Hydrographic phenomena influencing early life stages of the Sicilian Channel anchovy

J. GARCÍA LAFUENTE,*[,1] A. GARCÍA,[2] S. MAZZOLA,[3] L. QUINTANILLA,[2] J. DELGADO,[1] A. CUTTITA[3] AND B. PATTI[3]

[1]*Departamento de Física Aplicada II, Universidad de Málaga, 29071 Málaga, Spain*
[2]*Centro Oceanográfico de Málaga IEO, 29640 Fuengirola, Málaga, Spain*
[3]*Istituto di ricerche sulle Risorse Marine e l'Ambiente, Consiglio Nazionale delle Ricerche, Mazara del Vallo, Italia*

ABSTRACT

The information collected from a European Union funded project on the 'Distribution Biology and Biomass Estimates of the Sicilian Channel Anchovy (*Engraulis encrasicolus*)' was used to analyse the linkage between the general circulation pattern of the Atlantic Ionian Stream (AIS) and the reproductive strategy of the Sicilian Channel anchovy. The main spawning ground is located in the NW region of the southern Sicilian coast. This region is a stable area of low current produced by the impingement towards the coast of the AIS and its bifurcation into two branches. The main branch heads towards the SE end of the Sicilian coast (Cape Passero) acting as a transport mechanism for the anchovy eggs and larvae. Along the AIS trajectory, there is a density front to the left of the current, facing downstream. This front is a consequence of the shoreward sloping of isopycnals that maintains the geostrophic flow, facilitating the mixing of deeper waters with surface layers and fertilization of coastal waters. The front enhances primary production assuring food availability for anchovy larvae during their advection by the AIS. The highest concentrations of larval anchovy were found off the SE Sicilian coast, in the area off Cape Passero. The greater average sizes of larvae found in this region, and their estimated age, support the evidence of advection by the AIS. The hydrographic features observed in this area, such as the existence of a well-defined cyclonic vortex, implies the existence of upwelling in its centre, providing a suitable environment for sustained enhanced rates of primary production and allowing the larval population to maintain their relative position. This retention area is conceived as favourable for providing the necessary feeding conditions. The data acquired from a survey carried out to evaluate the anchovy recruitment strength confirm that larvae reach the juvenile stage in the south-eastern coast of Sicily, since most of the young-of-the-year anchovy were located in the Cape Passero region.

Key words: anchovy, distribution, egg, *Engraulis encrasicolus*, hydrography, larvae, transport

INTRODUCTION

Biological background

Anchovy (*Engraulis encrasicolus*) is a short-living pelagic species that represents one of the most important resources in some areas of the Mediterranean. Its distribution along the Mediterranean coasts is not regular or widespread, but is rather a set of independent population or stock units (Garcia *et al.*, 1994) that are concentrated in particular regions of the western Mediterranean (Catalan Sea and the Gulf of Lions), and of the eastern Mediterranean (Adriatic and Aegean Seas). Nevertheless, no genetic differentiation has been observed for anchovy in the north-western Mediterranean (Tudela *et al.*, 1999).

The species is exploited mainly by purse seiners along the Mediterranean coasts. Some regions have developed other forms of exploitation, such as bottom trawlers off Tarragona (Spain) (Alvarez, 1990), and midwater pair trawls off the Adriatic coasts (Cingolani *et al.*, 1996). The anchovy in the Sicilian Channel is exploited both by purse seiners and midwater pair trawlers. However, its biology and the influence of environment on its variability is poorly known.

Anchovies are characterized by their interannual variability in biomass due to recruitment failure. This recruitment variability is highly conditioned to environmental fluctuations which appear to be much more

*Correspondence. e-mail: glafuente@ctima.uma.es
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important than the effects of variations in fishing intensity (Southward *et al.*, 1988; Sharp and McLain, 1993; Cingolani *et al.*, 1996). In some Mediterranean regions, the resource has undergone collapses, such as in the Alborán Sea during 1984 (Abad *et al.*, 1988) and in the Adriatic during 1987 (Cingolani *et al.*, 1996). Regner (1996) attributes this decrease to the eutrophication of the northern Adriatic Sea (Legovic and Justic, 1994). Climatic variability also showed an important role in the variability of the Aegean anchovy resource (Stergiou and Lascaratos, 1997).

The spawning habitat of the Mediterranean anchovy has some common features. Its outer limits are confined to the shelf-edge, where rather important enrichment processes occur, such as the shelf-slope front running along the Catalonian shelf (Font *et al.*, 1988) which concentrates anchovy eggs and larvae along the shelf edge (Garcia and Palomera, 1996). Other enrichment processes are associated in many cases with important river discharges (Rhône and Ebro river deltas in the Mediterranean, and the Garonne river in the Bay of Biscay) enhancing potential survival of the larvae. Water temperature is important in regulating the spawning cycle of anchovy (Motos *et al.*, 1996). King *et al.* (1978) showed for the South African anchovy that the likelihood of abnormalities in egg development increases in water <14°C, which would represent a lower limit for successful spawning. Suitable temperatures for a successful spawning are usually >14°C but differ from one geographical area to the other. Richardson *et al.* (1998) identified temperatures between 16 and 19°C as the preferred spawning range for the Cape anchovy (*Engraulis capensis*) in the Benguela upwelling region. In some regions of the Mediterranean Sea, such as the Gulf of Lions, the spawning temperature range is 19–22°C (Garcia *et al.*, 1994).

Hydrography plays a key role in the anchovy environmental scenario, contributing to dispersion, transport or retention of the eggs and larvae. Hypothetical models of the early life history of anchovy, related to the Bakun's 'fundamental triad' of enrichment, concentration and retention processes underlying favourable reproductive habitat, have been proposed for different small pelagic species in recent years (Bakun and Parrish, 1991, for *Engraulis anchoita*; Hutchings *et al.*, 1998 and Painting *et al.*, 1998 for *Engraulis capensis*). The influence of the hydrographic circulation on the anchovy egg and larval distribution off the southern coast of Sicily is the main topic of the present paper.

Physical background

The Strait of Sicily connects the two major basins of the Mediterranean Sea. This is the most important characteristic regarding physical phenomena and has been the focus of many scientific studies (e.g. Bethoux, 1980; Grancini and Michelato, 1987; Manzella *et al.*, 1988; Robinson *et al.*, 1991; Moretti *et al.*, 1993; Robinson *et al.*, 1999).

