Table 2
Analysis of variance to test differences in the mean length of sardine larvae between inshore (inside the 100 m isobath) and offshore (outside the 100 m isobath) stations

Groups	Count	Sum	Average	Variance	
Inshore stations	61	369.31	6.05	1.81	
Offshore stations	81	846.95	10.46	22.00	
Source of variation	*SS*	*df*	*MS*	*F*	*P*-value
ANOVA					
Between groups	674.23	1	674.23	50.52	<0.001
Within groups	1868.30	140	13.35		
Total	2542.53	141			

Coriolis parameter and d an estimate for the Ekman layer depth ($d = \sqrt{2v/f}$, where the eddy viscosity, $v = 10^{-2}\,\mathrm{m^2/s}$). Finally, τ is the surface stress calculated according to

$$(\tau_x, \tau_y) = \rho_\mathrm{a} \cdot C_\mathrm{D} \cdot |W|(w_x, w_y), \qquad (3)$$

where ρ_a is the air density ($1.22\,\mathrm{kg/m^3}$), C_D is the drag coefficient (0.0012) and W the wind velocity (m/s). The resulting two-dimensional fields were interpolated into a regular grid with the same size as the sampled area and with a 1.1 km space resolution. All velocity estimates were interpolated to produce a time evolving velocity field with 6-h time steps over a period of 5 days (approximately 18–22 February 2002). The Lagrangian trajectories were calculated using a Range–Kutta 2nd order scheme.

Groups of particles randomly distributed inside a 10 km radius were released at several locations over the shelf and were tracked along the domain during the 5 days (particles reaching the boundaries are retained there). The time step for tracking the particles was 5 min and the velocity fields were considered stationary between the velocity upgrades (each 6 h). Fig. 12 shows the paths of five groups of 30 particles each (in a total of 150) together with the initial (open circle) and final (star) position of the particles.

The particles were generally advected off the coast and to the south over the shelf. At the outer shelf, where the velocity transition occurs, it is possible to observe that the aggregation at the northern zone is different from the one in the south. In the former the particles were retained approximately at the shelf-break and drifted northward under the influence of the poleward flow. Note that a meridional strip of particles was formed. This strip is similar to the one observed in the ichthyoplankton distributions (e.g., Fig. 11a).

This simple simulation shows some important features of the transport but fails to capture the

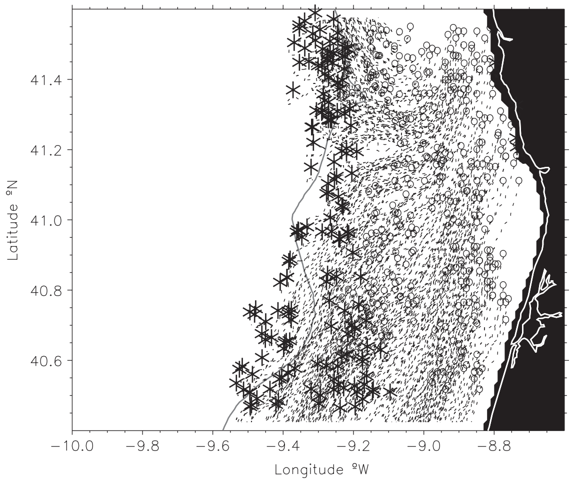

Fig. 12. Lagrangian model showing trajectory paths of particles between 18 and 22 February 2000, obtained with velocity estimates as described in the text. Circles represent the initial position and stars the final location. The solid line is the 200 m bathymetry line. Particles arriving to the meridional boundaries are artificially retained there by the model.

role of the surface buoyant plume and convergence zone. The influence of the plume in the transport is only implicitly included in this simple model as far as it represents the surface velocity and the particles are always maintained at the surface. If the particles were allowed to migrate vertically they might leave the surface Ekman layer and thus be advected to the interior. However, the mixing inside the plume and the circulation associated with the density gradients are not included in this simple model.

