



# Planktonic stages of small pelagic fishes (*Sardinella aurita* and *Engraulis encrasicolus*) in the central Mediterranean Sea: The key role of physical forcings and implications for fisheries management

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## ABSTRACT

Multidisciplinary studies are recently aiming 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 to understand those processes that control the dispersion and fate of fish larvae and eggs, and thus tuning the inter-annual variability of the biomass of small pelagic fish species. In this paper we analyse the distribution of eggs and larvae as well as the biological features of the two species of pelagic fish, *Engraulis encrasicolus* and *Sardinella aurita* in the north-eastern sector of the Sicily Channel (Mediterranean Sea) from ichthyoplanktonic data collected during the 2010 and 2011 summer cruises. We use Lagrangian simulations and satellite data (i.e., sea surface temperature, wind, and chlorophyll-a concentration) to recognize the main oceanographic patterns that mark eggs and larvae transport processes. We provide a mechanistic explanation of a cross-shore transport process by using a potential vorticity (PV) model that takes into account the role of wind stress in generating cold filaments. Our results show that the strong offshore transport towards Malta occurred in 2010 was likely due to a persistent Mistral wind forcing that generated high-PV cold filaments. This phenomenon was not found in the 2011 analysis, which indeed showed an along-shore transport towards the retention area of Capo Passero. Since, for the first time, we describe the spatial distribution of the early life stage of *Sardinella aurita* in the northern part of the Sicily Channel and we clarify the link between the ocean dynamics and the fate of small pelagic fish larvae, this work provides a useful, diagnostic tool for the sustainable management of fishery resources.

## 1. Introduction

Small pelagic fish are fundamental elements of the coastal marine ecosystem because of their role in energy transfer from primary and secondary producers to top predators of the food web (Cury et al., 2000; Bănaru et al., 2013). Constituting approximately 48% of the total reported landings, *Engraulis encrasicolus* (Linnaeus, 1758), *Sardina pilchardus* (Walbaum, 1792), *Sardinella aurita* (Valenciennes, 1847) and *Sprattus sprattus* (Linnaeus, 1758) are considered among the most important fishery resources in the Mediterranean Sea (Leonart and Maynou, 2003, FAO-GFCM, 2015). Typically, the biomass of these

species is characterized by large inter-annual fluctuations (Lloret et al., 2001, 2004, Patti et al., 2004). Assessing and understanding the root causes of this harvested fish population variability is one of the challenges for the sustainable management of fishery resources and marine ecosystems. Previous studies attributed biomass fish variations of small pelagic fish to those environmental factors that are able to change the natural mortality rate of the early life stage, affecting the recruitment of the new generation in the adult fish population as well (Cury and Roy, 1989; Bernal, 1991; Hunter and Alheit, 1995; Bakun, 1996; Patti et al., 2004). This process, paired with life history traits (i.e., short lifespan and large fecundity) (Bakun, 1996), makes the population size of small

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pelagic fish strongly dependent on the abiotic environment.

In this framework, oceanographic processes play a key role in shaping the spatial distribution of the planktonic fish stages, controlling the conveyance from the spawning areas to more or less suitable retention zones (Shelton and Hutchings, 1990; Pepin et al., 2003; Petitgas et al., 2006). In particular, “food” concentration and availability are often modulated by mesoscale oceanographic structures that have a crucial effect on the fate of several fish species during their larval and juvenile stages (McNamara and Houston, 1987; Cushing, 1990). Therefore, the understanding of the link between ocean currents, atmospheric forcing, spatial distribution of early life stages, and other environmental parameters is crucial for the sustainable management of fishery resources (Chavez et al., 2003; Pörtner and Knust, 2007).

Several studies have been attempting to define the transport dynamics that affect the recruitment of important commercial species in the Mediterranean Sea. Most of them have been carried out focusing on the most exploited species among small pelagic fishes, such as *Engraulis encrasicolus* (e.g. Garcia and Palomera, 1996; Agostini and Bakun, 2002; Lafuente et al., 2002; Cuttitta et al., 2003, 2006; Zarrad et al., 2006; Somarakis and Nikoliodakis, 2007; Sabatés et al., 2007, 2013) and *Sardina pilchardus* (e.g. Olivar et al., 2001, 2003; Santos et al., 2004; Alemany et al., 2006; Tugores, 2011). On the other hand, less has been done to take other species into account, which are characterized by a rapid change in terms of abundance and distribution. Among them, *Sardinella aurita* represents one of the most abundant coastal fish species in the summer larval fish assemblage of the Mediterranean Sea (Somarakis et al., 2002; Sabatés et al., 2006; Isari et al., 2008; Olivar et al., 2010; Zarrad et al., 2013; Cuttitta et al., 2007, 2016a, 2016b), and it is one of the most exploited fish species over the Mediterranean fishery resource, especially in the Ionian and Levant FAO division fishing areas (FAO-GFCM, 2015). Moreover, an increasing abundance and a gradual northward expansion of this thermophilic species have been reported along different areas of the Mediterranean as a consequence of global warming (Sabatés et al., 2006; Tsikliras, 2008; Sinovčić et al., 2004), with expected effects on ecosystem and fisheries. Nevertheless, knowledge of the spatio-temporal distribution of the early life stages of *Sardinella aurita*, is very poor and restricted to the north-western basin (e.g. Maynou et al., 2008; Sabatés et al., 2009, 2013). Studies investigating the spatial distribution (Zarrad et al., 2012) or the biological larval features (Cuttitta et al., 2000, 2007) of this species in the central Mediterranean Sea were performed without providing any insight into the main transport dynamics. By controlling the fate of larvae, oceanographic processes could indeed play a key role in affecting mortality rates as well as the recruitment and fluctuations of the adult population.

To fill this gap and, concurrently, to focus on the physical oceanographic structures that can affect spatial distribution of the early life stage of summer fish spawners, we correlated biological and physical patterns occurring in the north-western sector (Sicilian side) of the Strait of Sicily (Fig. 1). In particular, we focus on the two most abundant species in the summer ichthyoplankton of the Central Mediterranean Sea into account: the European anchovy (*Engraulis encrasicolus*) and the round sardinella (*Sardinella aurita*) (Zarrad et al., 2013; Cuttitta et al., 2016a, 2016b). The reproductive period of these small pelagic fishes in the Mediterranean Sea occurs during the warmest months of the year, i.e. from April to October (Palomera and Sabatés, 1990; Tsikliras and Antonopoulou, 2006; Palomera et al., 2007). The spawning peak of anchovies lasts longer than that of the round sardinella and it is related to a wider range of temperature and salinity (Palomera et al., 2007). This difference is in accordance with the tropical origin of the round sardinella (Ben-Tuvia, 1960). Both species are spawn on the continental shelf, though studies highlighted a partial spatial segregation, with round sardinella's early life stages being located in shallower water (Palomera and Sabatés, 1990; Cuttitta et al., 2017). In the northern side of the Sicily Channel, anchovy biomass of adults as well as eggs and larvae were found along the Sicilian and

Maltese continental shelf (Cuttitta et al., 2003, 2015; Patti et al., 2004; Bonanno et al., 2013; Patti et al., 2017), while no studies focusing on the spawning site of the round sardinella have been carried out in this study area.

In the Sicily Channel, wind forcing (the Mistral, in particular) forms and enhances the coastal current flowing southeastwards, along the Sicilian coast, due to up-welling effects (Pratt and Whitehead, 2007). The wind, blowing along the coastline, creates offshore Ekman transport at the sea surface; consequently, the water that is moved offshore is then replaced by deeper fluid that upwells and leads to colder surface temperatures along the coast; the resultant sloping interface implies a cross-shelf pressure gradient that triggers a geostrophic, along-shore flow (Falcini et al., 2015). However, significant wind-induced effect can be also at the base of the formation of cold filaments propagating offshore from Sicilian coasts (Bignami et al., 2008). This kind of jets is often related to instability of the upwelling front (Flament et al., 1985; Washburn and Armi, 1988; Wang et al., 1988; Strub et al., 1991; Haynes et al., 1993), particularly when a short-term wind bursts through restricted areas of the near-shore sea surface (Bignami et al., 2008).

