from the Technical University of Lisbon. The model adopted an object oriented philosophy model for surface water bodies which integrates different scales and processes. The core of the model is a fully 3D hydrodynamic model which is coupled to different modules comprising water quality, atmosphere processes, discharges, oil dispersion, mixing zone model for point source discharges, catchment area. The Mohid Water model has been applied to several coastal and estuarine areas and has shown its ability to simulate successfully very different spatial scales from large coastal areas as the northern European Atlantic front or the Western Iberia coast to estuaries and coastal structures [4, 25-28].

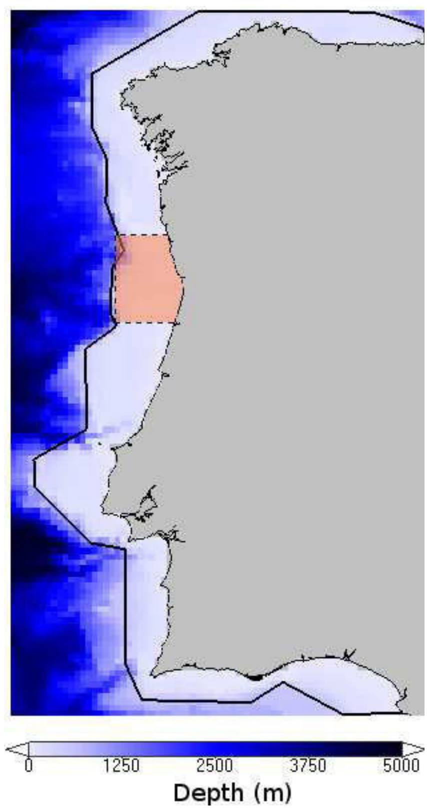

Figure 1. *Bathymetry (color scale) and boxes for the initial larvae particles distribution (broken line)and for calculating the continental shelf particle retention (continuous line).*

The MOHID model is programmed in ANSI FORTRAN 95 using an object orientated philosophy able to simulate eulerian and lagrangian processes. Lagrangian transport model manages the evolution of water parcels and has been used to simulate different processes as near field outfall dispersion, oil spills trajectories and during this work was adapted to include the fish larvae vertical migration as explained in the next section.

The PCOMS is a Mohid application that simulates hydrodynamics since 2009 and biogeochemistry since 2011 in the Western Iberia region. Every day the model hindcasts the previous day, in order to optimize the meteorological forcing, and obtain the following three days forecasts providing a solution which is also used as open ocean boundary conditions for local higher spatial resolution models [29].

The atmospheric forcing for the hydrodynamic model is provided by MM5 model application with 9 km of horizontal resolution running at IST [30]. The forcing includes air temperature, wind intensity and direction, atmospheric pressure, solar radiation and cloud coverage. From the last two properties is obtained the solar radiation that reaches the water surface. The Mohid water model would compute from these values the light extinction in the water column for each grid cell.

2.2 Larvae model

In order to study the larvae dispersion due to the interaction of their movement with the hydrodynamics a larvae lagrangian model was coupled off-line using results from the PCOMS model. Archived hindcasts results for the area shown in Figure 1 were the basis for the simulations of the present work. The time resolution of the PCOMS hindcasts was 15 minutes in order to represent the tidal variations accurately while the lagrangian model was computed using a time step of 180 seconds.

In order to simulate larvae dynamics, the lagrangian larvae model developed by Nogueira [31] was upgraded to compute the vertical migration. Larvae movements were restricted to the vertical direction, thus a vertical velocity term was added to the local vertical advective and diffusive term obtained from the hydrodynamic model while larvae horizontal velocity was given by the PCOMS model velocity.

Bearing in mind that vertical movement is obtained from the balance between the body weight and buoyancy and due to the reduced larvae dimension, it could be assumed that larvae vertical velocity was constant, in other words larvae would reach instantly the terminal velocity. It was assumed for this work that larvae vertical swimming velocity is constant along this life-story stage.

To determine the sardine larvae vertical velocity value, results from an oceanographic cruise conducted in May 2002 were used [21]. Sardine larvae were mainly distributed in the upper 20–25 m and - presented a negative relation with solar radiation, being located during the night near the surface and swimming down began around dawn. Based on this information, it was assumed that during the dusk larvae would swim to a defined minimum depth of 5m and during the dawn larvae would swim away from light to a maximum depth of 30 m. These limits were not rigid as the hydrodynamic model vertical advection could force the lagrangian particles out of these limits; however the particles would swim against these currents to return inside these depth limits.

