

Wind forcing and fate of *Sardinella aurita* eggs and larvae

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Wind forcing and fate of *Sardinella aurita* eggs and larvae in the Sicily Channel (Mediterranean Sea)

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Abstract

Multidisciplinary studies are recently seeking to define diagnostic tools for fishery sustainability by coupling ichthyoplanktonic datasets, physical and bio-geochemical oceanographic measurements, and ocean modelling. The main goal of these efforts is the understanding of those processes that control fate and dispersion of fish larvae and eggs and thus tune the inter-annual variability of biomass of fish species. We here analyzed eggs and larvae distribution and biological features of *Sardinella aurita* in the northeast sector of the Sicily Channel (Mediterranean Sea) collected during the 2010 and 2011 summer cruises. We make use of satellite sea surface temperature, wind, and chlorophyll data to recognize the main oceanographic patterns that mark eggs and larvae transport processes and we pair these data with Lagrangian runs. To provide a physical explanation of the transport processes that we observe, we hire a potential vorticity (PV) model that takes into account the role of wind stress in generating those cold filaments responsible for the offshore delivery of eggs and larvae. Our results show that the strong offshore transport towards Malta occurring in 2010 is related to a persistent wind forcing along the southern Sicilian coast that generated an observable cold filament. Such a pattern is not found in the 2011 analysis, which indeed shows a more favorable condition for sardinella larvae recruiting with a weak offshore transport. Our results want to add some insights regarding operational oceanography for sustainable fishery.

1 Introduction

Small pelagic fishes are essential elements of marine ecosystems due to their significant biomass at intermediate levels of the food web, playing a considerable role in connecting the lower and upper trophic levels (Rice, 1995; Bakun, 1996; Cury et al., 2000).

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The link among ocean currents, transport and distribution of small pelagic fish species, atmospheric forcing, and other environmental parameters is fundamental for the sustainable management of fishery resources (Chavez et al., 2003; Pörtner and Knust, 2007). “Food” concentration and availability is often modulated by oceanographic structures that have a crucial effect on the fate of several species, especially during their larval and juvenile stages (McNamara and Houston, 1987; Cushing, 1990). Moreover, dispersion and advection of fish larvae due to ocean fronts and filaments are the main causes for the weakening of reproductive strategies. This is the case of the *Sardinella aurita* in the Sicily Channel (Mediterranean Sea) and of similar small pelagic such as the *Sardina pilchardus* and the *Engraulis encrasicolus* (Olivar and Shelton, 1993; Lloret et al., 2000). Several studies have been carried out to define the dynamics of transport of eggs and larvae and the effects on recruitments of important commercial species in the Mediterranean sea (i.e., *E. encrasicolus* (Garcia and Palomera, 1996; Agostini and Bakun, 2002; Lafuente et al., 2002; Cuttitta et al., 2003, 2006; Somarakis and Nikolioudakis, 2007; Sabates et al., 2007; Zarrad et al., 2006; Sabates et al., 2013) and *S. pilchardus* (Olivar et al., 2001, 2003; Santos et al., 2004; Alemany et al., 2006; Tugores, 2011)). Nevertheless, knowledge on spatio-temporal distribution of eggs and larvae of *Sardinella aurita*, in relation to mesoscale oceanographic and wind-forcing structures, are very limited in Mediterranean sea. In the recent years an increasing abundance and gradual northward expansion of this specie has been reported along different areas of the Mediterranean in correspondence to warming of the sea water (Sabatés et al., 2007; Tsikliras and Antonopoulou, 2006; Sinovčić et al., 2004) with possible effects of fisheries catches.

Sardinella aurita is a thermophilic pelagic fish that is widely distributed throughout the tropical and subtropical seas of the world, including the entire Mediterranean and the Black Sea (Froese and Pauly, 2003). The reproductive period in the Mediterranean stretches over the warmest period of the year, from July to October (Palomera and Sabates, 1990; Somarakis et al., 2002; Tsikliras and Antonopoulou, 2006; Palomera et al., 2007) in accordance with its tropical origin (Ben Tuvia, 1960). Eggs and larvae

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of *Sardinella aurita* are often associated with warm coastal and enriched-chlorophyll water (Ben Tuvia, 1960; Sabates et al., 2009). Affecting the dispersal mechanism, mesoscale oceanographic structure play a key role in shaping the spatial distribution of early life stages of this small pelagic (Sabates, 2009, 2013). However, studies about spawning area and advection of eggs and larvae in relation to a hydrographic condition along coasts of the northern part of the central Mediterranean Sea, are absent.