We investigate this scenario by pursuing a Lagrangian back-trajectory analysis of both *Sardinella aurita* and *Engraulis encrasicolus* eggs and larvae that were sampled in the Sicily Channel during the 2010 and 2011 summer spawning period. By pairing this analysis with biological and environmental data, we try to depict the dynamic connection between spawning and retention areas, in the light of the role of wind forcing in delivering larvae offshore. We finally confirm our hypothesis regarding the observed and simulated patterns by giving a physical interpretation of those Lagrangian dynamics. Our study contributes to improved understanding of the spatial and temporal dynamics affecting the planktonic stage of fish, providing essential information in the framework of an ecosystem approach addressed to a sustainable management of the fishery resources.

## 2. Data and methods

### 2.1. The biological dataset

Ichthyoplanktonic data were collected during two cruises carried out for the period 25 June–14 July 2010 (Bansic 2010) and 8–27 July 2011 (Bansic 2011) on board the R/V *Urania*, in correspondence with the main reproductive activity of this species (Tsikliras and Antonopoulou, 2006). 190 and 131 stations were sampled in Bansic 10 and Bansic 11, respectively (Fig. 1). The systematic sampling is constituted by a regular grid of stations ( $1/10^\circ \times 1/10^\circ$  along the continental shelf, and  $1/5^\circ \times 1/5^\circ$  further offshore). Planktonic sampling was conducted day-night independently by using vertical CalVET (one mouth of 25 cm inlet diameter, 150  $\mu\text{m}$  mesh) and oblique Bongo 40 net (two mouths of 40 cm inlet diameter, 200  $\mu\text{m}$  mesh, towed at 2 knots). The nets were hauled from within 5 m from the bottom to the surface, or from 100 m to the surface in deep stations. In each mouth, calibrated flow-meters were mounted in order to calculate the volume of filtered water ( $\text{m}^3$ ). To preserve planktonic samples, a borax-buffered solution of 4% formaldehyde and seawater (for CalVET and mouth 1-Bongo 40 samples) and a solution of 70% ethanol (for mouth 2-Bongo 40 samples) were used. In order to identify eggs and larvae of European anchovy and round sardinella, all samples were observed under a microscope in a land-based laboratory and fish eggs and larvae were sorted from the rest of the plankton and identified according to Whitehead et al. (1988).

The number of eggs and larvae, collected at each station, was normalized as  $Y_i = \frac{10 \times d_i \times x_i}{v_i}$ , where  $Y_i$  is the number of eggs or larvae of each species under  $10 \text{ m}^2$  of sea at station  $i$ ,  $x_i$  is the number of larvae/eggs taken at station  $i$ ,  $v_i$  is the volume of water filtered in  $\text{m}^3$  and  $d_i$  is the maximum depth reached by net. Larvae were photographed using a

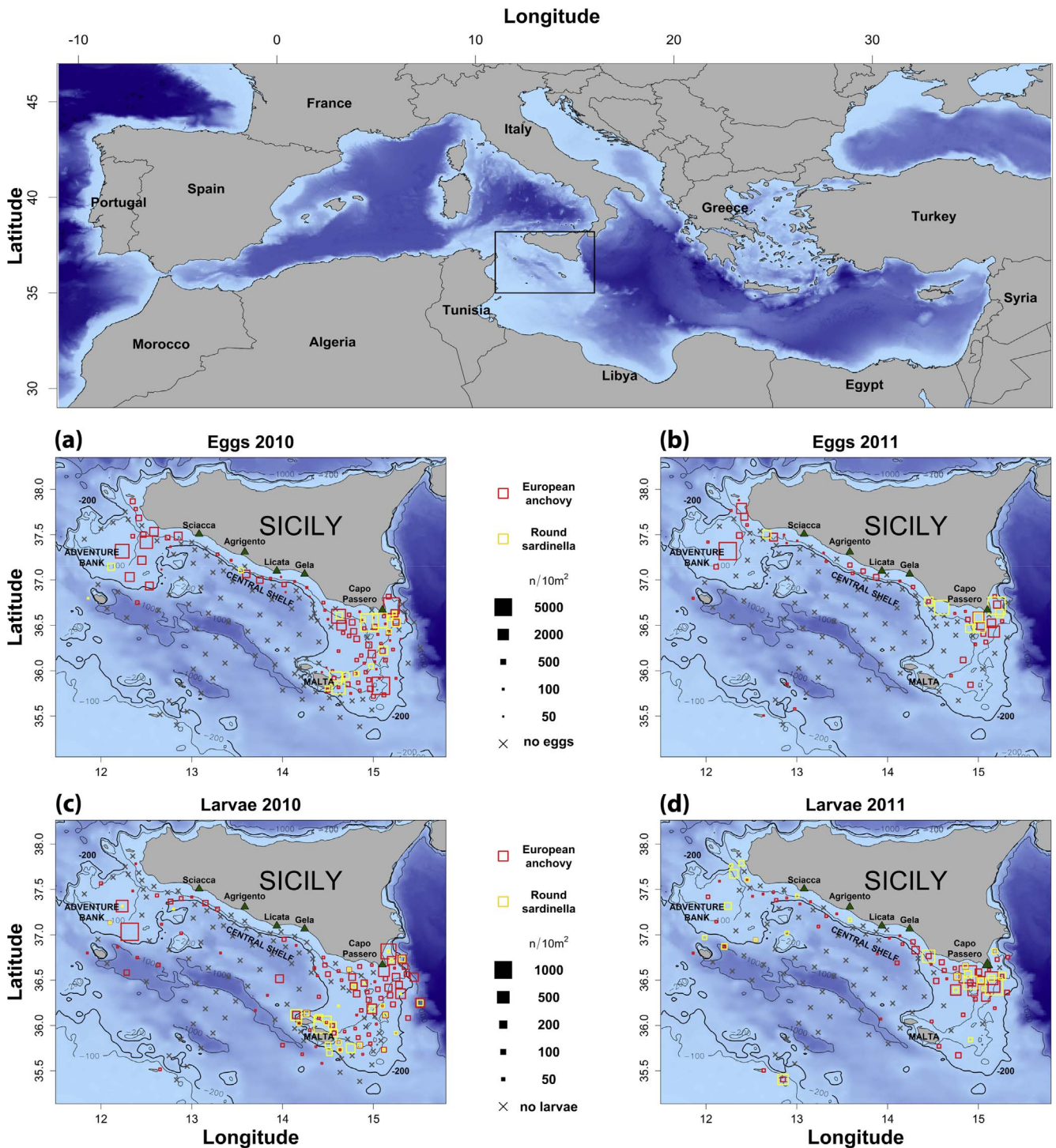


Fig. 1. Map of the Mediterranean Sea (upper panel) and the Sicily Channel (a–d) showing the sampling stations of the two Binsic surveys. Bathymetry is indicated by contours and background colors, from cyan (shallower) to blue (deeper). The isobaths of 200 m are highlighted in bold. Spatial distribution and concentration of eggs (panels a and b) and larvae (panels c and d) of European anchovy (red squares) and round sardinella (yellow squares) for both 2010 and 2011 are indicated in the map. Green triangles indicate the main toponyms cited in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

binocular stereo microscope with integrated camera and total length (TL, mm) was obtained from the analysis of image performed with suitably calibrated software (Image Pro Plus 6.0, Image Cybernetics, RoperIndustries, SilverSpring, MD, USA).

## 2.2. The remote sensing dataset

We paired the biological dataset with daily sea surface temperature

(SST) and chlorophyll-a concentration (Chl-a) data from remote sensing (Table 1), and we evaluated cruise-averaged spatial maps (for each environmental parameter). This allowed us to first recognize the main hydrographic features that occurred at sea surface of the Sicily Channel and the relations between eggs and larvae distributions and environmental parameters. Moreover, daily SST data of a period preceding two surveys (June–July 2010 and 2011) allowed us to identify cold filaments in the spawning areas that could affect the adults spawning due



**Table 1**

Satellite products that have been used in this work.  $\Delta t$  and  $\Delta x$  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-a: sea surface chlorophyll-a 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 from QuikSCAT and ADEOS-II, AMSR-E, TRMM TMI, SSM/I).