This conceptual model was parameterised using a scheme related to the light radiation intensity. In absence of light, fish larvae were assumed to swim to the defined top depth limit of 5 meters and when light radiation over the particle exceeded a defined radiation intensity larvae would swim down until a maximum defined depth of 30 m. Since the main spawning period takes place during winter and the maximum defined deep was 30 m, the radiation limit value was considered as the mean light intensity value of at midday during winter (50 W m^{-2}). This value would determine the time spent by fish larvae at different depths. The light radiation at the lagrangian particle depth were obtained from the PCOMS model. According to the permanence time at surface, it was considered that fish larvae could not spend more than 7 hours in swimming the distance between both depth limits corresponding to a vertical swimming speed of 1 mm s^{-1}. This value was also used for different fish species larvae by van der Molen et al. [14].

3 MODEL SIMULATIONS

During wintertime sardine spawn takes place in the entire Western Portuguese coast [16], for this study is was chosen the area studied in Santos et al. [4] that corresponds to the ICES Subdivision IXa – Central North. This area is characterised by a wide continental shelf of around 40 km and gentle slopes until the shelf break, reaching maximum depths around 5000 m in the model domain (Figure 1). Using as reference the larval stage duration estimated of 46 days for the Pacific Sardine *Sardinops sagax* [17] and that the swimming bladder is fully functional for performing vertical migrations at the age of 17 days [19], the simulations consisted on 29 days periods.

To represent realistic upwelling and downwelling scenarios, two different periods for the year 2011 were selected. The first simulation included the period between the 19th May 2011 and the 17th June 2011 that corresponded to a typical summer scenario in the Western Iberia coast with predominant northern winds (see figure 2-top), hereafter referred as the May-June period. This wind regime is associated with upwelling conditions as could be observed in the model horizontal residual velocity (Figure 3-left). This period was characterised by low cloud cover as can be observed in the uniformity of the solar radiation peaks obtained from the MM5 atmospheric model (figure 4-top).

The second simulated period was between the 9th November 2011 and the 8th December 2011 coinciding with winds blowing predominantly from the South (see figure 2-bottom) inducing downwelling conditions (see figure 3-right), hereafter referred as the November-December period. On contraposition with the May-June period, it was registered a high variability of cloud coverage that would severely affect the solar radiation reaching the sea surface (Figure 4-bottom).

The residual velocities are the net velocities obtained after balancing velocities in different directions and they are of particular importance with regard to transport of particulate matter defining persistent currents during the whole simulated period. The horizontal residual velocities for the simulations performed during November-December period show a typical downwelling pattern with a strong poleward current (Figure 4-left). In the May-June period, the pattern changed dramatically showing an offshore current, typical of an upwelling regime (Figure 4-rigth). These patterns could also be observed in the horizontal residual velocity near the seabed (Figure 5).

For each period, two identical simulations were performed, one with the diel vertical migration implemented, adding the extra vertical velocity to the lagrangian tracers respect to the advection given by the hydrodynamic model and a second simulation with passive lagrangian particles where the vertical velocity was entirely determined by the PCOMS model. All simulations began with 8580 particles uniformly distributed between 10 and 30 m depth released in the box represented in Figure 1. For each simulation, the retention percentage in the continental shelf between the water surface and 100 m deep was obtained using the monitor box defined in Figure 1. The Portuguese continental shelf was assumed to have enough food to avoid larvae starvation during their planktonic life stage.