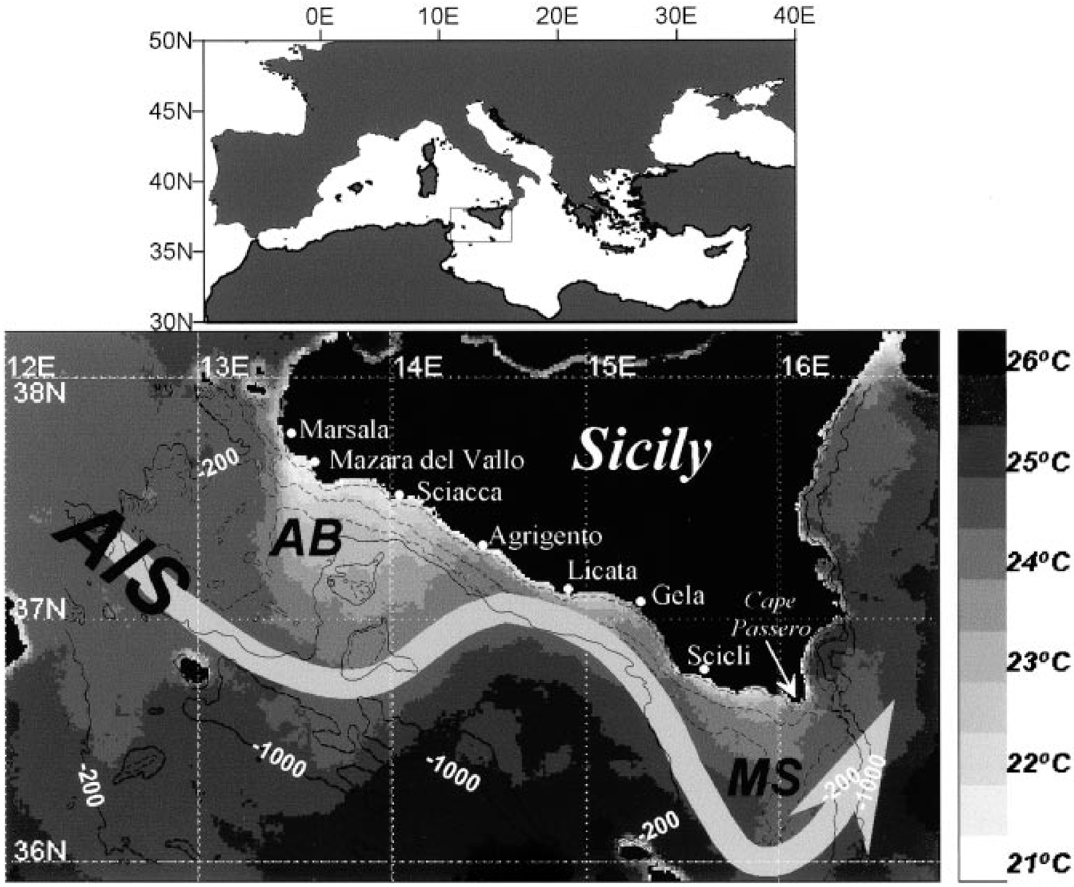
A useful representation of the water exchange that takes place in this region is a two-layer model in which relatively fresh water, of Atlantic origin (modified Atlantic water, MAW), flows eastward into the eastern Mediterranean, while salty water formed in the eastern Mediterranean during winter (Levantine intermediate water, LIW) flows out as an undercurrent into the western Mediterranean.

The word 'Strait' for this passage is somewhat misleading. It is more than 120 km wide at its narrowest section, sufficient for sustaining mesoscale structures, such as eddies or well-developed meanders. However, the word seems adequate for the LIW flow at depth. Below 200 m depth in the flow of the LIW, the Adventure Bank, a widening of the NW Sicilian shelf, reduces the width of the passage to 30 km. This Bank and the Maltese continental shelf at the eastern end of the channel are the most outstanding topographic features. Between them, the shelf is much reduced in width (Fig. 1).

The MAW flow, the so-called Atlantic-Ionian Stream (AIS, Robinson *et al.*, 1999) controls the surface circulation. According to these authors, it enters the channel at the western boundary and describes a large cyclonic meander around Adventure Bank towards the coast of Sicily before moving further offshore in the region of the Maltese shelf (Fig. 1).

The AIS encircles two large cyclonic vortices, one over Adventure Bank, mentioned above, and a second one off Cape Passero, at the southernmost tip of Sicily. Cold water associated with these vortices is clearly visible in the monthly averaged sea surface temperature (SST) image (Fig. 1). When the AIS approaches the coast on its anticyclonic meander, the underlying LIW ascends closer to the surface due to geostrophic adjustment forcing a shoreward sloping of the isopycnals to maintain the alongshore geostrophic current. By this means, nutrient rich, cold deep water (LIW) can intrude into the shelf, thereby enriching the upper water layers. The constant presence of a line of cold water along the Sicilian coast reported by Piccioni *et al.* (1988) is a signature of this mechanism. These authors also describe intensified events of wind-induced upwelling. Grancini and Michelato (1987) suggest that local wind is the driving mechanism of the subinertial variability of the currents along the Sicilian coast. According to the results of these authors, the characteristic time scale for the near-shore circulation

Figure 1. Average sea surface temperature (NOAA14 AVHRR) in the Sicily Channel during June 1998. The mean path of the Atlantic-Ionian Stream (AIS) is sketched. Contours of 200 m and 1000 m depth are labelled. Non-labelled contours (dashed lines) correspond to 50 m and 100 m depths. Adventure Bank (AB) and the Maltese Shelf (MS) are shown.



to adjust to new local meteorological conditions is around three days.

The objective of the present paper is to illustrate the coupling between the reproductive strategy of the anchovy and the hydrographic circulation in the Sicilian Channel. The data analysed were collected as part of a European Union funded project 'Distribution Biology and Biomass Estimates of the Sicilian Channel Anchovy' (MED 96–052), the objective of which was to study the distribution, biology and abundance of this species, together with an analysis of the main hydrological factors affecting its different early life stages.

MATERIALS AND METHODS

Two multidisciplinary surveys were carried out off the southern Sicilian coast during the peak spawning period for anchovy. The first survey (F/V Santa Anna, 19 July–8 August 1997) defined the boundaries of the anchovy spawning grounds and the characteristics of the surrounding water masses over the south-western Sicilian shelf and slope. However, the physical data of this survey were not adequate for a detailed oceanographic description. Therefore, the present paper relies mainly on the physical and biological information collected during the second survey (24 June–14 July 1998) on the R/V Urania of the Consiglio Nazionale delle Ricerche (CNR). In addition, ancillary information from an acoustic survey carried out in October 1999 provided information on the distribution of the 0-group recruits.

Biological data

Vertical CalVET (25 cm inlet diameter, 150-μm mesh) and oblique Bongo 40 (40 cm inlet diameter, 200-μm mesh) plankton tows were carried out to define the anchovy egg and larval distributions. A basic station grid of 4 × 4 nautical miles was used for the vertical CalVET egg sampling hauls; the oblique

Bongo plankton hauls were carried out at every third station (i.e. a 12 × 12 nautical mile grid) for data on egg and larval abundance (Fig. 2). To ensure that the full depth range of the eggs was sampled, the plankton tows were carried out to a depth of 100 m (Palomera, 1991), wherever possible.

A total of 253 CalVET tows and 128 Bongo 40 hauls were completed. All plankton samples were fixed and preserved in 5% buffered formaldehyde solution. CalVET samples were analysed on board with a stereoscopic microscope to examine for the presence of anchovy eggs and subsequently counted in the laboratory. The Bongo samples were analysed for eggs and larvae after the cruise. All the samples used were from the same side and cod-end collector of the Bongo. All counts were standardized to numbers m^{-2}. The larvae were measured to standard length.