We here aim to connect the dots between *Sardinella aurita* eggs and larvae distribution and the main oceanographic patterns that characterize central Mediterranean Sea (i.e., the Sicily Channel). The Sicily Channel is mainly characterized by a meandering surface current, the Atlantic Ionian Stream (AIS), which transports the surface waters of Atlantic origin eastwards (Lermusiaux and Robinson, 2001). The climatological pattern of the AIS encircles two cyclonic vortices over the Adventure Bank and off Cape Passero, i.e., the Adventure Bank Vortex (ABV) and the Ionian Shelf Break Vortex (IBV), respectively, and it describes a pronounced anticyclonic meander in between, i.e., the Maltese Channel Crest (MCC). The most important feature for this study is, however, the role of wind (the Mistral in particular), which forms and enhances the coastal current flowing southeastward along Sicilian coast due to up-welling effects (Pratt and Whitehead, 2007; Falcini et al., 2015). This current often gives rise to the formation of cold filament that propagates offshore from the eastern Sicilian tip (i.e., Capo Passero; Fig. 1) (Bignami et al., 2008; Falcini et al., 2015).

Palatella et al. (2014) introduced a Lagrangian approach (LaCasce, 2008) as a first step towards a better understanding of the relationship between anchovy population and sea surface dynamics. This type of study is focused, in particular, on the Lagrangian connectivity (Cowen et al., 2000) between spawning and nursery areas. More specifically, the approach seeks to estimate the amount of larvae coming from a certain spawning region that are able to reach a particular nursery region.

Here we focus on Lagrangian transport of *Sardinella aurita* eggs and larvae within the Sicily Channel during the summer spawnings of 2010 and 2011. By pairing this analysis with biological and environmental data we try to depict the dynamic connection

between spawning and nursery areas and, in particular, the role of wind forcing in delivering *Sardinella aurita* larvae offshore. We finally set and confirm some hypothesis regarding the causes behind the observed and simulated patterns by giving a physical interpretation of those Lagrangian dynamics (Falcini et al., 2015).

2 Data and methods

2.1 The biological dataset

Ichthyoplanktonic data were collected during two cruises carried out from 25 June to 14 July 2010 (“Bansic 2010”) and from 8 to 27 July 2011 (“Bansic 2011”) on board the R/V *Urania*, in correspondence with the main reproductive activity of this species (Whitehead, 1985). 190 and 131 stations were sampled in Bansic 2010 and Bansic 2011, respectively (Fig. 1). Systematic sampling is constituted by a regular grid of stations ($1/10^\circ \times 1/10^\circ$ along the continental shelf, and $1/5^\circ \times 1/5^\circ$ offshore) placed along transects perpendicular to the coast. Planktonic sampling was conducted using vertical CalVET (one mouth of 25 cm inlet diameter, 150 μm mesh) and oblique Bongo 40 net (two mouth of 40 cm inlet diameter, 200 μm mesh, towed at 2 knots). The nets were hauled within 5 m from the bottom to the surface, or from 100 m to the surface ad deep station. In each mouth, calibrated flow-meters were mounted on in order to calculate the volume of filtered water (m^3). To preserve planktonic samples, borax-buffered solution of 4 % formaldehyde and seawater (for CalVET and mouth 1-Bongo 40 samples) and solution of 70 % ethanol (for mouth 2-Bongo 40 samples) were used. In land based laboratory, all samples were observed at binocular and fish eggs and larvae were sorted from the rest of the plankton. Eggs and larvae of *Sardinella aurita* were identified (Whitehead, 1988).

The number of fish eggs and larvae collected at each station was standardized to the number beneath a unit of sea surface (10 m^2) using the equation of Nonaka et al. (2000): $Y_i = \frac{(10 \times d_j \times x_i)}{v_i}$, where Y_i is the number of larvae/eggs of each species under

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Clain and Firestone, 1993). Ekman transport is then calculated as (Pickett and Paduan, 2003)

$$\mathbf{M} = (\rho_{\text{water}} f)^{-1} \boldsymbol{\tau} \times \hat{\mathbf{k}}, \quad (2)$$

where ρ_{water} is the water density, f the Coriolis parameter, and $\hat{\mathbf{k}}$ is the vertical unit vector.