Parameter	$\Delta t$	$\Delta x$	Data source
SST – Pathfinder V5.2 (PFV52) AVHRR L4 data	Daily	4 × 4 km	<a href="http://www.myocean.eu.org">http://www.myocean.eu.org</a>
Chl – ESA-CCI-L4 data	Daily	4 × 4 km	<a href="http://www.myocean.eu.org">http://www.myocean.eu.org</a>
Ocean wind	6 h	25 × 25 km	<a href="http://podaac.jpl.nasa.gov">http://podaac.jpl.nasa.gov</a>

to the influence of water temperature (Ben-Tuvia, 1960; Palomera and Sabatés, 1990; Ettahiri et al., 2003; Tsikliras, 2008). We considered SST values recorded in the identified spawning area (14–15.5° of longitude and 35.4–37° of latitude) on the continental shelf (between 0 and 200 bottom depth meters) for each day from 1 June to 27 July 2010 and 2011, i.e. from the beginning of the spawning period (Tsikliras and Antonopoulou, 2006) to the end-day of the 2011 survey.

Moreover, we made use of wind stress ( $\vec{\tau}$ ) from remote sensing, which is derived from ocean surface 6-hourly wind data ( $\vec{U}_{wind}$ ), provided by the Cross-Calibrated Multi-Platform project (Table 1). Wind stress is obtained as:

$$\vec{\tau} = \rho_{air} C_d |\vec{U}_{wind}| \vec{U}_{wind}, \quad (1)$$

where  $\rho_{air}$  indicates the air density and  $C_d$  is the dimensionless friction coefficient, equivalent to  $C_d = 0.0012$  for  $0 < |\vec{U}_{wind}| < 11 \text{ m s}^{-1}$  and  $C_d = 0.00049$  for  $|\vec{U}_{wind}| \geq 11 \text{ m s}^{-1}$  (Large and Pond, 1981; McClain and Firestone, 1993).

### 2.3. The Lagrangian simulations

Modern Lagrangian modelling techniques have been developed recently to simulate the forward and backward-in-time evolution of passive tracers Eulerian velocity fields. Palatella et al. (2014) introduced a Lagrangian approach (LaCase, 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 Lagrangian connectivity (Cowen et al., 2000) between spawning and nursery areas. More specifically, the approach aims to estimate the amount of larvae coming from a certain spawning region that is able to reach a certain nursery region, or vice versa in the case of backward analysis. However, there are two main issues related to the simulation of transport and mixing of particles in 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, these two aspects are handled by adopting a kinematic Lagrangian modelling strategy.

Conservative chaotic flows are exploited to generate trajectories that accurately simulate (at least at a low order moment level) the typical small-scale turbulent motions affecting the dispersion of a given tracer distribution (Lacorata et al., 2008, 2014; Palatella et al., 2014). For this purpose, the kinematic velocity fields are composed by 3D time oscillating convective cells of various length and with a given spatio-temporal scaling relationship (e.g. Kolmogorov's scaling). Anomalous behaviour due to unrealistic “sweeping effect”, i.e., a known drawback affecting kinematic simulations of turbulence, is ruled out by adopting the quasi-Lagrangian coordinates technique (Lacorata et al., 2008).

Here we use the model provided by the Mediterranean Forecasting

System (MFS; Tonani et al., 2008) as Eulerian input. Its domain covers the entire Mediterranean basin; the horizontal resolution is  $1/16 \times 1/16$  degree ( $\sim 6.5 \text{ km}$ ); the model has 72 vertical layers, ranging from 1.5 m to 5000 m depth; wind forcing is provided by ECMWF data every six hours. The daily re-analysis velocity fields from the MFS model are used for the large-scale circulation while a 3D convective cell field is added to the main model in order to compensate the lack of effective mesoscale turbulent dispersion and vertical migration in the mixed layer, as discussed above. Such a pioneering approach represents a novelty, since it uses a kinematic model for mesoscale turbulent dispersion coupled with a large-scale ocean circulation model (see details on the kinematic model set up, the 3D vertical mixing model, and the 2D mesoscale turbulence model in Palatella et al., 2014; Lacorata et al., 2014).

To strengthen our analysis we also consider a second Eulerian field, i.e., the version 2.0 of the Geostrophic fields, provided by the GlobCurrent project (Chapron, 2015; Johannessen et al., 2016), which consists of L4 satellite retrieved geostrophic, daily currents at  $0.125^\circ$  space resolution.

From the two Eulerian fields and 3D kinematic additive field we then evaluate backward-in-time evolution of Lagrangian particles, starting from the position where larvae were observed (or where they were supposed to be observed). Field observations are used to generate a large number of virtual larvae with a given age distribution chosen from the larval size analysis. The age has been estimated from the total length data, taking into account the length-age relationship estimated by Mazzola et al. (2000) for European anchovy and round sardinella larvae, collected during the summer period in the same study area (European anchovy:  $TL = 2.71 + 0.3139 * \text{age}^{1.2302}$ ; round sardinella:  $TL = 1.5468 * \text{age}^{0.6917}$ ). Each trajectory's backward travel ends when its age turns to zero. This approach is fundamental to recognize the original spawning regions and to highlight the dynamical connections between spawning and recruiting areas. The boundary conditions of our simulations are open (relatively to the Sicily Channel sub-domain), with rebound conditions of the Lagrangian particles against the coasts (an accurate modelling of the circulation in the proximity of coastal boundaries is outside the capabilities of the Ocean model we used). We assumed passive neutrally buoyant particles. For the 2010, we investigated the origin of those eggs and larvae that were observed around the Maltese archipelago. With regard to 2011, in spite of the fact that very few and recently hatched larvae were found around Malta, we simulate back-trajectories as initialized from the sampling stations that were carried out in that region and we investigated the backward evolution of these “missing” particles for 10 days. This aims to demonstrate the weakness (or absence) of any advective process that would transport eggs and larvae around Malta from coastal spawning areas.

## 3. Results

### 3.1. Spatial distribution pattern of eggs and larvae

In both surveys, most of the eggs and larvae of European anchovy and round sardinella were found between the coastline and the 200 m isobaths, in agreement with the coastal habitat of the adult population (Fig. 1).

The highest eggs and larval density was found in 2010, for both species (Table 2). In both 2010 and 2011, anchovy showed higher abundance and a wider distribution of eggs and larvae in the study area, than that of round sardinella, suggesting a higher tolerance of different environmental conditions.

Anchovy eggs and larvae were widely distributed along the whole Sicilian coast (Fig. 1). In both years, the highest eggs and larval density were found over the Adventure Bank (north-west area), over the Siculo-Maltese Bank (south-west area) and, in particular, off Capo Passero. However, differences in terms of spatial patterns emerged between the

**Table 2**

Occurrence frequency (OF) and mean density  $\pm$  standard error (MD  $\pm$  SE) of European anchovy (*E. encrasicolus*) and round sardinella (*Sardinella aurita*) among stations investigated in 2010 and 2011.

	2010 (190 stations)				2011 (131 stations)			
	Eggs		Larvae		Eggs		Larvae	
	OF [%]	MD $\pm$ SE [n/10 m <sup>2</sup> ]	OF [%]	MD $\pm$ SE [n/10 m <sup>2</sup> ]	OF [%]	MD $\pm$ SE [n/10 m <sup>2</sup> ]	OF [%]	MD $\pm$ SE [n/10 m <sup>2</sup> ]
<i>Engraulis encrasicolus</i>	45.3	241.2 $\pm$ 50.6	49	54.1 $\pm$ 9.9	32.1	65.5 $\pm$ 19.2	45	47.1 $\pm$ 11.7
<i>Sardinella aurita</i>	9.5	36.7 $\pm$ 12.9	16.3	22.8 $\pm$ 7.6	6.1	14.1 $\pm$ 6	19.1	9.3 $\pm$ 2.9

two surveys in the Maltese area: high density of eggs and larvae were found in the Maltese waters in 2010 while very few were observed in 2011 (Fig. 1, Table 2).

Round sardinella was mostly concentrated in the south-eastern part of the study area, between Capo Passero and Malta, in both surveys (Fig. 1). For the first time in this study area, the high abundance of the planktonic stage of round sardinella in the coastal water off Capo Passero and Malta allowed to identify this zone as the most important spawning and retention area of the south Sicilian coast for this species. Conversely, a somewhat low presence of *Sardinella aurita*'s eggs and larvae was detected on the Adventure bank, e.g. in the northwestern part of the study area (Fig. 1). Similar to the anchovy distribution, in 2010 the highest density of early life stages were detected in the south-eastern area (Capo Passero and Malta), while in 2011 eggs and larvae were concentrated in the waters off Capo Passero and only one larva were recorded in the Maltese zone (Fig. 1).