Hydrographic data

A conductivity–temperature–depth (CTD) SeaBird-25 probe with fluorometer was deployed at 187 stations (Fig. 2). The greatest sampling effort was concentrated on a strip running along the south-western Sicilian coast, with 14 offshore transects to provide a description of the AIS circulation at the surface and to detect the core of the LIW at depth.

The path of the AIS was defined by connecting the points of minimum salinity at each transect. The line thus obtained depicts the trajectory of the AIS core. The AIS current structure was also described from the geostrophic velocity field. The 200 db depth was selected for the geostrophic calculation. Only 57 stations were deeper than 200 m, which are insufficient to provide a good description of the velocity field. To overcome this limitation, dynamic heights referred to 200 db (DH_{200}) and 100 db (DH_{100}) were evaluated from the CTD data in these 57 stations and the results used to calculate the linear regression function $DH_{200} = -0.7408 + 1.4050\ DH_{100}$ ($n = 57$; $r = 0.9677$; $P < 0.0001$). The DH_{200} value could then be estimated for all stations with water depths between 100 m and 200 m. Thus, the number of available stations for geostrophic computation purposes was increased to 102.

Two different weather conditions predominated during the survey. From 24 June to 3 July, the weather was remarkably stable, providing reliability on the global synopticity of the measurements. A mid-survey halt due to strong westerlies caused a 4-day gap between the transect in front of Liccata and the next one off Gela (Fig. 2). This stop and the sudden change in weather conditions may have broken down the 'synoptic' nature of the survey. Thus, the circulation pattern described for the first half of the survey does not necessarily hold for the second half. Station 122 which had been sampled before the weather change, was repeated on 8 July after this change to examine the effect of short-term atmospheric variations on the water column structure.

RESULTS

Temperature and salinity distribution

The temperature data for the survey are plotted in Fig. 3 as contours of the vertically averaged temperature in the uppermost 20 m of the water column, as well as the contoured depth of the 15°C isotherm. Both of these clearly show the two cold-water cores over Adventure Bank and off Cape Passero, separated by a region of warmer water.

Figure 4(a) shows the path of the AIS plotted as the line of minimum salinity. Figure 4(b) shows how

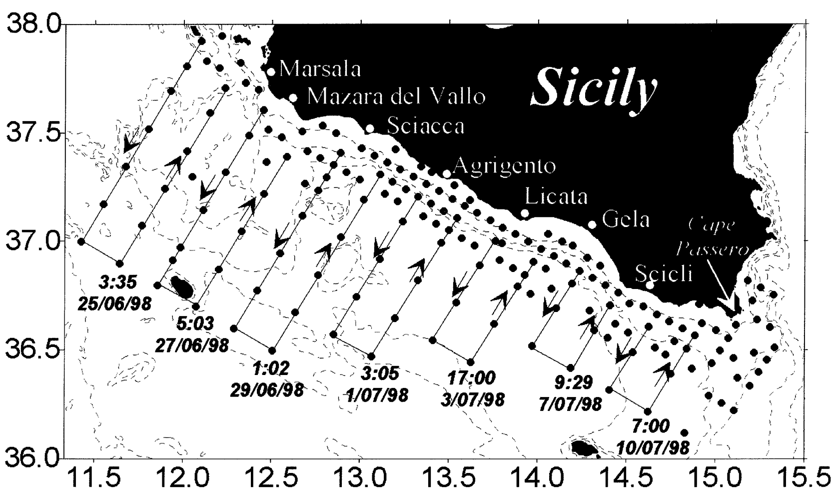
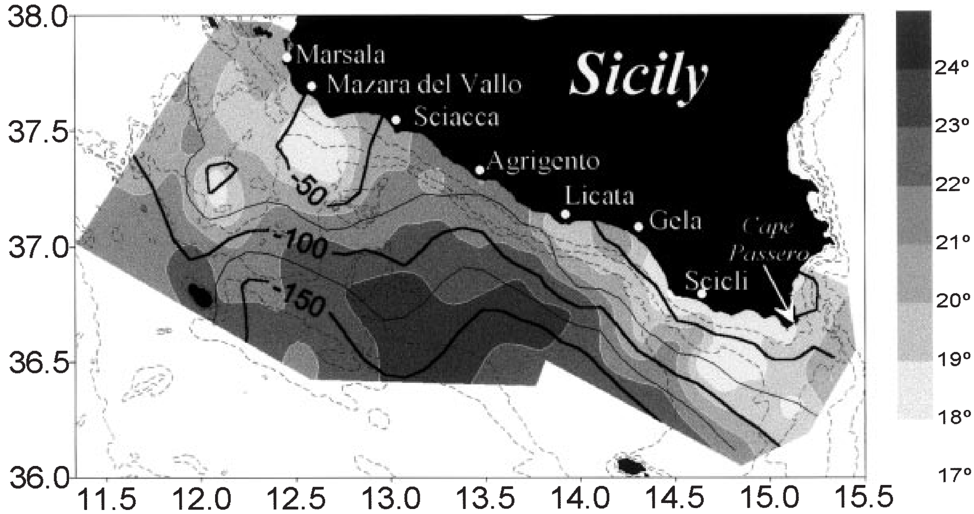


Figure 2. Station grid of the BANSIC98 survey. Numbers adjacent to the outermost stations of each transect indicate the time and date of sampling.

Figure 3. Depth (in metres) of the 15°C isotherm (black contours) and depth-averaged temperature of the uppermost 20 m of the water column during the period 24 June–14 July 1998 (shaded contours, right-hand scale).



the minimum of salinity is eroded from a salinity of 37.1 in the east to 37.25 in the west and becomes shallower (10 m) as the AIS proceeds eastward.

The contours of salinity at 10 m depth (Fig. 4a) show good agreement with the AIS path. The minimum salinity line shows the split in the path of the AIS near 37.0°N and 13.3°E, off Agrigento. There is also a close correspondence between the distribution of surface temperature and the path of the AIS (Figs 3 and 4a), the areas influenced by the AIS being warmer. Consequently, relatively warmer waters are found where the AIS approaches the shore, i.e. from Sciacca to Liccata where the thickness of the layer of water above 15°C near the coast attains its maximum.