Even with the simplifications used in this particle tracking Lagrangian model, the retention of the particles along the shelf-break is similar to the observed features. This retention is due to the role of the along-slope jet that acts as a barrier to the offshore Ekman transport. An outcome of the model is that the convergence band can be explained, at least partially, by these two circulation features once the processes related to the vertical circulation referred to before are excluded. It is also clear that there is a certain resemblance between the distribution of the particles in Fig. 12 and of the larvae in Figs. 11c and d; namely the offshore pattern in the southern part and in the convergence zone in the northern part. However, in the southern part of the domain a concentration of particles close to the slope is not evident, as in the case of fish eggs in Fig. 11a. Here, the influence of the plume may be decisive in retaining the material. However, as already stated, the model does not simulate the plume.

8. A mechanism for retention

The feature that retained most of the biological material, including the eggs and larvae of sardine and of other fish, was the convergence band located at the outer shelf.

A number of mechanisms may contribute to an explanation of the origin of the convergence band: (i) the strong along-slope component of the poleward flow; (ii) the vertical recirculation associated with the upwelling; and finally (iii) the dynamics of the bottom layer in the presence of an equatorward upwelling current over the shelf and poleward flow over the slope. All these mechanisms are a consequence of the joint effect of the poleward slope-flow (IPC) and of the presence of the low salinity plume (WIBP) during the upwelling event.

The plume essentially provides a vertical retention mechanism, whereas the poleward current acts horizontally, retaining most of the plume close to the slope and advecting it northward. In this process, a convergence zone is created where the plume is trapped and deepens, thus increasing the potential for retention. This process of retention is schematically presented in Figs. 13a and b.

Part of the plankton will probably return to the coast following the wind relaxation. However, the presence of the slope-flow may induce a return to a northern or to a southern zone depending on the sense of the advection at the slope and outer shelf. In fact, at the scale of several weeks or months the slope current may modulate this transport by introducing an along-slope component to the cross-slope component forced by the wind. Off Western Iberia the slope is essentially dominated by the presence of the IPC and it is expected that the resulting larval drift will be poleward as it was schematically represented in Fig. 13c. However, these hypotheses require further modelling efforts and observations.

9. Final discussion and conclusions

The results presented here provide indications that upwelling events during the spawning season of sardine could significantly change the distribution of their early life stages. The most significant features of the ichthyoplankton distributions are their accumulation along convergence zones, and their association with low-salinity surface distributions. In what concerns sardines, which are known to spawn over the shelf, the observed offshore distribution of their larvae (in particular older ones) may be interpreted as an indication of seaward transport.

Chícharo et al. (2003) observed that almost all sardine larvae caught during the survey are in good condition and only 0.64% were classified to be in a starving state. These results are even better than those obtained in other areas off the Iberian