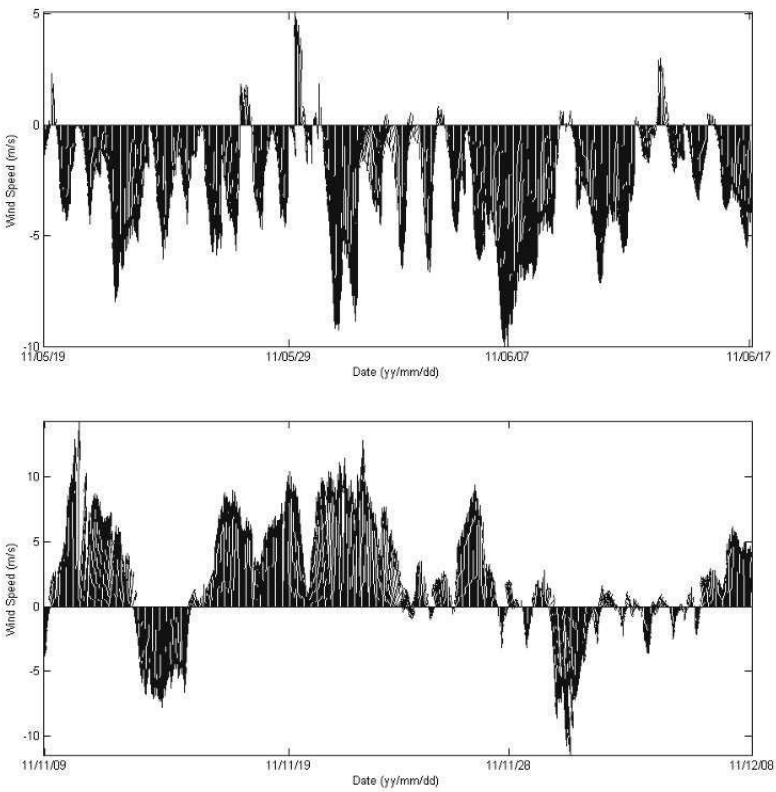

Figure 2. *Wind velocity and direction for the two simulated periods: May-June period (top) and November-December period (bottom).*

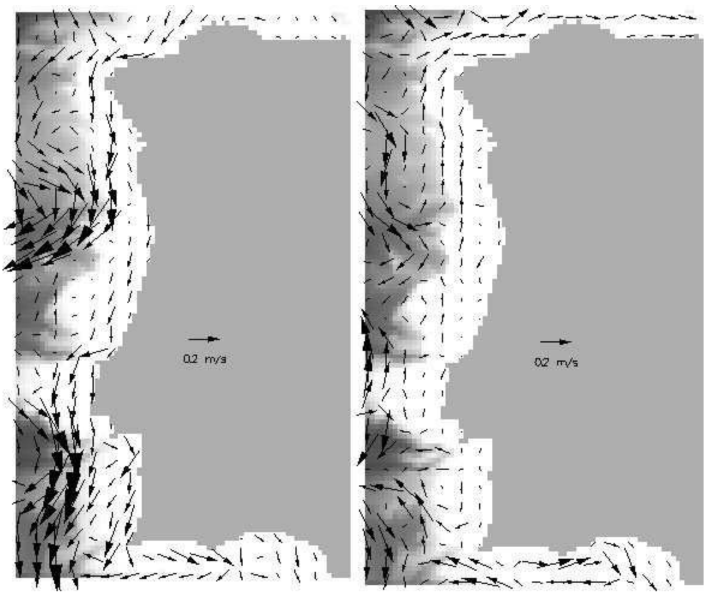

Figure 3. *Horizontal residual velocity from the PCOMS model at the surface: May-June period (left) and November-December period (right). Note that vectors are represented each four model cells to allow a clearer visualisation.*

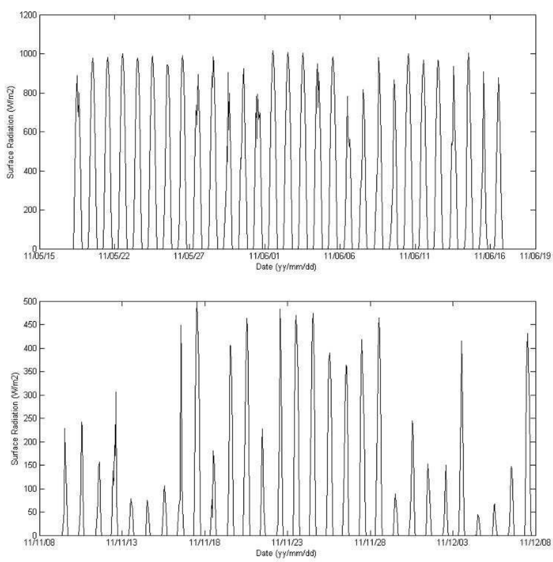

Figure 4. *Surface radiation from the MM5 model at the initial particle release: May-June period (top) and November-December period (bottom).*