Geostrophic velocity field

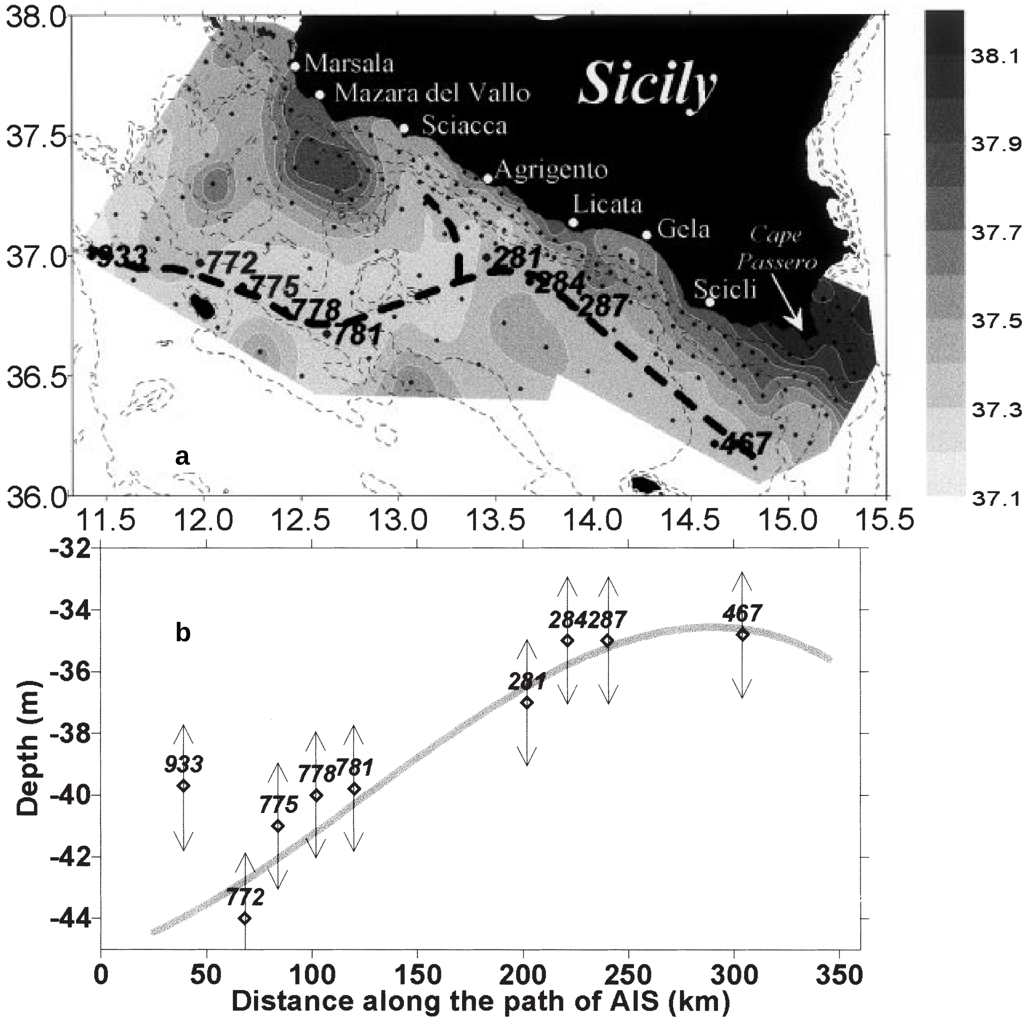
Figure 5 represents the geostrophic velocity and dynamic heights at 10 m depth. The geostrophic velocity field also shows the bifurcation of the AIS, with one branch following the Sicilian shore towards the east and the other turning to the west to close the cyclonic circulation over Adventure Bank. Although the geostrophic calculation is not valid near the shore, where the jet impinges the coast (geostrophic streamlines cannot end at the coast), it holds where the Rossby number ($R_0 = u/fL$) is low. In the area of the jet split, R_0 was approximately 0.1, based on a typical velocity of $u = 0.25$ ms^{-1} for the AIS (Fig. 5), a typical width L of 25 km, and $f = 8.7 \times 10^{-5}$ s^{-1}, the Coriolis parameter at 37°N. The independent method of using the salinity core as the representation of the trajectory of the AIS provides a similar path as the geostrophic approximation. Therefore, the divergence off Agrigento as shown in Fig. 5 is consistent from the physical point of view.

The following contour maps are the result of two situations. The first one is the situation before 3 July, when the weather was calm, and the second situation after 3 July, when the westerly winds may have broken down the previous circulation pattern. The *in situ* temperature and salinity variation observed at station 122 (Fig. 6) demonstrates this change. Despite the fact that surface temperature was higher on 2 July, the depth-averaged temperature over the upper 41 m of the water column was 0.7°C higher on 8 July. This implies greater thermal energy per unit surface stored in the water column on the second date. The thermal energy increase cannot be explained by an energy input across the surface because the sea surface temperature was warmer on 2 July. A more realistic cause is the lateral advection of heat produced by a shift of warmer offshore waters to inshore areas, i.e. a northward drift of the AIS. This hypothesis is evidenced by the presence of fresher water at station 122 on the second day (depth-averaged salinity over the first 41 m on 2 July is 0.3 units higher than on 8 July). The northward drift of the AIS could also account for the strong near shore AIS flow along the southern half of Sicily (Fig. 5).

Anchovy egg and larval distribution

A total of 1439 anchovy eggs and 392 anchovy larvae were captured on the 40 cm Bongo net hauls,

Figure 4. (a) Salinity at 10 m depth during the period 24 June–14 July 1998 (shaded contours, right-hand scale). The thick dashed line is the path of the core of minimum salinity of the AIS. (b) Depth of the salinity minimum at the different stations where the core was detected (see labels in the upper panel). A standard error of ± 2 m has been assigned to this depth and a third degree polynomial is fitted to the data (grey line).



representing 49% and 22% of the total fish egg and larval catch, respectively. Figure 7(a) shows that the anchovy eggs were distributed mainly along the narrow continental shelf between Adventure Bank and the Maltese shelf, over water depths of around 60 m. The main spawning nucleus is centred adjacent to the coast off Sciacca. Other spawning areas of lesser intensity were located off the Gulf of Gela off Licata and Scicli. CalVET tows showed a similar pattern of egg distribution.

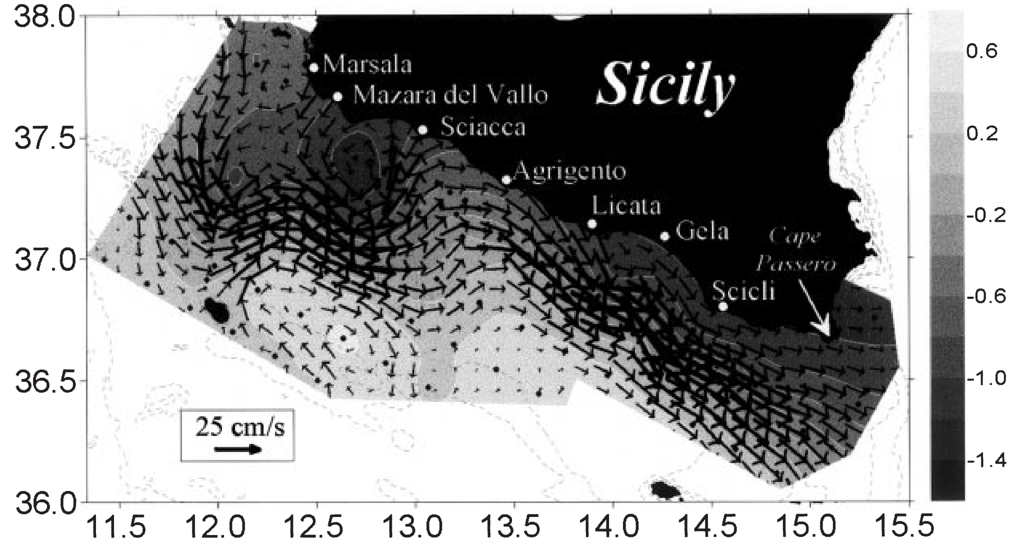
The main anchovy larval concentrations were observed in waters of the south-eastern end of Sicily (Fig. 7b), with low larval concentrations being observed at the main anchovy spawning grounds off Sciacca and in the Gulf of Gela. The fish symbols in Fig. 7(b) indicate the distribution of the mean larval size. Figure 7(b) shows that not only the greatest larval concentration, but also that the largest individuals were found in the Cape Passero area. The nonspatial coincidence of spawning and nursery areas is also evidenced by the similar results of the 1997 survey (Fig. 8a,b).