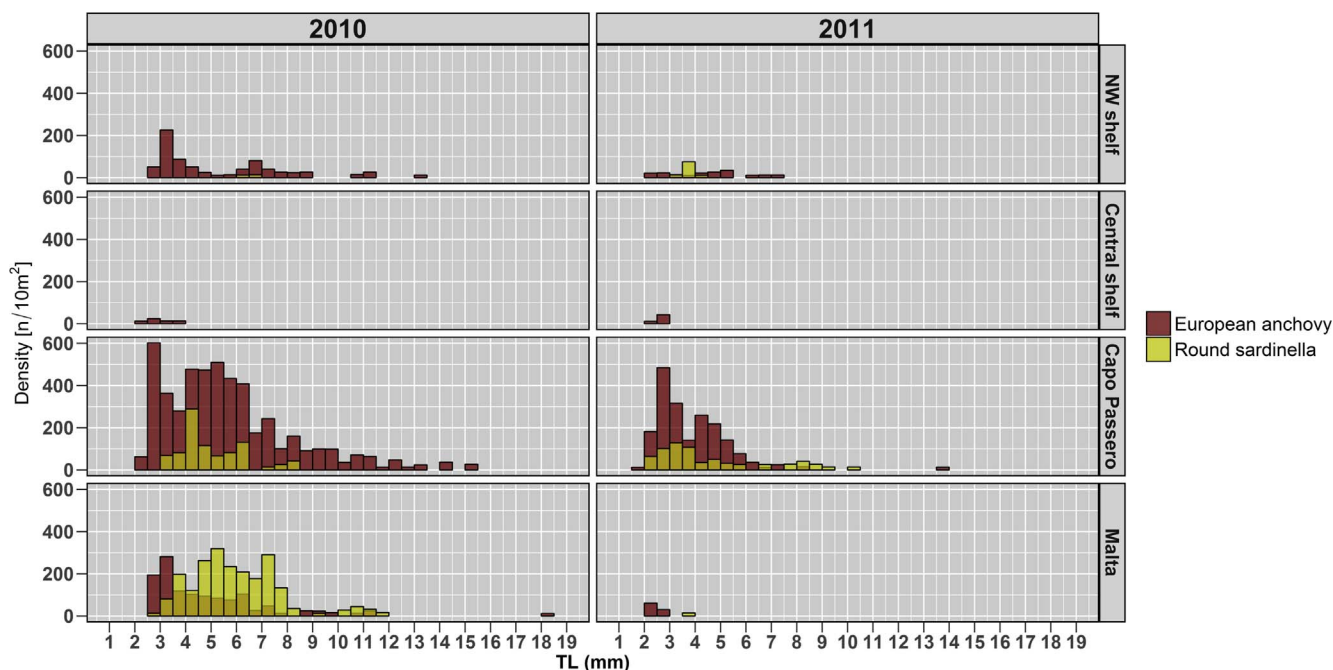
Frequency distribution of larval length allowed to characterize the size structure in the zone of the study area, where larvae of European anchovy and round sardinella were found (Fig. 2). The zone off Capo Passero gathered larvae of European anchovy and round sardinella belonging to a wide range of size in both years. However, differences in terms of the frequency of size classes existed among species. In this zone, anchovy larvae showed the widest size range in both years, though a broad range of classes were also found in Malta (in 2010) and in the NW sector of the Strait, over the Adventure Bank (in both years). Conversely, round sardinella showed the widest range in Malta waters

(2.5–12 mm of TL) in 2010 and in Capo Passero area (2–10.5 mm of TL) in 2011. On the continental shelf located in the middle of the study area (Central shelf in the Fig. 2), only few and small larvae of anchovy (2–4 mm of TL) were found in both years. Differences between 2010 and 2011 in terms of eggs and larvae distribution and densities led to some hypotheses with regard to the joint action between *in situ* spawning and eggs/larvae advection due to mesoscale, coastal oceanographic structures.

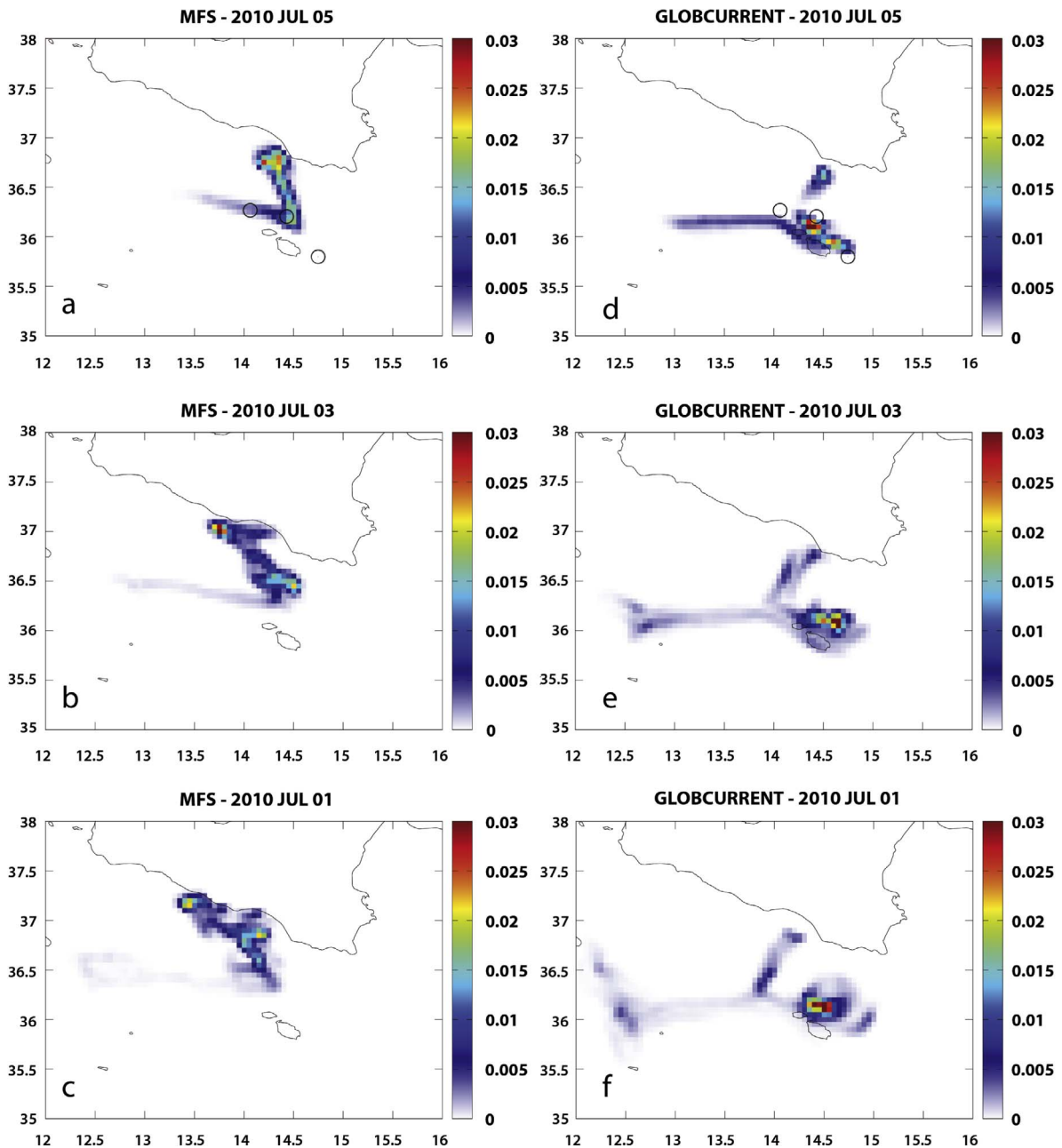
### 3.2. Results from Lagrangian simulations

The advection dynamics of *Sardinella aurita* and *Engraulis encrasicolus* eggs and larvae occurred during the 2010 and 2011 summers is here explored by means of a Lagrangian analysis (Figs. 3 and 4; Supplementary movies S1–S4).