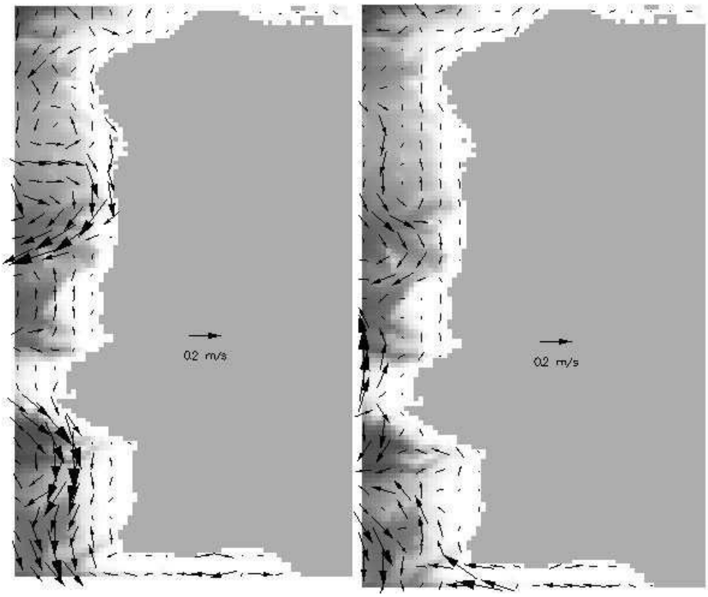

Figure 5. *Horizontal residual velocity from the PCOMS model at 150 m deep: May-June period (left) and November-December period (right). Note that vectors are represented each four model cells to allow a clearer visualisation.*

4 MODELLING RESULTS

The horizontal larvae distribution at the end of the simulated periods reflected the influence of the hydrodynamic conditions and the larvae vertical movement in the larvae dispersion patterns. In one side the upwelling simulations, May-June period, showed a strong Ekman transport offshore in whether or not the vertical migration was active (Figure 6). On the other hand, the downwelling simulations, November-December period, showed higher larvae coastal retention capacity regardless of the vertical migration (Figure 7). Simulations including the larvae vertical migration obtained higher retention values for both periods (Table 1).

Modelling results also showed that vertical migration during both periods increased the larvae retention in the continental shelf (Table 1). In the November-December period, the vertical migration increased the larvae retention in around 20%, being the particles inside the monitored box of more than 99% of the total particles released in the model domain. In the May-June period, the vertical migration also reduced the offshore larvae export in more than 10%, however both simulations with and without vertical movement showed lower values when compared with the November-December period.

The horizontal residual currents obtained close to the seabed (figure 5-left) could explain the decrease in lagrangian particles retention for the simulation with no larvae vertical migration. It could be observed a zonal current that would transport the larvae reaching transported by the hydrodynamic model to those depths offshore. It should be noted that during downwelling periods, the vertical velocity tend to be mostly negative and a passive particle would sink, which implies its offshore transport.

Figure 6. *Larvae lagrangian tracers position at the end of the May-June simulation: without vertical migration (left) and with vertical migration (right).*

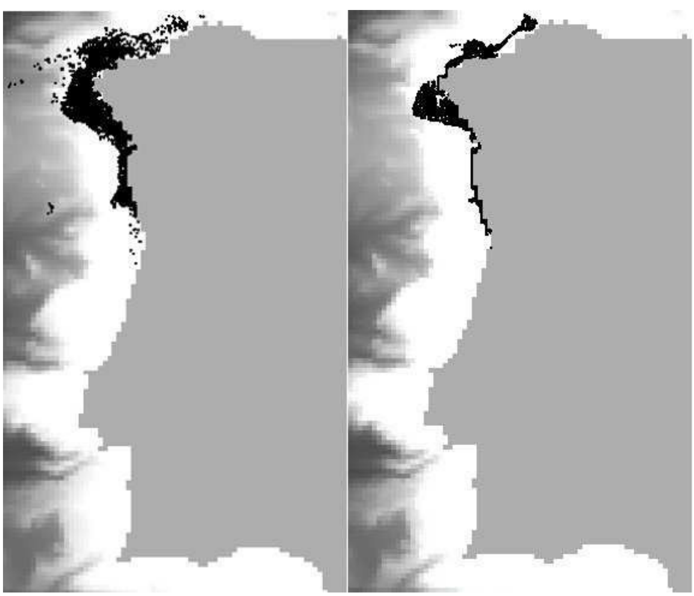

Figure 7. *Larvae lagrangian tracers position at the end of the November-December simulation: without vertical migration (left) and with vertical migration (right).*