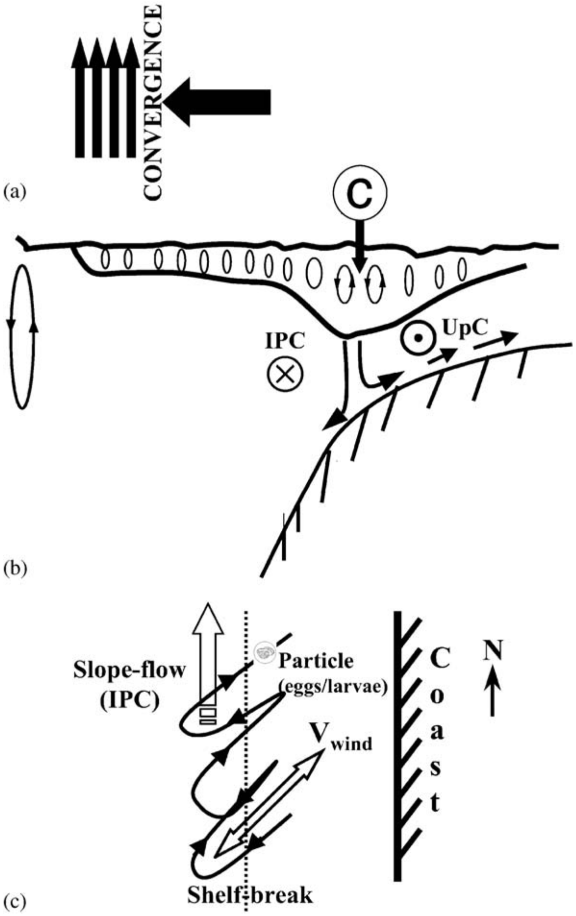

Fig. 13. Schematic representation of a retention mechanism and poleward egg and larval drift: (a) the convergence zone mechanism; (b) the vertical retention inside the buoyant plume (IPC—Iberian Poleward Current; UpC—Upwelling current; C—Convergence zone); and (c) the hroizontal retention and modulated poleward transport due to the joint effect of the poleward slope flow (IPC) and the cross shelf Ekman transport (V_{wind}).

Peninsula during the spring (Chícharo, 1997; Chícharo et al., 1998). Despite the upwelling favourable winds, the offshore transport and survival of sardine larvae was constrained by other local features such as the Western Iberia Bouyant Plume (WIBP) and the Iberian Poleward Current (IPC); with the joint effect of both being the creation of conditions for retention of the larvae close to the shelf break.

In fact, the eggs and larvae were clearly associated with the low salinity pools and were probably advected inside them. In the process of offshore transport part of the larvae were also retained in the convergence zone. In both cases, the concentration of phytoplankton was relatively high (Figs. 4d and 6d), thus the larvae had access to a sufficient concentration of food to keep them in good nutritional condition. According to Govoni and Chester (1990), Grimes and Finucane (1991) and Sabatés et al. (2001) the plumes of continental fresh water are habitats that afford conditions favourable to the growth and survival of fish larvae.

The data indicate that older larvae (larger) tend to be advected northward along the convergence zone on the shelf break (Fig. 11d). In a previous work on the distribution of sardine larvae off the northern coasts of Spain, López-Jamar et al. (1995) also found the highest mean lengths off southern Galicia near the Portuguese border (about 42°N in the north of the present survey area) during March, and indicated that the prevailing surface current off northern Portugal during previous months was poleward.

These results suggest that in this area upwelling events might not have an immediate impact on the survival of sardine early life stages by reason of their transport offshore alone. However, the negative impact could be on longer time scales due to the combination of offshore advection and the presence of a shelf break/slope poleward current (Fig. 13c), which favours advection of sardine eggs and larvae from the spawning area, where other conditions could lead to poor survival conditions, such as strong upwelling off Galicia in the spring (e.g., López-Jamar et al., 1995).

The mechanisms reported herein may be found in other upwelling areas where slope flows and coastal buoyant discharge are important. This study indicates that the processes of larvae transport are strongly dependent on local features and cannot be treated with simplified Ekman models. In some cases, it can be far more complex. Within the same coastal upwelling region, different areas may exist where the transport patterns are specific and dependent on local aspects. The case of the Western Iberia Upwelling region is illustrative, since both the poleward flow and especially the buoyant discharge are much increased in the northern part.

As these local factors can vary seasonally or interannually, significant fluctuations in the transport patterns are also introduced. In the case of Western Iberia, the buoyant discharge and poleward flow exhibit such variations. In years of strong poleward flow and an enlarged plume the negative impact of coastal upwelling on the transport is reduced. On the other hand, the absence of one or both of these factors will play the opposite effect contributing to interannual fluctuations.

Acknowledgements

This work was carried out with the financial support of the Portuguese Science Foundation (FCT) under the frame of the project "Assessing the Impact of Hydrodynamic Forcing on the Survival of Small Pelagic Fish Early Life Stages of Western Iberia (SURVIVAL)" (PRAXIS/P/CTE/11282/1998). SURVIVAL is affiliated with IGBP core project GLOBEC and the PELAGICOS programme (IPIMAR-FCT POCTI/PLE/13/00).

AMPS and AP wish to thank the former President of IPIMAR (Marcelo de Vasconcelos) for his support to our work.

We wish to acknowledge the use of Ferret program for analysis and graphics of this paper. Ferret is a product of NOAA's Pacific Marine Environmental Laboratory.

Finally, we would like to thank an anonymous referee for the helpful comments, and to Evan Mason for the revision of the English.

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