The Lagrangian simulations (backward-in-time) confirm the presence of a narrow, intense filament that, in 2010 only, dynamically connected the spawning areas along the Sicilian coast (in particular, east of the Gulf of Gela) with Malta (Fig. 3). Backward motion of the Lagrangian particles reveals a preferential, fast path that brings back eggs and larvae from the northern sector of Malta's coasts (sampled on 7 July 2010) to the Gulf of Gela and then off Agrigento in about 5 days (corresponding to a surface current of  $\sim 10$  cm/s) (Fig. 3; Supplementary movie S1). Even though very few eggs and larvae were collected around Malta in 2011 we performed a similar analysis, investigating the backward-in-time motion of virtual Lagrangian particles



**Fig. 2.** Frequency distribution (n/10 m<sup>2</sup>) of total lengths (TLs) of *Engraulis encrasicolus* (red) and *Sardinella aurita* (yellow) larvae collected in the different zones of the Sicily channel; NW shelf (Adventure Bank, AB), Central Shelf, Capo Passero, and Malta during the two Binsic 2010 and 2011 cruises. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 3.** Snapshots of the 2010 Lagrangian analysis, showing the backward evolution of particle concentration, normalized by the number of the total particles that were released into the source areas (probability density in the colour bar), for both MFS (from panel a to c) and GlobCurrent (from panel d to f). Circles in panels (a) and (d) represent the source areas where Lagrangian particles were released, on 7 July 2010, according to the sampling dataset of the Bansic 2010. Spatial distribution of particle concentration in the MSF case (panels a to c) clearly shows the net transport of eggs and larvae from Malta to the spawning area of the Gulf of Gela and off Agrigento. Such a pattern is slightly confirmed by the GlobCurrent case.

that were expected to be found during the Bansic 2011 sampling (i.e., 22 July 2011). For this case, the backward motion does not show any strong advective process and particles tend to remain in the Maltese area, slightly approaching the Sicilian coast after 10 days (Fig. 4; Supplementary movie S2). Forward Lagrangian analysis confirms both the results we obtained for both 2010 and 2011. By assuming a source area off the Gulf of Gela, the result obtained in 2010 shows a strong preferential path (i.e., a filament) connecting this area with Malta, while in 2011 particles are dispersed all around the source area (see Supplementary movies S3 and S4). We therefore hypothesize that the

2011 spawning season was not characterized by a cross-shore transport phenomenon that might significantly affect larvae's fate and distribution. The difference between the 2010 and 2011 spawning seasons is further stressed by two distinct Eulerian velocity fields, i.e., the MFS fields (Tonani et al., 2008) and the GlobCurrent fields (Chapron, 2015; Johannessen et al., 2016), averaged through the two oceanographic surveys (Fig. 5). 2011 shows a much weaker velocity field – and the absence of the cold filament – that did not deliver larvae from Capo Passero to offshore.

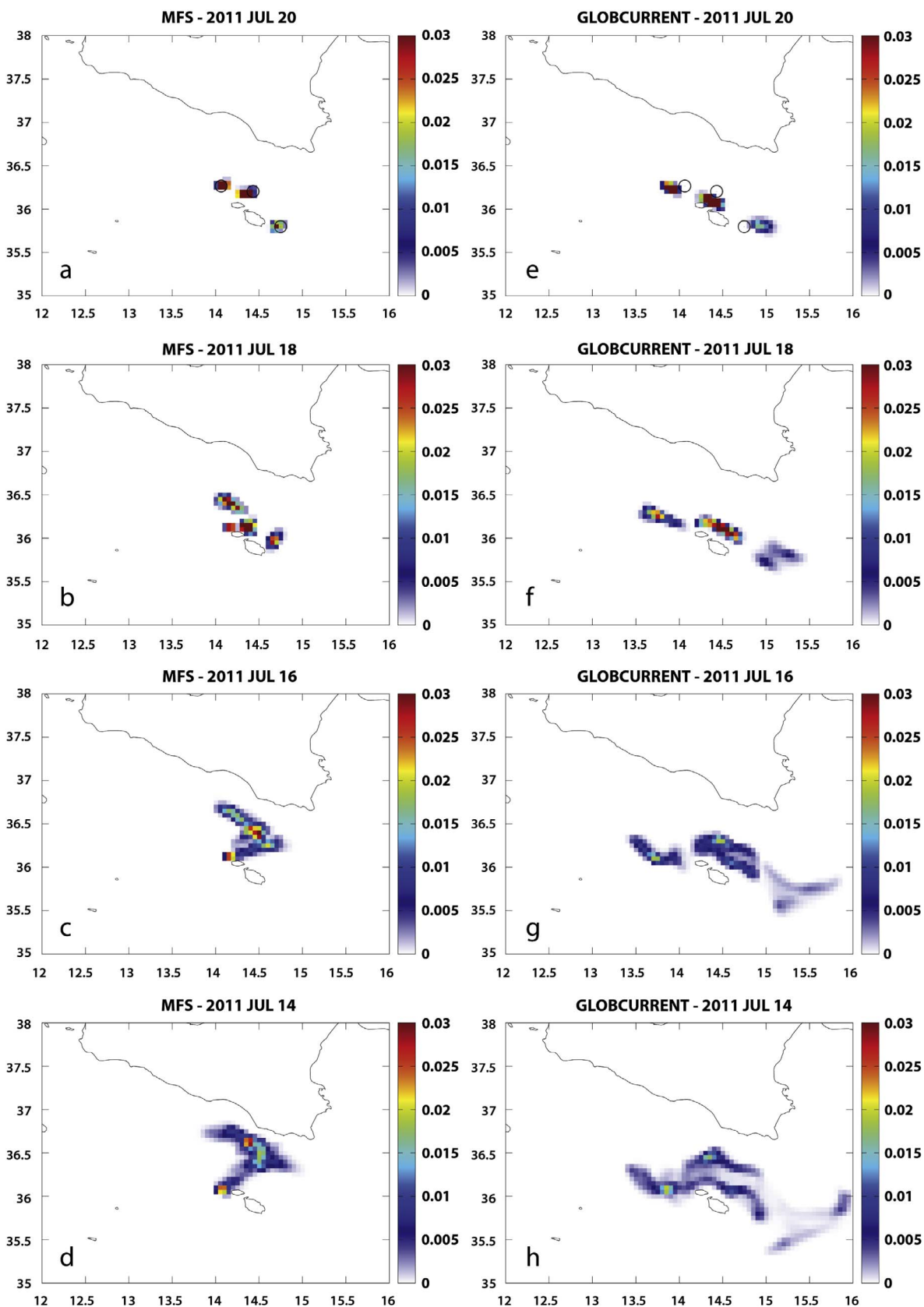
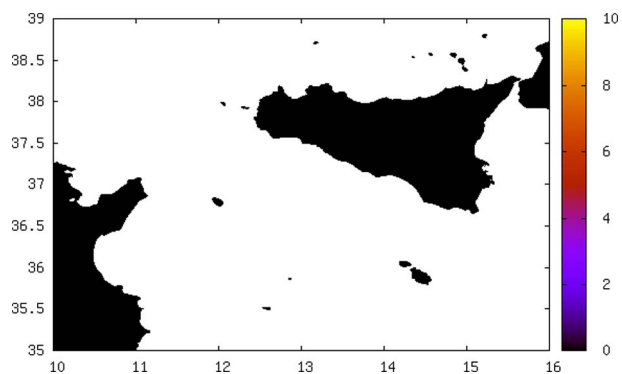


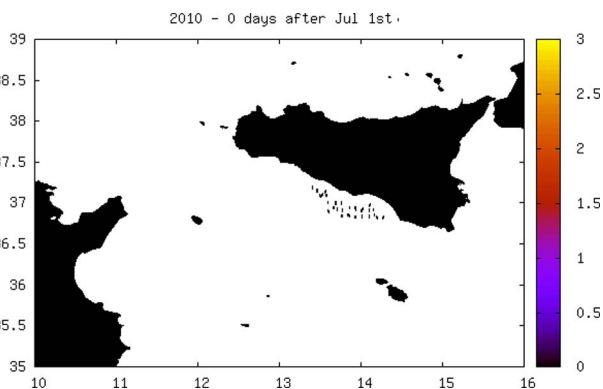
Fig. 4. Snapshots of the 2011 Lagrangian analysis, showing the backward evolution of particle concentration, normalized by the number of the total particles that were released into the source areas (probability density in the colour bar), for both MFS (from panel a to d) and GlobCurrent (from panel e to h). Circles in panels (a) and (e) represent the source areas where Lagrangian particles were released, on 22 July 2011, according to the sampling dataset of the Binsic 2011. Spatial distribution of particle concentration in both MSF and GlobCurrent cases (panels a to d and panels e to h, respectively) clearly shows a very weak transport of eggs and larvae, which tends to remain confined to the three sources areas.