Table 1. *Percentage of larvae retention in the first 100 m of the continental shelf at the end of the simulations respect the total particles remaining in the domain.*

	Without vertical migration	**With vertical migration**
May-June	67.50 %	79.70 %
November-December	81.39 %	99.88 %

According to the defined parameterisation and the light radiation limit in the larvae model and regarding the MM5 model radiation values, it was verified that during the November-December simulation the larvae would swim towards the surface between 16h and 17h and would dive between 9h and 10h in a relatively clear day. During the May-June simulation, fish larvae would swim to the surface between 18h and 19h and swim down between 6h and 7h. These values are in agreement with the migration times observed in the May 2002 cruise [21].

5 DISCUSSION

In recent times, larvae dispersion has been studied through numerical modelling using lagrangian particles in 3D hydrodynamic models and its diel vertical migration related to particular timings. These studies have been performed in different coastal areas, from the Arctic coasts [15] to South Africa [11]. This kind of applications have become common for coastal managers and scientists, being developed generic tools as Ichthyop where the modeller was able to determine the timing for diel vertical migration [9]. The latter tool has been applied in several studies focused in larvae retention in nursery areas showing all of them the importance of these larvae movements in the dispersion patterns of the analysed species [7,8,10,12].

In this work, a conceptual model based on the light availability and an optimum depth interval was implemented in an existing open source model. The main singularity in this model was the definition of diel migration related to light intensities obtained from realistic meteorological simulations instead of defined fixed timings. The combination of the meteorological light radiation and its propagation through the water column would impact the position of the fish larvae depending of the season of the year and the cloud coverage. The coupling of the meteorological model with the 3D hydrodynamic-biogeochemical model for the Western Iberian coast and the vertical migration behaviour of the fish larvae would be able to support some possible explanations in recruitment variability applied for the sardine in the Portuguese coast.

From the performed simulations it could be concluded that vertical migration had a significant importance in the horizontal dispersion of fish larvae. This conclusion was supported by model results (figure 6-right and figure 7-right) in which it could be seen that during both periods lagrangian particles remain more spatially structured when the vertical migration was active and particles presented a greater horizontal dispersion for passive particles, as pointed out by similar works [7,15]. Regarding the two simulated periods (Table 1), a clear relationship between the sardine spawning period and the typical oceanographic scenarios associated to the dominant atmospheric regimes could be observed. The downwelling period increased the coastal retention, even for passive particles the coastal retention increased around 15% compared to the values obtained during the upwelling period. These results are in agreement with the inverse correlation between the winter upwelling index and the sardine recruitment described by Santos et al. [2]. In fact, an increase on upwelling events during the spawning season would lead to a decrease of larvae recruitment.

The obtained results are in agreement with the hypothesis formulated by Parada et al. [11] that states that vertical migration could oppose the offshore transport, thus increasing the retention in the nursery areas. While the formulated hypothesis was not proven on that work, in the present work this hypothesis seems to be verified as the May-June scenario results shows that vertical migration increased 12% the continental shelf retention under a strong upwelling scenario. Bearing in mind that the May-June simulated period would correspond to a spawn by the end of April, model simulations would support the idea that main spawning peak would take place during wintertime [16] while during springtime spawning would be located in other areas, as the Cantabric Sea [32].

During the November-December period, simulations showed a northern migration along the continental shelf towards the North. These results would agree with the South-North age gradient observed by Carrera and Porteiro [33] and would support these authors' idea of an Ibero-Atlantic sardine metapopulation.

Another interesting outcome from the modelling results was the longer permanence of the sardine larvae near surface waters during the November-December simulation in comparison with the May-June period. This fact was related with the different solar radiation reaching the surface waters in both periods (Figure 3). In addition to the daylength differences between the two periods, it should be noticed the radiation reduction due to cloud coverage as pointed out by the MM5 model results. From these results and considering as daytime any moment with any solar radiation, it was obtained an average day length of 9.30 hours for the period November-December and 15 hours for the May-June period. As could be observed in Figure 3, the surface radiation intensity in the May-June period is almost twofold the obtained for the November-December period.