2.3 The Lagrangian simulations

Modern Lagrangian modelling techniques have been developed to simulate tracer trajectories from available velocity fields, such as those provided by the Mediterranean Forecasting System (MFS) (Tonani et al., 2008). Broadly speaking, there are two main issues related to the simulation of transport and mixing of particles from an ocean circulation model: (i) the lack of resolution of meso- and submeso-scale horizontal motions and (ii) the underestimation of the vertical mixing in the upper layer. In our Lagrangian approach both instances are treated by adopting a kinematic Lagrangian modelling strategy. Deterministic chaotic flows work very efficiently at this scope, since they can generate trajectories that accurately simulate the typical small-scale turbulent motions, which in turn affect the dispersion of a given tracer distribution at early stage (Palatella et al., 2014). In order to capture such a dispersion the kinematic velocity field is composed by 2-D or 3-D time oscillating convective cells of various length sizes and with a given spatio-temporal scaling relationship (e.g. Kolmogorov's scaling). Anomalous behaviors due to the "sweeping effect", i.e., a known drawback affecting kinematic simulations of turbulence, are ruled out by adopting the quasi-Lagrangian coordinates technique (Lacorata et al., 2008).

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3 Results

3.1 Spatial distribution pattern of eggs and larvae

Ichthyoplanktonic data have revealed the main principal spawning and retention area of *Sardinella aurita* in the Italian side of the Sicily Channel (Fig. 1). The south-eastern part of the Sicilian coastal zone, off Capo Passero, has been identified as the main spawning area for this species (Fig. 1). Indeed this area exhibited the highest value of density of eggs for both years. However, we also found different spatio-temporal patterns of abundance and distribution of eggs and larvae. In 2010 the overall density of eggs and larvae was higher with respect to the 2011 (mean of 36.65 against 14.13 eggs m⁻² in survey 2010 and 2011; mean of 22.83 against 9.38 larvae m⁻² in survey 2010 and 2011). The main abundance differences between 2010 and 2011 in Malta zone (Fig. 1). Eggs and larvae were found also in the northwestern part of the study area, the Adventure bank, although in very low abundance in both years (Fig. 1).

Analysis of staging of eggs revealed a different spatial distribution of stage in the south-eastern part of the Sicily Channel. In 2010, the areas off Capo Passero was characterized by presence of all different stage in similar amounts (early stage: 36%; middle stage: 38%; late stage: 26%). Otherwise, in the region of Malta we observed a predominance of middle and late stage (early stage: 20%; middle stage: 53%; late stage: 27%). Differently, in 2011 we observed a dominance of late stage off Capo Passero (early stage: 7%; middle stage: 31%; late stage: 62%). For this year, we also recognize that *Sardinella aurita* eggs are exclusively found only off Capo Passero, with exception of one eggs of stage 6 (middle stage) on Adventure Bank, and a dominance of late stages was emerged.

Spatial distribution of the length classes of larvae (total length ranging from 2 to 12 mm) are shown in Fig. 2. In 2010 the zone off Capo Passero was characterized by a dimensional range of 3–9 mm while in the zone off Malta we observed larvae longer than 8 mm (range 2–12 mm). This indicates that *Sardinella aurita* larvae did not find the ideal dynamic conditions for a local recruiting and were likely delivered offshore. The

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2011 showed a more different pattern: off Capo Passero we observe larvae that belong to a wide dimensional range (from 2 to 11 mm) while, around Malta, we did not record any larvae.

These evidences mark a joint action of in situ spawning (early stage) and eggs/larvae advection due to mesoscale oceanographic structures. In 2010, the presence of several stages of *Sardinella aurita* eggs and a less dimensional range of larvae in the southeast coast of Sicily could be the mutual effect of:

1. coastal, upwelling induces current from northwest to southeast (Agostini and Bakun, 2002; Cuttitta et al., 2006; Falcini et al., 2015) that delivers those eggs released in the 24–48 h days before along the Sicilian coasta and mixes them with in situ spawning eggs;
2. offshore advection of larvae of dimension higher than 8 mm due to the resulting cold filament that generates off Capo Passero due to the wind forcing.

Conversely, results about distribution of stages of development of eggs and larvae can be explained by the lack of durable oceanographic structure able to remove early life stages of *Sardinella aurita* from the spawning area (i.e., off Capo Passero).