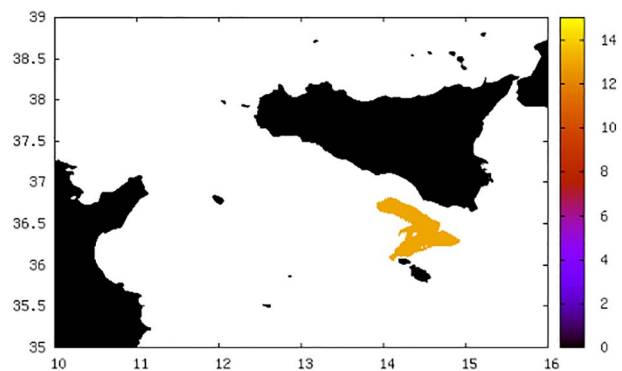
Supplementary movie S1.

2011 - 7 days before Jul 22

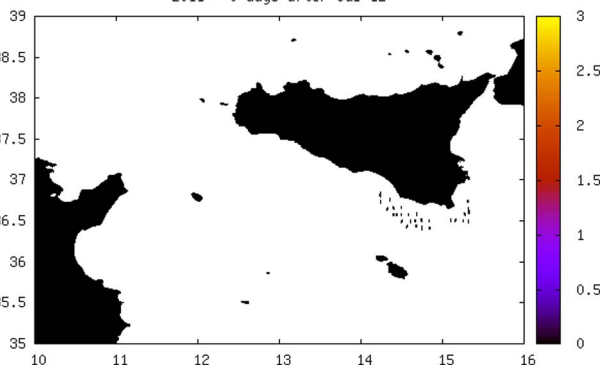


Supplementary movie S3.

2010 - 0 days after Jul 1st



Supplementary movie S2.



Supplementary movie S4.

2011 - 0 days after Jul 12

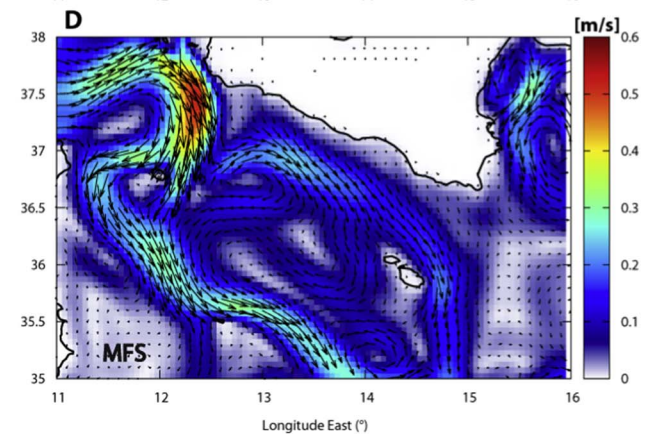
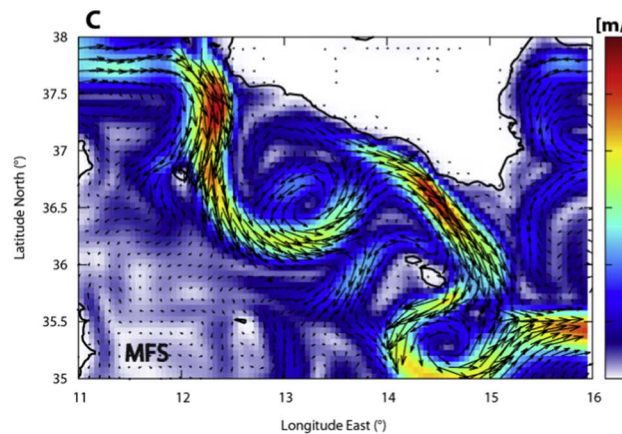
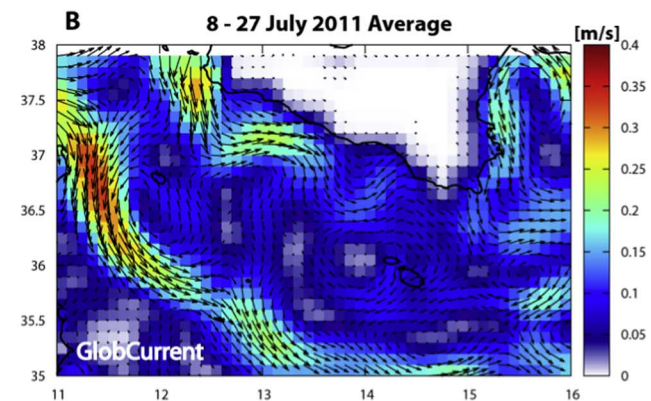
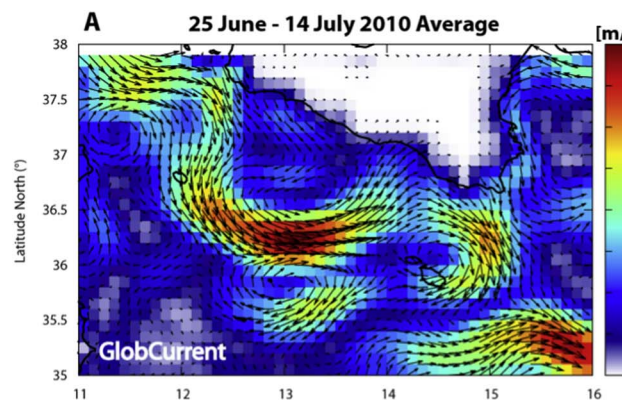


Fig. 5. Cruise averaged Eulerian velocity fields for the two Binsic cruises: 25 June to 14 July 2010 (A and C); 8 to 27 July 2011 (B and D). The two Eulerian velocity fields are from GlobCurrent (A and B) and MFS (C and D). Although the two fields show some differences, both of them confirm a strong advection from the south-east Sicilian coast to Malta in 2010.



### 3.3. Results from the satellite datasets

Satellite patterns of SST and Chl-a concentration support the evidence of two different oceanographic conditions in the two years of the study (Fig. 6). In 2010 the Sicily Channel was characterized by a colder surface water and a higher Chl-a concentration (mean SST = 23.59 °C; mean Chl-a = 0.044 µg/l), compared to 2011 (mean SST = 25.08 °C; mean Chl-a = 0.042 µg/l). In particular, in 2010 satellite maps show a cold and Chl-rich structure that protrudes, anti-cyclonically, offshore from the Gulf of Gela and Capo Passero (Fig. 6a, b), in accordance with the corresponding Lagrangian analysis (Fig. 3; Supplementary movies S1 and S3). This structure is characterized by the values SST ≈ 23.20 °C and Chl-a ≈ 0.07 µg/l and traces a curved path (i.e., a filament). The 2011 does not show a similar pattern (Fig. 6c, d).

We further analyzed SST and Chl-a concentration time series averaged over the spawning and retention area of Capo Passero, from 1 June to 27 July of both 2010 and 2011 (Fig. 7). The 2010 shows the presence of two cold and Chl-rich events: a weaker one, around the 13th of June and a colder, trophic-enhanced, and longer one between the 19th and 27th of June. On the contrary, no intense phenomenon was observed in 2011 (Fig. 7).

In understanding the role of wind in the formation of such a cold and Chl-rich filament, we find a comforting agreement with the wind stress patterns (Figs. 8 and 9). From the end of June to 8 July 2010, significant Mistral wind events characterized the NW sector of the Strait (i.e., over the Adventure Bank). This forcing could be reasonably at the base of the cold filament we observe from both satellite and Lagrangian analysis (Fig. 3, Fig. 5a and c, Fig. 6a and b, Fig. 7). Although 2011 was also characterized by strong wind events over the same region, it does not record the same persistency that we observed in 2010, when the Mistral wind blew steadily for 8 days (Figs. 8 and 9). The different wind pattern we observed for the two years is better investigated in the next section in a mechanistic way.

### 4. The surface cold filament model

Based on the first results, we rationally hypothesize that the particularly strong Mistral wind pattern occurred during the 2010 summer spawning triggered the southward transport of eggs and larvae from Capo Passero, along with the cold and chlorophyll-rich filament. To diagnose this pattern, and to provide a mechanistic explanation of the link between the wind field and the onset of the cross-shore transport, we use a surface cold filament model (Bignami et al., 2008). Wind forcing can directly produce 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 possibility of these cold filaments and jets to propagate offshore and maintain their coherent structure, based on their potential vorticity (PV). These jets, indeed, are generated by a strong PV input due to upwelling and/or 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 ( $\Pi$ ) increase, due to the wind stress ( $\vec{\tau}$ ), is described by

$$\frac{d\Pi}{dt} = \frac{1}{\rho h} (\nabla \times \vec{\tau})_z, \quad (2)$$

where  $\rho$  is the water density,  $h$  is the cold water thickness, and the subscript  $z$  denotes the third component (i.e., the vertical one) of the curl.