DISCUSSION

Hydrographic conditions in the anchovy spawning areas

Anchovy spawns along the narrow shelf off the southern Sicilian coast from Sciacca to Gela with the most important spawning ground located off Sciacca, where a branch of the AIS impinges the coast (Figs 5 and 6). Whitehead (1985) analysed the deflection of a geostrophically balanced baroclinic jet by a wall. He

Figure 5. Geostrophic velocity at 10 m depth (proportional arrows) and dynamic heights during the period 24 June–14 July 1998 (cm dyn × 10, shaded contours, right-hand scale) referred to 200 dbar (~200 m depth).



showed that when a jet impinges on a wall, it splits into two branches. The proportion of water transported by either stream depends on the angle which the jet impinges the coast and, to a lesser extent, on its potential vorticity. Laboratory experiments by Gleizon (1994) confirm these results.

The incidence angle (positive anticlockwise from normal to the shore) estimated from either Fig. 4 or Fig. 6, is –25° or –30°, approximately. For this range of angles, the proportion of re-circulated water that closes the cyclonic gyre (westward flow in Figs 5 and 6) is around 10–15% of the total volume (Gleizon, 1994). Thus, most of the flow continues along the Sicilian coast toward the east. Theoretically, there must be a 'stagnant point' where the jet impinges the shore. In practice, and taking into account the simplicity of the model analysed by Whitehead (1985), this point would be a more or less extended region near Sciacca. This region would provide suitable conditions for anchovy spawning because of its stable conditions due to the low flow velocities associated with the bifurcation of the AIS.

Other places can provide similar favourable spawning conditions, such as the region off Cape Passero. East of Cape Passero, the continental shelf drops sharply, making a geostrophically balanced jet gain positive vorticity by vortex stretching when it flows out of the shelf. Robinson *et al.* (1999) put forward this mechanism to explain the northward bending of the AIS when it flows into the deep Eastern Mediterranean Basin. Additionally, the lateral friction with the coastline that the left side of the jet encounters would augment the positive vorticity. Therefore, one expects to find a cyclonic circulation cell off Cape Passero. Our hydrological sampling was not adequate to resolve this structure, although the salinity map of Fig. 4(a) suggests such a situation. If so, this area would act as a retention area with low current velocities. A second area of low flow velocities is in the south-east end of the Gulf of Gela off Scicli, caused by the detachment of the AIS from the shore, as observed from the general circulation pattern (Fig. 1).

The two zones, off Cape Passero and off Scicli, show suitable conditions for spawning, but their relative importance is obscured by the high egg concentrations found off Sciacca. This may be due to the difference in temperature between the waters off Sciacca and the waters off Scicli and Passero. Warm offshore surface water advected by the branch of the AIS deflected towards Sciacca is accumulated in this region, increasing the temperature throughout the water column. Figure 3 shows that the depth-averaged temperature is greater than 21°C off Sciacca, while it is less than 19°C in Scicli and Cape Passero. Anchovy eggs are mostly in the surface layers (Coombs *et al.*, 1997) and their development is temperature dependent; according to Lo (1985), the development time of eggs increases from 30 h at 21°C to 38 at 19°C. This prolongation of development could have an effect on egg survival since anchovy eggs are highly prone to predation (Alheit, 1987).

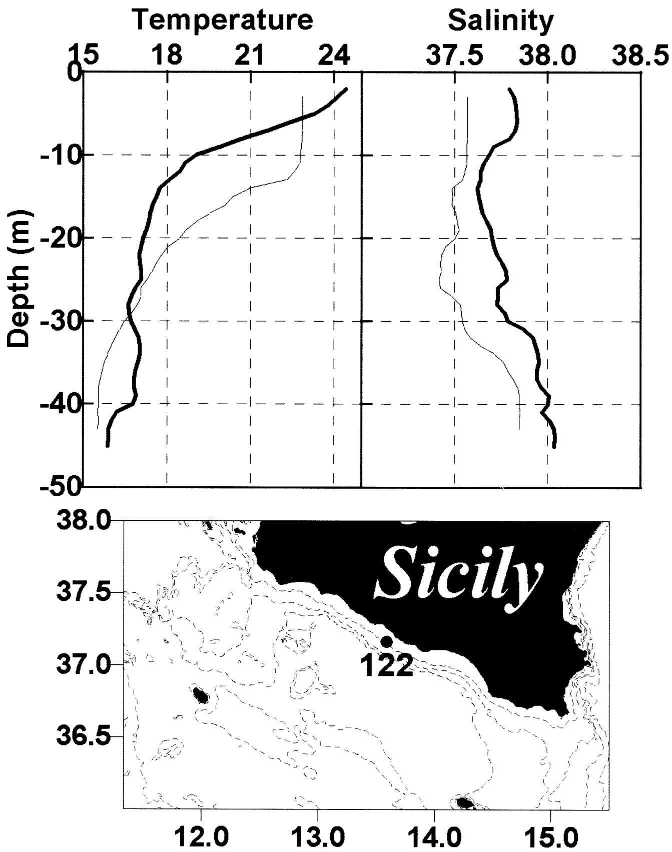


Figure 6. Vertical profiles of temperature and salinity at station 122 (see lower panel) on 2 July (thick line) and on 8 July (thin line).