During the during the day central hours of May-June period, these solar radiation levels would influence larvae survival, as, even at the maximum defined depth, larvae would be exposed to solar radiation intensities higher than the defined limit radiation and would be more vulnerable to predation. During winter, the clouds coverage would allow larvae to remain longer at the surface and its movement and dispersion would be more related to the surface currents.

Summarising, vertical migration strategies are important for the sardine larvae survival in the Portuguese continental coast, not only because of food abundance or protection from predators, but also because it increases their retention in coastal areas as was described by Heath [18] in his study of the marine fish early life stages.

At last, it should be highlighted the contribution of modelling tools on the study of fish larvae mechanistic behavioural and the high adaptability of the numerical models used in the present work to the different fish species and coastal study areas.

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REFERENCES

1. Stratoudakis, Y., Bernal, M., Borchers, D.L., Borges, M.F., 2003. Changes in the distribution of sardine eggs and larvae off Portugal, 1985–2000. Fisheries Oceanography, 12(1): 49–60.
2. Santos, A.M.P., Borges, M.F., Groom, S., 2001. Sardine and horse mackerel recruitment and upwelling off Portugal, ICES Journal of Marine Science, 58(3): 589–596.
3. Santos, A.M.P., Peliz, A., Dubert, J., Oliveira, P.B., Angélico, M.M., Ré, P., 2004. Impact of a winter upwelling event on the distribution and transport of sardine eggs and larvae off western Iberia: a retention mechanism. Continental Shelf Research, 24: 149–165.
4. Santos, A.J.P., Nogueira, J., Martins, H., 2005. Survival of sardine larvae off the Atlantic Portuguese coast: a preliminary numerical study. ICES Journal of Marine Science, 62: 634–644.
5. Cowen, R. K., Paris, C.B., Srinivasan, A., 2006. Scaling of connectivity in marine populations. Science 311(5760): 522–527.
6. Gallego, A., North, E.W., Petitgas, P., 2007. Introduction: status and future of modelling physical–biological interactions during the early life of fishes. Marine Ecology Progress Series, 347: 121–126.
7. Brochier, T., Lett, C., Tam, J., Fréon, P., Colas, F., Ayón, P., 2008. An individual-based model study of anchovy early life history in the northern Humboldt Current system. Progress in Oceanography, 79(2-4): 313–325
8. Brochier, T., Colas, F., Lett, C., Echevin, V., Cubillos, L.A., Tam, J., Chlaida, M., Mullon, C., Fréon, P., 2009. Small pelagic fish reproductive strategies in upwelling systems: A natal homing evolutionary model to study environmental constraints. Progress in Oceanography 83: 261–269
9. Lett, C., Verley, P., Mullon, C., Parada, C., Brochier, T., Penven, P., Blanke, B., 2008. A Lagrangian tool for modelling ichthyoplankton dynamics. Environmental Modelling & Software 23: 1210–1214
10. Nicolle, A., Garreau, P., Liorzou, B., 2009. Modelling for anchovy recruitment studies in the Gulf of Lions (Western Mediterranean Sea). Ocean Dynamics, 59: 953–968.
11. Parada, C., Mullon, C., Roy, C., Fréon, P., Hutchings, L., van der Lingen, C.D., 2008. Does vertical migratory behaviour retain fish larvae onshore in upwelling ecosystems? A modelling study of anchovy in the southern Benguela. African Journal of Marine Science, 30(3): 437–452.
12. Soto-Mendoza, S., Parada, C., Castro, L., Colas, F., Schneider, W., 2012. Modeling transport and survival of anchoveta eggs and yolk–sac larvae in the coastal zone off central-southern Chile: Assessing spatial and temporal spawning parameters. Progress in Oceanography 92–95: 178–191.
13. Sundelöf, A., Jonsson, P.R., 2012. Larval dispersal and vertical migration behaviour – a simulation study for short dispersal times. Marine Ecology, 33(2): 183–193.
14. Van der Molen, J., Rogers, S.I., Ellis, J.R., Fox, C.J., McCloghrie, P., 2007. Dispersal patterns of the eggs and larvae of spring-spawning fish in the Irish Sea, UK. Journal of Sea Research, 58: 313–330.
15. Vikebø, F., Jørgensen, C., Kristiansen, T., Fiksen, Ø., 2007. Drift, growth, and survival of larval Northeast Arctic cod with simple rules of behaviour. Marine Ecology Progress Series, 347: 207–219.
16. Ré, P., Silva, R.C., Cunha, E., Farinha, A., Meneses, I., Moita, T., 1990. Sardine spawning off Portugal. Boletim do Instituto Nacional de Investigação das Pescas, 15: 31–44.
17. Lo, N., Smith, P., Butler, J., 1995. Population growth of northern anchovy and Pacific sardine using stage-specific matrix models. Marine Ecology Progress Series, 127: 15–26.
18. Heath, M., 1992. Field investigations of the early life stages of marine fish. Advances in Marine Biology, 28, 1–174.