3.2 Results from Lagrangian simulations

The hypothesis of a more intense offshore transport of *Sardinella aurita* occurred from the recruiting area of Capo Passero during the summer 2010 with respect to the 2011 is here explored by means of Lagrangian runs (see Fig. 3 and in the Supplement). These simulations confirm the presence of a narrow filament that dynamically connect the spawning/recruiting area off Capo Passero with Malta. During the middle of June 2010 we notice a strong southward advection of particles that are thus delivered to Malta in a few days (i.e., ~ 50 km in 5 days that corresponds to a surface current of ~ 10 cm s⁻¹). In particular, we observe two events with this intensity: one around the 10 June and the second at between the 30 June and the 8 July. The 2011 shows a similar pattern,

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although the southward advection is much weaker with respect to the 2010 case. The comparison between these two scenarios is further stressed by the Eulerian velocity fields, averaged through the two oceanographic surveys (Fig. 4). The 2011 shows a much weaker velocity field – and the absence of the cold filament – that did not deliver larvae offshore.

3.3 Results from the satellite datasets

SST and Chl concentration satellite patterns confirm the hypothesis of two different oceanographic conditions in the two study years (Fig. 5). In the 2010 the Sicily Channel was characterized by a colder surface water and a higher Chl concentration (mean SST = 23.59 °C; mean Chl = 0.044 $\mu\text{g L}^{-1}$) with compared to the 2011 (mean SST = 25.08; mean Chl = 0.042 $\mu\text{g L}^{-1}$). In particular, in 2010 maps evidenced a cold and Chl-rich structure that protrudes offshore from the Capo Passero (Fig. 6a, b). Such a structure is characterized by a SST \approx 23.20 °C and a Chl \approx 0.07 $\mu\text{g L}^{-1}$, and traces a curved path (i.e., a filament). The 2011 does not show a similar pattern.

In seeking to understand the role of upwelling in the formation of such a cold, Chl-rich filament we find a comforting agreement from wind stress and Ekman transport maps (Supplement). Between the 30 June and 8 July 2010 a significant Ekman transport likely induced the formation of an upwelling induced coastal current (Fig. 6). Although the 2011 is also characterized by strong wind events, it does not record the same persistency that we observe in the 2010, where the Mistral wind steadily blown for 8 days (see in the Supplement).

4 The surface cold filament model

Based on our results we reasonably hypothesize that the particularly strong Mistral wind pattern, and thus the offshore Ekman transport, occurred during the summer spawning in 2010, triggered the southward transport of *Sardinella aurita* larvae and

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eggs along the Capo Passero and chlorophyll reach filament. To diagnose this pattern and to provide a mechanistic explanation regarding the link between the wind field and the onset of the cross-shore transport we hire the surface cold filament model (Bignami et al., 2008). Wind forcing can directly produces shelf-blocked jets that are subsequently driven offshore by the general circulation (Crépon and Richez, 1982; McCreary et al., 1989; Salusti, 1998). The model describes the origin to these cold filaments and jets generated by strong input of potential vorticity (PV) into the sea due to upwelling and/or the funneling of strong, cold and short-term wind bursts that blow over a restricted, shallow area of the sea surface near the coast (Holland, 1967). This PV (Π) increase due to the wind stress (τ) is described by

$$\frac{d\Pi}{dt} = \frac{1}{\rho h} (\nabla \times \tau)_z, \quad (3)$$

where ρ is the water density, h is the cold water thickness, and the subscript z indicates the third component (i.e., the vertical one) of the curl.

Equation (1) can be integrated in order to estimate, and to compare, the amount of PV accumulated on the shelf area during the two summer spawning periods in 2010 and 2011.

$$\Pi = \frac{1}{\rho h} \int_0^t \left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right) dt \quad (4)$$

Figure 7 shows the temporal integral of the curl of wind stress in Eq. (4) and fully confirms our hypothesis. Based on the surface cold filament model the higher PV (i.e., higher $(\nabla \times \tau)_z$) we observe in the 2010 – with respect to the 2011 – mark the strong role of the wind stress in “loading” the coastal water PV. Once the high PV is set such a strong and localized input does not remain confined to the coastal zone, but propagates offshore as filaments or jets (Bignami et al., 2008).

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5 Discussions and conclusions

The dynamics of marine surface layer plays a fundamental, and for many aspects unpredictable, role as far as the life and the evolution of pelagic species are concerned. In the early stage, fish larvae move as passively advected by the currents, and their fate is strictly related to their Lagrangian pathways across the sea and to the selection rules that may strongly affect their population. A systematic study of the dynamical evolution of marine species can only be assessed by means of accurate modeling of velocity fields and Lagrangian transport, as well as by a deep understanding of the physical processes that rule larvae fate and dispersion.