Anchovy egg and larval advection

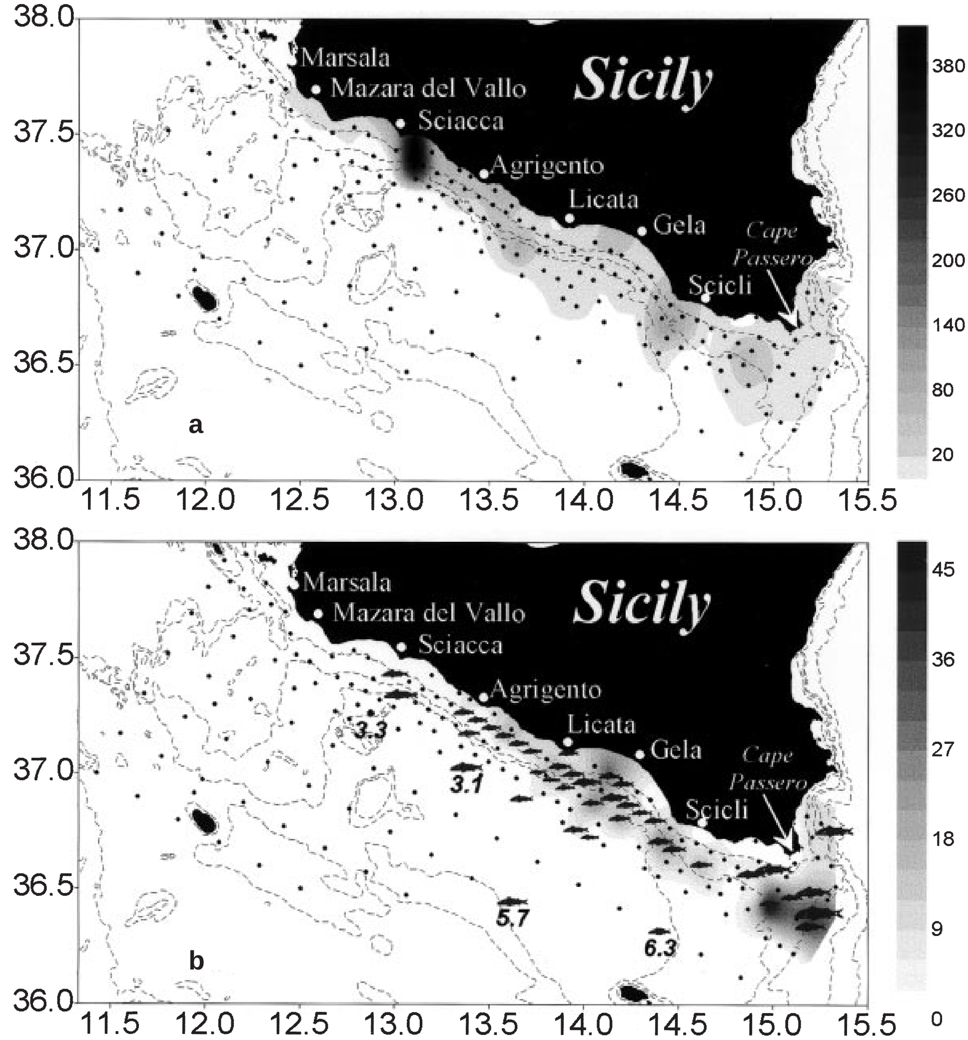
The asymmetric pattern of egg and larval distribution shown in Fig. 7(a,b) suggests along-shore transport. Taking into account the duration of egg development and the typical alongshore velocities of the AIS near the shore from Sciacca to the south-east (approximately 25 cm s^{-1} or 22 km day^{-1}, see Fig. 5), the distance that the eggs can travel before hatching will not exceed 30 km. Thus, the overall pattern of egg distribution cannot be explained solely by egg transport from the main spawning ground off Sciacca. The egg distribution at different development stages indicated that other spawning nuclei were located over the surveyed area. While temperature appears to be the key factor to explain the dominance of the Sciacca spawning area compared with Cape Passero or the Gulf of Gela areas, it does not account for the heterogeneous egg distribution from Sciacca to Liccata, since temperature is nearly homogenous over this entire area. The difference in anchovy egg abundance between Sciacca and Liccata may be due to the low flow velocities observed off Sciacca caused by the impingement of the AIS jet on the coast.

The larval distribution shows the role played by advection. Larval abundance and larval size increase towards the south-east (Fig. 7b). Cape Passero not only registers the maximum larval densities but also larger individuals. On the other hand, the local unbalanced ratio of anchovy eggs vs. anchovy larvae in this zone indicates that the larvae had not hatched here, but were advected from elsewhere.

With a typical velocity of the AIS of 22 km day^{-1}, estimated above, any planktonic organism placed 220 km upstream of Cape Passero could reach this site in 10 days. Since Sciacca is about 200 km upstream of Cape Passero, a larva hatched from an egg spawned near the main spawning grounds off Sciacca and subject to AIS advection will be at an age of around 9 or 10 days when it arrives at Cape Passero.

The size range of anchovy larvae specifically sampled for daily growth off Cape Passero was from 6.7 to 20.4 mm SL, with a mean size of 11.5 mm (SD = 3.07 mm). The Sicilian anchovy followed a daily growth pattern that fitted a power function (Mazzola *et al.*, 1999). Based on this, the estimated daily growth rate for an 8-mm larva is 0.62 mm day^{-1}

Figure 7. (a) Anchovy egg distribution during the period 24 June–14 July 1998 (egg m^{-2}). (b) Anchovy larvae distribution during the period 24 June–14 July 1998 (larvae m^{-2}). Fish symbols are proportional to the average size of larvae at each station. Numbers below selected offshore stations are the concentration of larvae (larvae m^{-2}) at isolated stations not included in the shaded contours.

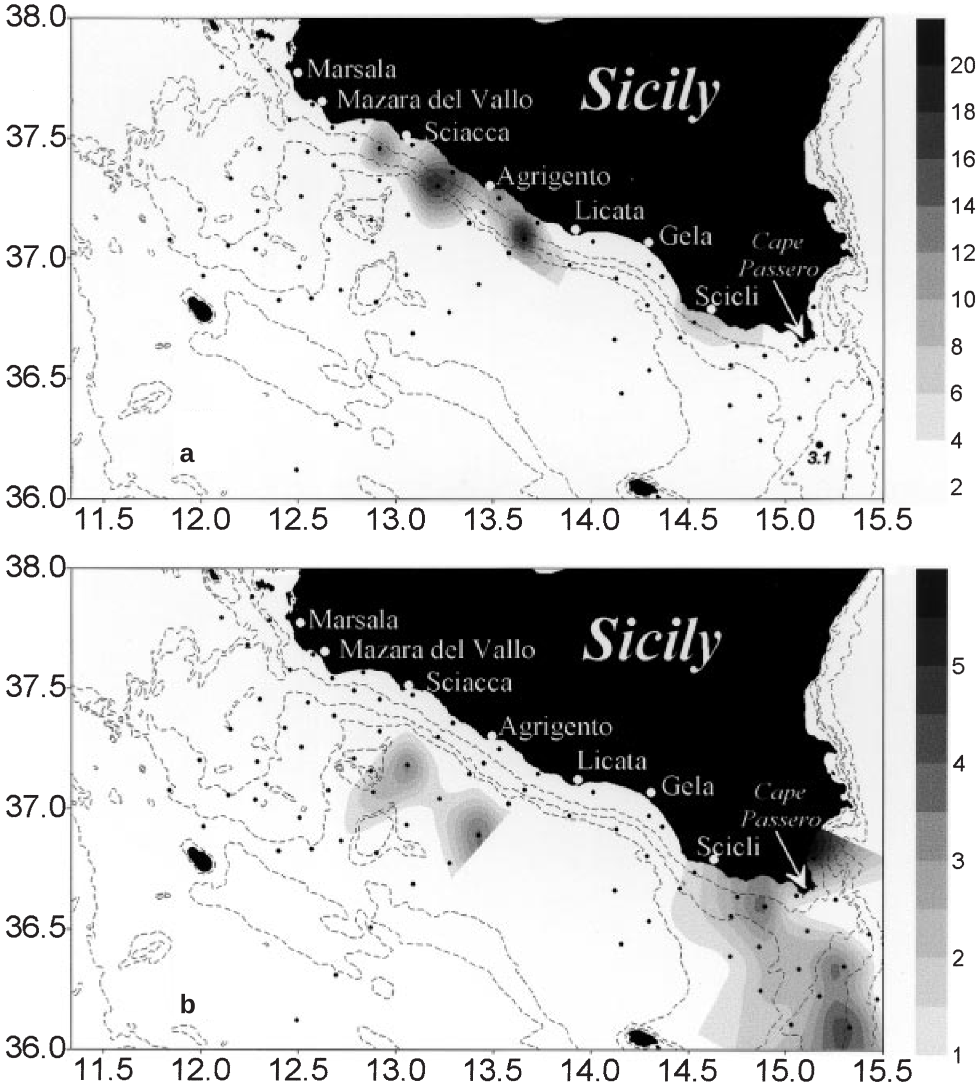


and its estimated age is 9.9 days, while for an 11-mm larva, its estimated daily growth rate is 0.71 mm day^{-1} and its estimated age is 14.3 days, a time span which is consistent with the estimated duration of advection from Sciacca to Cape Passero.