Eq. (2) 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:

$$\Pi = \frac{1}{\rho h} \int_0^t \left( \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right) dt, \quad (3)$$

Fig. 10 shows the temporal integral of the curl of wind stress in Eq. (3) and fully confirms our hypothesis. Based on the surface cold filament model, the higher PV (i.e., higher  $(\nabla \times \vec{\tau})_z$ ) we observe in 2010 –

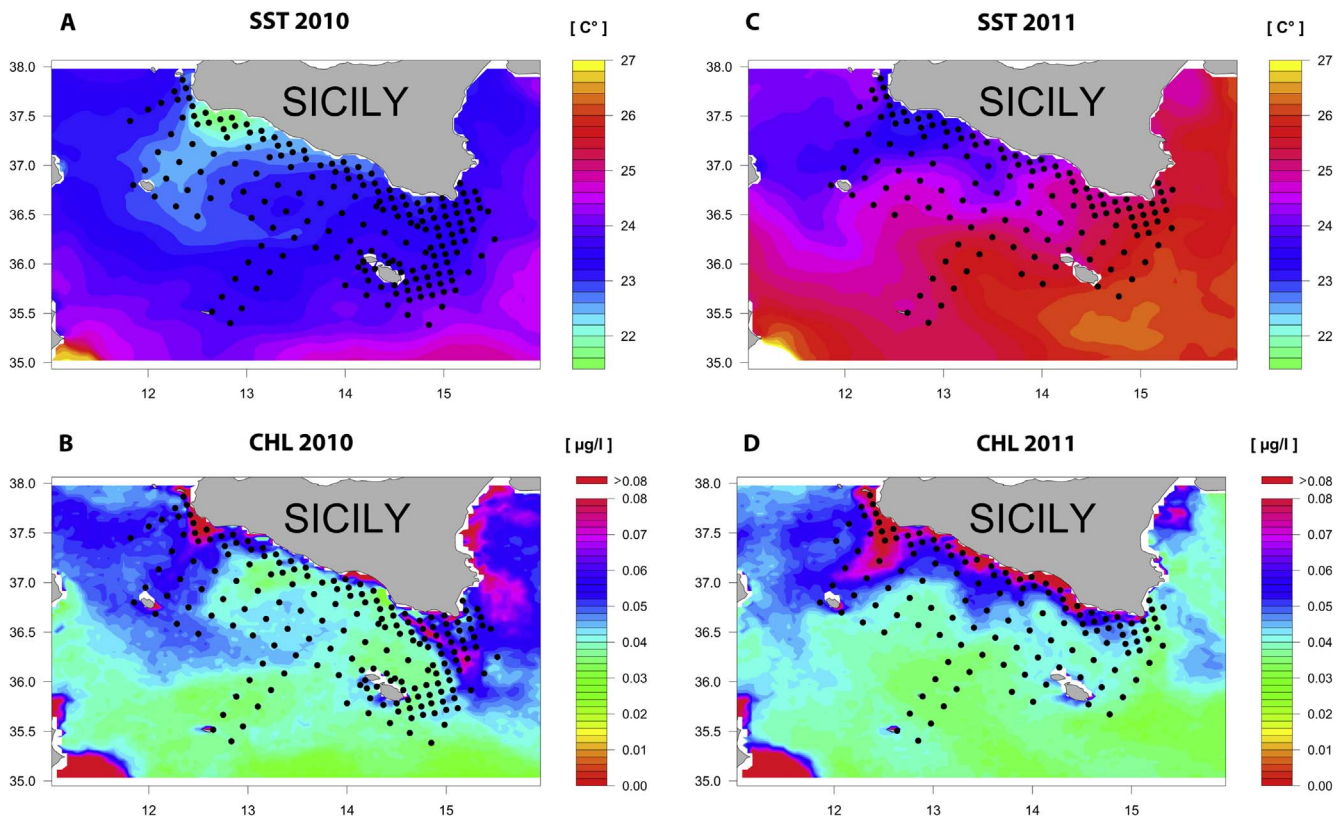


Fig. 6. Cruise averaged Sea Surface Temperature (A, C) and Chlorophyll-a concentration (B, D) for the two Bansic 2010 and 2011 cruises.

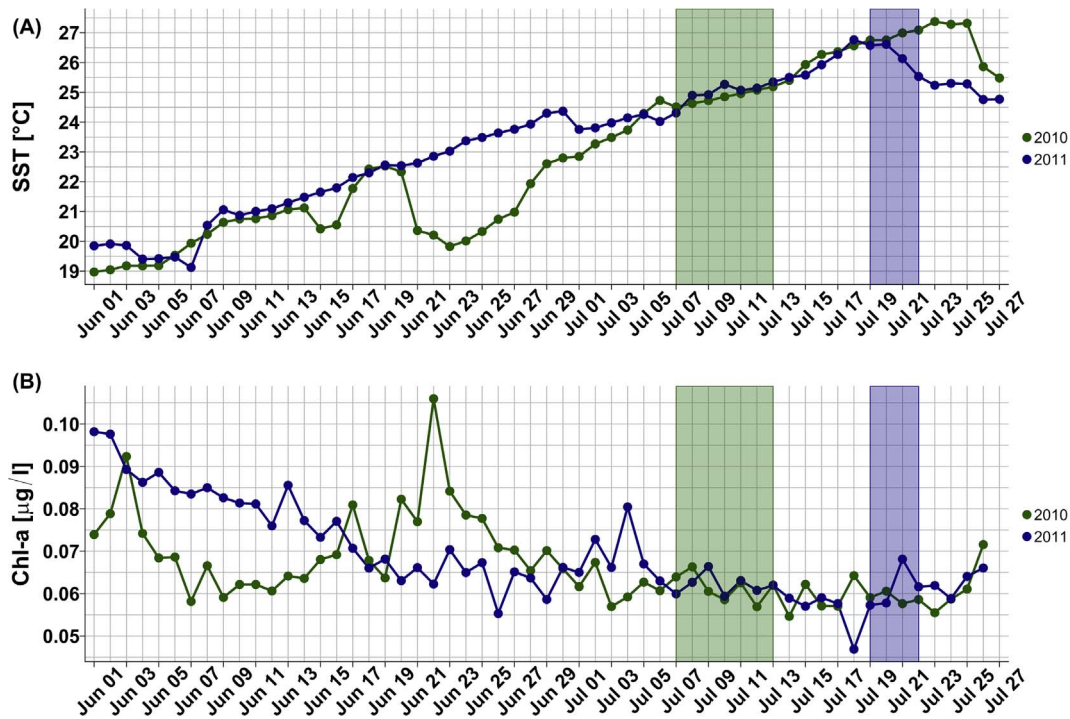


Fig. 7. Mean daily SST (A) and Chl-a (B) in the spawning and retention area (14–15.5 W; 35.4–37 N) of Capo Passero, from 1 June to 27 July 2010 (green dots) and 2011 (blue dots). Green and blue rectangles show the sampling period in the spawning area in 2010 and 2011 respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with respect to the 2011 – marks the strong role of the wind stress in “loading” PV to the coastal water. Once the high PV is set such a strong and localized input does not remain confined to the coastal zone, but propagates offshore as a filament (Bignami et al., 2008).

Therefore, we point out that the Mistral wind was particularly active in both years, thus generating a cold coastal current that efficiently transported eggs and larvae to Capo Passero from the whole Sicilian coast. However, only in 2010 there has been a high PV input off Agrigento (east of the Gulf of Gela), able to trigger the filament that delivered eggs and larvae offshore (i.e., around Malta).