Our work provide some insights regarding the potential of remote sensing and Lagrangian techniques to monitor and predict the abundance of small pelagic larvae in recruiting areas. Cross-shore transport phenomena remove small pelagic eggs and larvae from the main, coastal conveyor belt that would deliver them to the recruiting areas (Garcia-Lafuente et al., 2002; Falcini et al., 2015). Estimating the rate of this removal is at the base of the prediction of the subsequent biomass, especially for short living species.

Our multidisciplinary analysis, by comparing two summer spawning season in 2010 and 2011, shows that intense wind-induced phenomena lead to cross-shore transport of *Sardinella aurita* larvae from the spawning/recruiting area of Capo Passero to Malta. This is the case of 2010, where we observed from the ichthyoplanktonic dataset a large larvae concentration off Malta, also marked by a wide dimensional range. The pairing of Lagrangian runs and the analysis of environmental parameters measured from remote sensing (i.e., SST, Chl, and wind stress) confirms, for this here, the presence of a cold, chlorophyll-rich filament that delivered the larvae to Malta from the Sicilian coast.

To give a mechanistic explanation to these correlations and to provide a diagnostic tool for the understanding of the role of Mistral wind in such a dynamics we make use of a PV theory for the evolution of surface cold filaments. Our application demonstrates

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that the higher PV occurred in the 2010, with respect to the 2011, was responsible for the formation a cross-shore jet.

The expected benefits for fisheries management in strategic areas, in the Mediterranean, as well as in other ocean basins, will consist in having a major and more detailed information about preferential sources and recruitment areas, in order to better estimate and possibly regulate the amount of future biomass. We believe that our approach, paired with the use of operational oceanographic tools, can lead to very interesting and useful results for a sustainable fishery management.

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Table 1. Satellite products that are used in this work. Δt and Δx indicate temporal and spatial resolutions, respectively. SST: sea surface temperature Pathfinder V5.2 (PFV52) AVHRR data interpolated through an Optimal Interpolation algorithm (Pisano et al., 2015); Chl: sea surface chlorophyll concentration computed by applying the MedOC4 algorithm (Volpe et al., 2007) to the ESA-CCI remote sensing reflectance (Rrs) spectra (ESA-CCI Rrs results from the merging of SeaWiFS, MODIS-Aqua and MERIS sensors); Ocean Wind: Cross-Calibrated, Multi-Platform Ocean Surface Wind Velocity Product (multi-sensor, made of SeaWinds su QuikSCAT e ADEOS-II, AMSR-E, TRMM TMI, SSM/I); Sea surface geostrophic velocity: multi-mission altimeter products (Saral, Cryosat-2, Jason-1&2, T/P, Envisat, GFO, ERS-1 & 2 and even Geosat).

Parameter	Δt	Δx	Data source
SST – Pathfinder V5.2 (PFV52) AVHRR L4 data	daily	4 × 4 km	http://www.myocean.eu.org/
Chl – ESA-CCI-L4 data	daily	4 × 4 km	http://www.myocean.eu.org/
Ocean Wind	daily	25 × 25 km	http://podaac.jpl.nasa.gov