Along the AIS trajectory, a density front is present to the left of the current, facing downstream. Geostrophic adjustment forces the isopycnal surfaces to rise up to the left of the AIS and to sink to its right. The presence of this front is manifested in the temperature and salinity maps of Figs 4 and 5(a). The shoreward sloping of isopycnals allows deeper waters of high salinity to mix with the surface layer. This is evidenced by the salinity distribution at the density surface of $\sigma_t = 27$ kg m^{-3}. Salinity at this density surface is significantly higher near the shore, where it is closer to the sea surface, than in any other area. Consequently, temperature at this density surface is lower to compensate the high salinity, favouring the formation of a cold sea surface signature running along-shore such as the one reported by Piccioni *et al.* (1988).

Other dissolved or suspended substances, nutrients in particular, would undergo the same process of isopycnal transport described for the salinity distribution, favouring photosynthesis and chlorophyll generation and therefore the existence of high fluorescence values. Figure 9 shows high values of fluorescence on the shoreward side of the AIS, which would be

Figure 8. (a) Anchovy egg distribution during the period 19 July–8 August 1997 (egg m^{-2}) and (b) anchovy larvae distribution (larvae m^{-2}) during the period 19 July–8 August 1997.



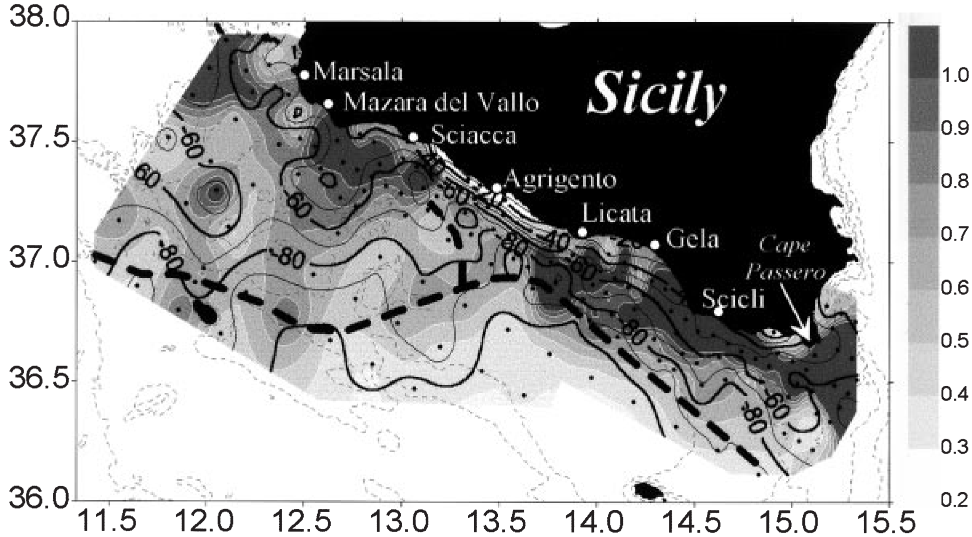
indicative of coastal water fertilization and availability of feeding resources for the larval stages of the anchovy.

Intuitively, the intensity of the front would depend on the proximity of the AIS to the coast being more intense the closer it is to the coast. Near-shore surface circulation may change in time periods as short as a week which will influence the transport of the biological material. A northward drift of the AIS such as the one hypothesized for the interpretation of Fig. 6, displaces warmer waters from offshore towards the coast, enhancing the intensity of the front and the velocity of the AIS. Moreover, it favours the trapping of biological components in the coastal areas. A more standard circulation pattern, as sketched in Fig. 1, would facilitate offshore transport, with more likely negative effects on the survival of anchovy larvae.

Is the zone off Cape Passero a retention area?

The higher larval concentration off Cape Passero raises the question of whether there are physical reasons for defining it as a retention area. The general surface circulation of the AIS generates advection of positive vorticity which results in the formation of a cyclonic vortex (Robinson *et al.*, 1999). The maintenance of this vortex implies the existence of upwelling at its centre to counterbalance friction effects. Thus, the area of Cape Passero is suitable for sustaining high rates of primary production, as confirmed by the high fluorescence values observed (Fig. 9). This

Figure 9. Depth of the maximum of fluorescence (meters, labelled contours) and numerical value of this maximum during the period 24 June–14 July 1998 (relative units, shaded contours, right-hand scale). The dashed thick line is the path of the AIS as shown in Figure 4.



type of circulation allows the larvae to maintain their relative position in an area with enhanced primary production, which provides favourable conditions for larval feeding and growth. The results from the survey carried out during the period of anchovy recruitment (October 1999) supports this hypothesis. The size frequency distribution of the pelagic trawls in the surveyed area shows that the major proportion of the juvenile fraction (sizes below 8 cm), the young-of-the-year, was located mainly in the area off Cape Passero (Fig. 10).

SUMMARY AND CONCLUSIONS

There is a clear influence of the circulation pattern of the Sicilian Channel on the distribution of anchovy eggs and larvae. The asymmetric distribution of anchovy eggs and larvae can be related to the schematic model depicted in Fig. 11. The anchovy spawning strategy is under the influence of a series of hydrographic processes. Stable warm waters formed by the bifurcation of the AIS off the north-western coasts constitute the most favourable spawning ground. The subsequent alongshore advection of the spawning products by the main branch of the AIS heading towards the south-east is the second step of the process.

The limited width of the continental shelf from Sciacca to Gela and the shoreward sloping of the isopycnals throughout this area forced by the geostrophic adjustment (i.e. the geostrophic front associated with the AIS) facilitates the pumping of nutrients from deep layers as shown by the high fluorescence found near the shore (Fig. 9). Thus, larvae are in an enriched environment while being transported downstream. Lastly, the advected larvae can take advantage of the cyclonic vortex off Cape Passero, retaining them in favourable conditions for feeding and growth because of its enhanced primary production associated with the upwelling. The retention role of the area is evidenced by the distribution of the young-of-the-year that were located mainly off Cape Passero (Fig. 10). In addition, the above strategy confers the advantage of separating spawning products from spawners, thus reducing cannibalism (Valdes-Szeinfeld and Cochrane, 1992).

A similar model, at a different spatial scale, was proposed for the anchovy population in the Southern Benguela off South Africa. In that ecosystem, the main spawning ground is at the Agulhas Bank, while the important nursery area is around 500 km further north (Hutchings, 1992; Hutchings *et al.*, 1998). Eggs and larvae are transported on the coastal side of the Benguela current in a manner similar to the AIS in the Sicilian system.