19. Ré, P., 1986. Ecologia da postura e da fase planctónica da Sardina pilchardus (Walbaum 1792) na região central da costa Portuguesa. Boletim da Sociedade Portuguesa de Ciências Naturais, 23: 5–81. (In Portuguese).

20. Ré, P., 1999. Ictioplâncton estuarino da Península Ibérica. Câmara Municipal de Cascais, 163pp. (In Portuguese).

21. Santos, A.M.P., Ré, P., Santos, A., Peliz, A., 2006. Vertical distribution of the European sardine (Sardina pilchardus) larvae and its implications for their survival. Journal of Plankton Research, 28: 523-532.

22. Drillet, Y., Bourdalle-Badie, R., Siefridt, L., Le Provost, C., 2005. Meddies in the Mercator North Atlantic and Mediterranean Sea eddy-resolving model. Journal of Geophysical Research 110(C3): C03016.

23. Lyard, F., Lefevre, F., Letellier, T., Francis, O., 2006. Modelling the global ocean tides: modern insights from FES2004. Ocean Dynamics 56: 394 – 415.

24. Braunschweig, F., Martins, F., Leitão, P., Neves, R., 2003. A methodology to estimate renewal time scales in estuaries: the Tagus Estuary case. Ocean Dynamics, 53: 137–145.

25. Santos, A., Martins, H., Coelho, H., Leitão, P., Neves, R., 2002. A circulation model for the European ocean margin. Applied Mathematical Modelling, 26(5): 563-582.

26. Coelho, H., Neves, R., White, M., Leitão, P., Santos, A., 2002. A model for ocean circulation on the Iberian Coast. Journal of Marine Systems, 32(1-3): 153-179.

27. Riflet, G., Leitão, P.C., Fernandes, R., Neves, R., 2007. Assessing the quality of a pre-operational model for the Portuguese coast. In European Geosciences Union 2007, number 09979 in 1607-7962/gra/EGU2007-A-09979.

28. Saraiva, S., Pina, P., Martins, F., Santos, M., Braunschweig, F., Neves, R., 2007. Modelling the influence of nutrient loads on Portuguese estuaries. Hydrobiologia 587: 5–18.

29. Mateus, M., Riflet, G., Chambel, P., Fernandes, L., Fernandes, R., Juliano, M., Campuzano, F., de Pablo, H., Neves, R., 2012. An operational model for the West Iberian coast: products and services. Ocean Science, 8: 713–732.

30. Trancoso, A. R., 2012. Operational modelling as a tool in wind power forecast and meteorological warnings. PhD Thesis, Instituto Superior Técnico, Universidade Técnica de Lisboa, 146p.

31. Nogueira, J. 2005. Estudo numérico do recrutamento de pequenos peixes pelágicos na Costa Ibérica. MSc dissertation thesis. Technical University of Lisbon. (Portuguese)

32. Solá, A., Motos, L., Franco, C., Lago, A., 1990. Seasonal occurrence of pelagic fish eggs and larvae in the Cantabrian Sea (VIIIc) and Galicia (IXa) from 1987 to 1989. ICES, C.M 1990/H: 25.

33. Carrera, P., Porteiro, C., 2003. Stock dynamic of the Iberian sardine (Sardina pilchardus, W.) and its implication on the fishery off Galicia (NW Spain). Scientia Marina, 67: 245–258.