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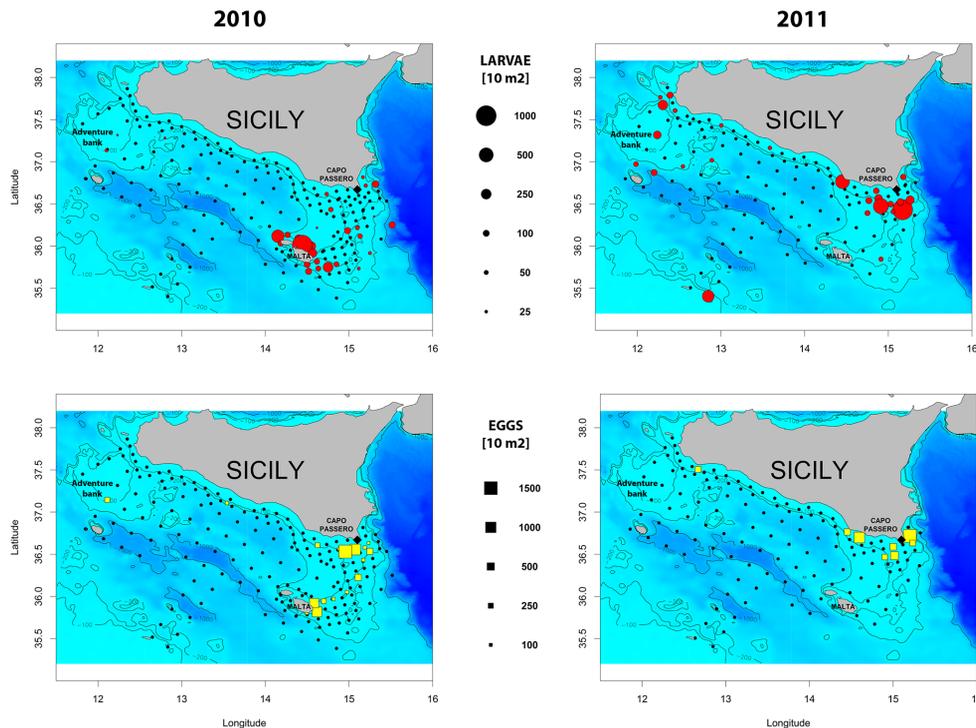


Figure 1. Map of the study area (i.e., Sicily Channel) showing the sampling stations. Bathymetry are indicated contours and by background colors, from cyan (shallower) to blue (deeper). The isobaths of 100, 200 and 1000 m are shown. Red circles and yellow squares represent larval (up) and eggs (down) density of *Sardinella aurita* during 2010 (left) and 2011 (right) surveys, respectively. The main points of interest are indicated (i.e., Adventure Bank Malta, and Capo Passero).

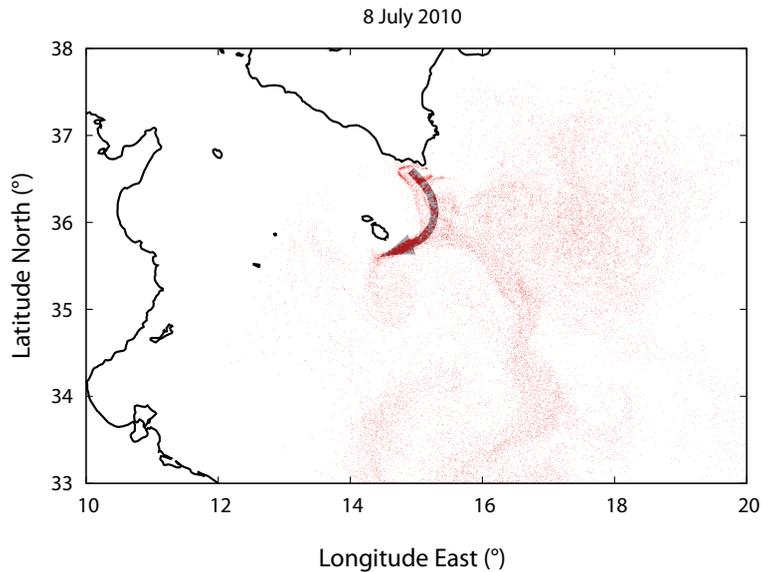


Figure 3. Lagrangian run snapshot on 8 July 2010 showing the net transport of *Sardinella Aurita* larvae (red dots) from Capo Passero to Malta that occurs along the cold filament forming off Capo Passero.

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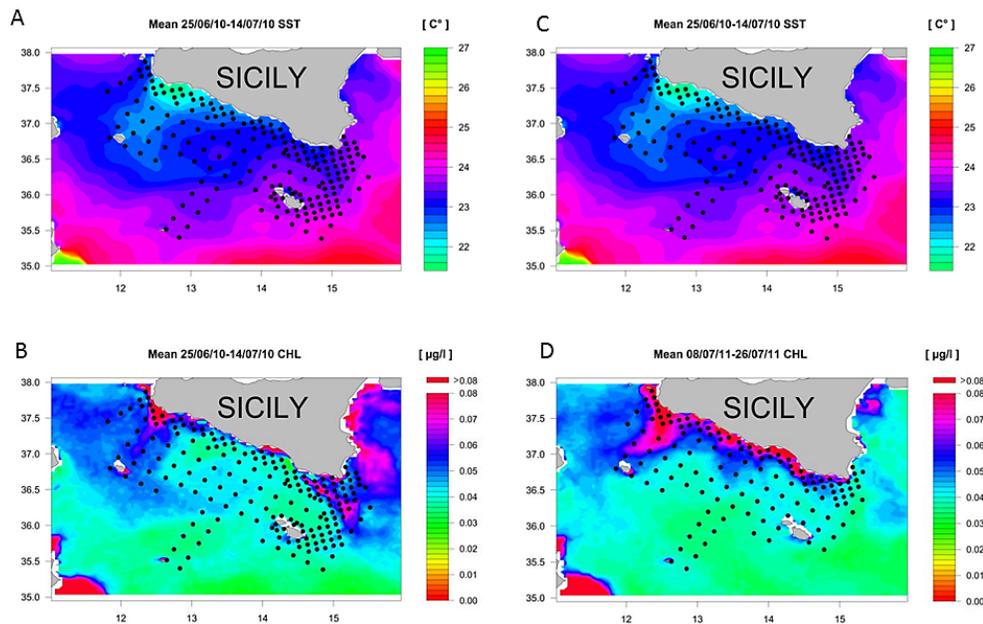