The main risks associated with such a strategy are related to mechanisms leading to offshore dispersion of the larvae. One of these is the advection of larvae by the minor branch of the AIS after it impinges the shore (see label 5 in Fig. 11). Such advection carries the larvae towards Adventure Bank, where no appropriate

Figure 10. Length-frequency (cm) of the young-of-the-year anchovy off the Sicilian coast in October 1999, grouped by trawls and areas: Sciacca spawning grounds (trawls 1–4), the mid-section of the Sicilian coast (5–9) and the Cape Passero region (10).

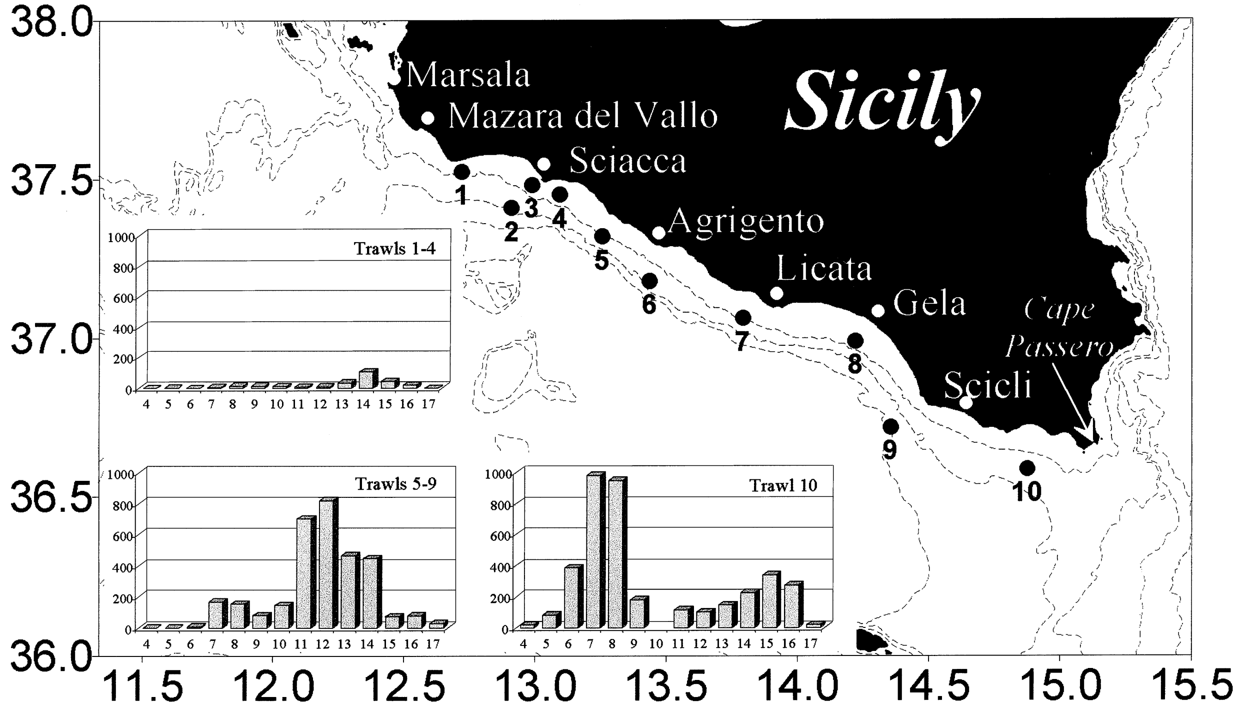
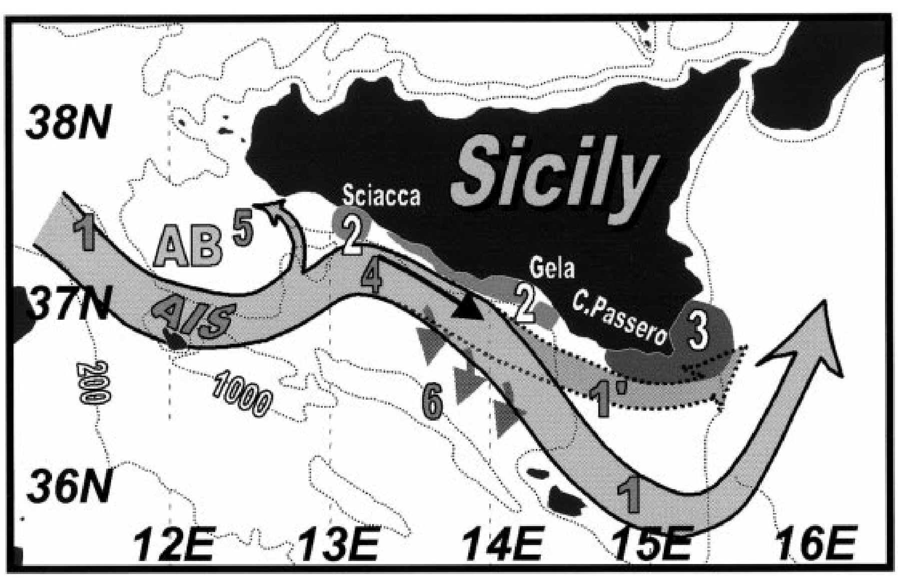


Figure 11. Schematic model of the spawning strategy of the Sicilian Channel anchovy, showing the main spawning grounds (2) off Sciacca (and Gela to a lesser extent) and the role played by the AIS (1 and 1′) in transporting the eggs and larvae (4) downstream to the nursery grounds off Cape Passero (3). Risks of offshore advection (mortality) of the spawning products either by the minor branch of the AIS after it impinges the shore (5), or by ageostrophic motion (6, see text) are also indicated.



retention mechanisms have been identified, leading to potential higher mortality. This risk may not be that important since, under the typical angles of incidence of the AIS, only a small percentage of the flow (10–15%) is deviated toward the west. Moreover, this risk can be overcome by a slight eastward shift of the spawning site, thereby reducing the probability of being advected in an adverse direction.

Another more likely possibility is the offshore transport by the major branch of the AIS. This mechanism would occur whenever this branch separates from the shore off the Gulf of Gela in the manner that Fig. 1 or path 1 in Fig. 11 suggests. The anticyclonic meandering of the AIS has associated ageostrophic cross-stream circulation, which follows a clockwise sense of rotation looking downstream (Bower and Rossby, 1989). This ageostrophic motion can transport larvae across the jet and disperse them to the open ocean. It is possible that larvae found far from the shore in the isolated stations off the Gulf of Gela (Fig. 7b) have undergone such advection. Note that a northward drifting of the AIS, such as that commented on previously, would suppress the anticyclonic meander labelled 1 in Fig. 11, making the AIS flow along path 1′, which cancels the ageostrophic motion and reduces or eliminates the risk. Thus, short-term variability may have an influence on the yearly recruitment of the Sicilian Channel anchovy.

Unfavourable strong winds may also influence the survival of the eggs and larvae of anchovy. For example, northerly winds would contribute to advective losses through offshore transport, enhancing any of the aforementioned mechanisms. Hutchings *et al.* (1998) report similar risks in the Southern Benguela system for the Cape anchovy under strong southeasterly winds.

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