Figure 5. Cruise averaged Sea Surface Temperature (**a**, **c**) and Chlorophyll concentration (**b**, **d**) for the two Bansic 2010 and 2011 cruises.

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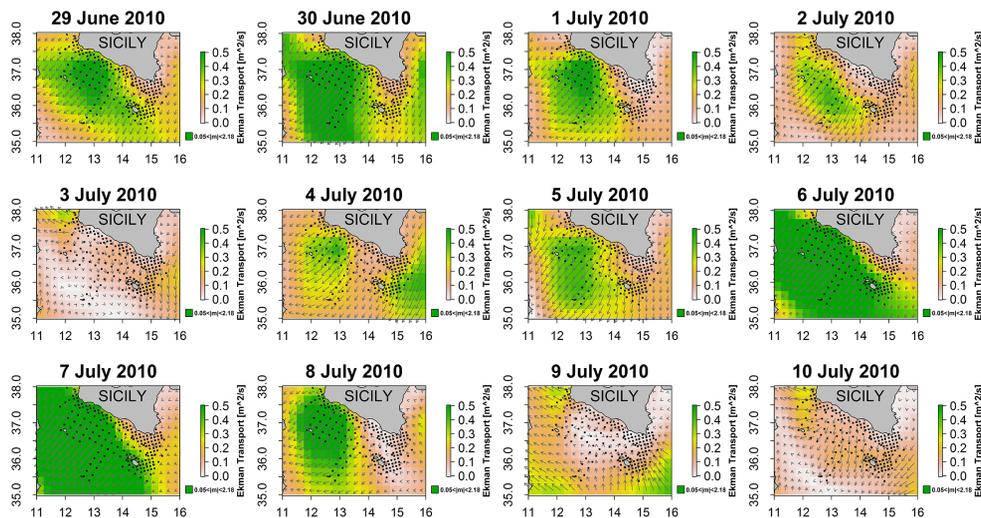


Figure 6. Daily Ekman transport during the Bansic 2010 cruise, from 29 June to 10 July.

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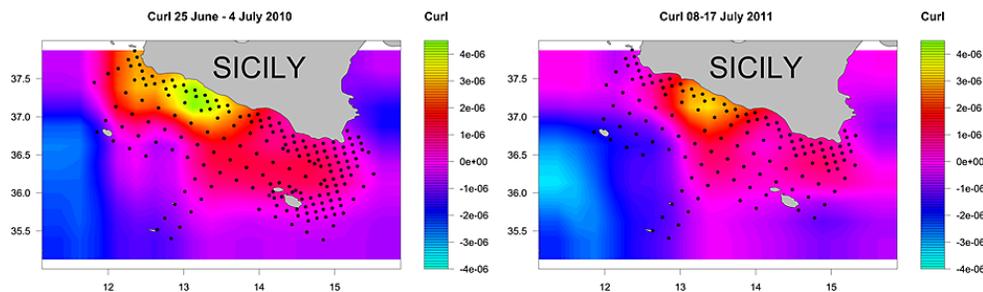


Figure 7. Integral of the curl of wind stress $\rho h \Pi$ (Ns m^{-3}) (see Eq. 4) performed throughout the Binsic 2010 (25 June–14 July) and Binsic 2011 (8–27 July) cruises showing the more intense potential vorticity increase that occurred in 2010. Such a potential vorticity input led to the formation of the cold filament.

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