## 5. Discussions

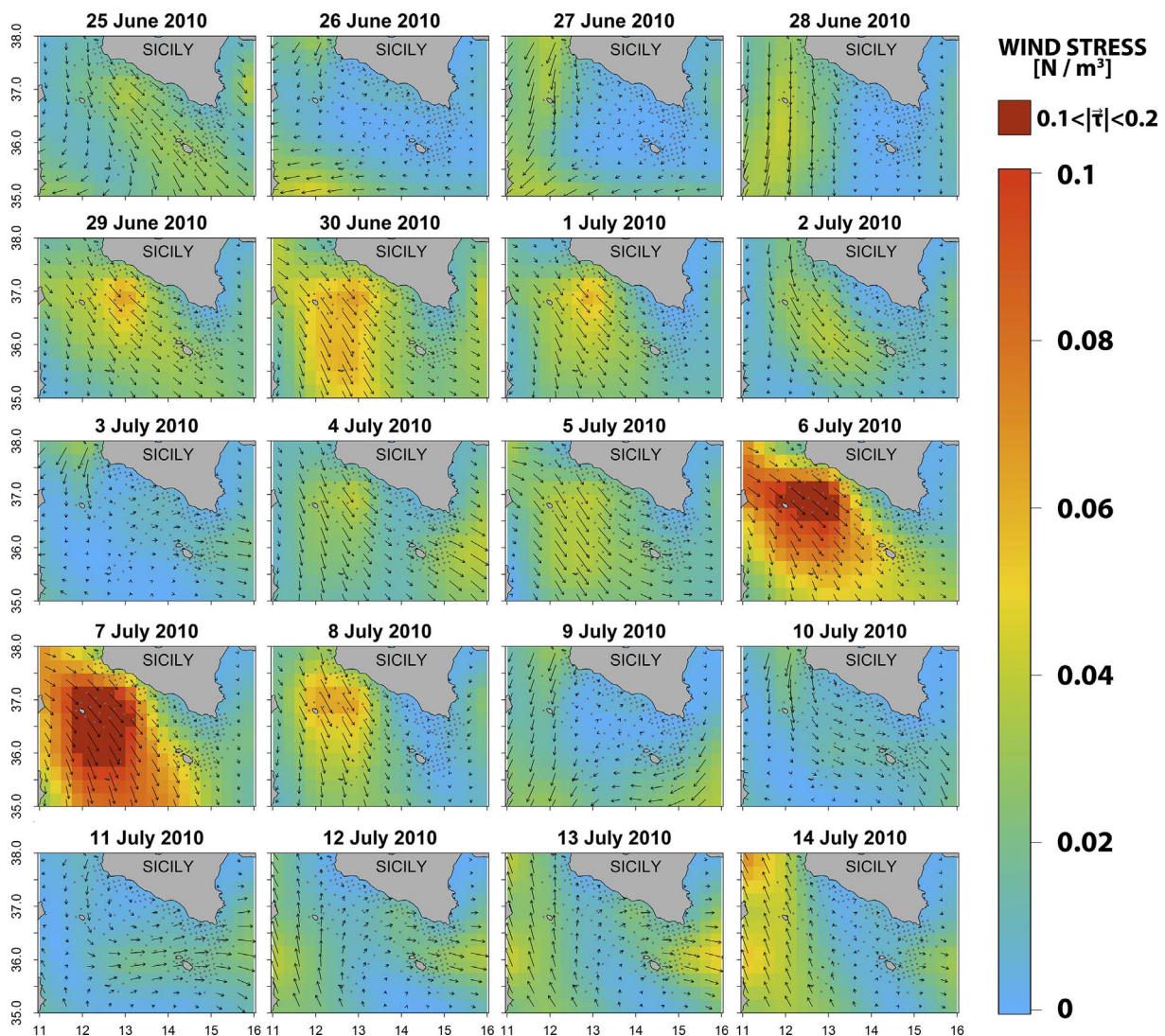
Among fishes breeding, during the summer period in the Mediterranean Sea on the continental shelf, European anchovy (*Engraulis encrasicolus*) and round sardinella (*Sardinella aurita*) are two of the most abundant species in the ichthyoplankton because of the high fecundity that characterizes the small pelagic fishes (Bakun, 1996). Spatial distribution analysis of eggs and larvae in the Strait of Sicily highlighted different spatial patterns between the species. Eggs and larvae of both small pelagic fishes were found on the continental shelf, according to the coastal behavior of the adults (Ben-Tuvia, 1960; Regner, 1996). However, anchovy was found from NW to SE, along all the Sicilian coast and Maltese archipelago, while round sardinella was concentrated in the waters between Capo Passero and Malta (SE zone). Remote sensing data showed very different environmental conditions in these areas in terms of temperature and chlorophyll-a concentration (Chl-a, considered a proxy of the food availability). The NW zone (i.e. Adventure Bank) was characterized by colder and Chl-rich waters, compared with the SE area. The widespread presence of anchovy eggs and larvae in all these zones evidenced a wide plasticity of this species to crucial environmental parameters (Regner, 1996; Palomera et al., 2007). Conversely, eggs and larvae of *Sardinella aurita* were found in correspondence of the warmer waters of the SE zone, between Capo Passero and Malta, in spite of the high food availability characterizing the NW zone. Taking into account the onset of the spawning, which

occurs when temperature reaches 23 °C (Navarro, 1932; Andreu and Rodriguez-Roda, 1951; Palomera and Sabatés, 1990), the absence of round sardinella in this zone could be reasonably linked to the presence of colder waters in both years (see Fig. 6a and c for the SST), in accordance with the tropical origin of this species (Ben-Tuvia, 1960). Against this background, the lower food availability in the SE zone could not be a limiting factor to the same extent as the colder temperature of the NW zone.

Spatial distribution analysis of the European anchovy and round sardinella’s early life stage also made it possible to identify the main spawning areas in the north-west sector of the Sicily Channel. The widespread occurrence of anchovy’s eggs and larvae along the Sicilian coast is consistent with other studies that focused on the planktonic stages (Lafuente et al., 2002; Cuttiitta et al., 2003) and biomass of adult distribution (Patti et al., 2004) in the same area. In our study, the highest density of anchovy early life stage was found mainly off Capo Passero (2010 and 2011) and secondary in the NW zone (2010 and 2011) and in Malta (only 2010). With regard to round sardinella, the presence of planktonic stages in the south-eastern Italian side of the Sicily Channel allowed us for the first time to identify the main spawning areas in this study area: coastal waters off Capo Passero and Malta.

Taking both small pelagic fishes into account, similar abundance and spatial distribution patterns of eggs and larvae emerged between the surveys (i.e., 2010 and 2011). We found a high density of eggs and larvae in 2010. Moreover, a very low density of eggs and larvae was found in Maltese waters during the 2011 period. One hypothesis suggested that explaining the overall dissimilarity could be linked to a match/mismatch between the peak of spawning and the sampling period, due to different temperature conditions that occurred in the two years. The onset and the peak of spawning in the fish species that breed in temperate waters is often temperature dependent (Moyle and Cech, 1988). European anchovy reaches its maximum egg production within the 17–22 °C range (Regner, 1996), while round sardinella begins the spawning period when temperature reaches 23 °C (Navarro, 1932; Andreu and Rodriguez-Roda, 1951; Palomera and Sabatés, 1990).





**Fig. 8.** Daily wind stress occurring from 25 June to 14 July 2010 in the Strait of Sicily. This period, temporally overlapped with ichthyoplanktonic data collection, showed a strong and persistent blowing of Mistral winds (from NW) in this period.

Hence, the overall higher density of the early life stage in 2010, could be the consequence of the match of the peak of spawning with an earlier sampling cruise. On the other hand, the lower density found in summer 2011 could be the result of a mismatch between the maximum production of eggs of this species and the sampling period (Fig. 7a). However, this picture does not provide a sufficient description of the differences detected among the different regions of the study.

Our analysis highlighted the crucial role of the physical forcing and the environment derived conditions in shaping the spatial distribution of the early life stage of these species. In 2010, the stronger action of Mistral winds gave rise to a net offshore water movement by means of a cold and Chl-rich filament (Bignami et al., 2008). These intense wind-induced phenomena (i.e., PV inputs due to wind forcing, acting over shallow, coastal areas) have triggered a cross-shore transport of larvae from the Agrigento and the Gulf of Gela to Malta, as confirmed by Lagrangian simulations and the PV model for cold filaments. In spite of the existence of anchovy eggs in both zones, the opposite findings in terms of larval density and size structure in the central shelf and Maltese waters support our hydrodynamic representation. Indeed, the central shelf has been identified as a crucial area for the European anchovy because of the high biomass concentration of adults during the spawning period (Patti et al., 2004). In addition, this study (as well as Lafuente et al., 2002; Cuttitta et al., 2003) highlights the presence of the

anchovy's eggs, suggesting an important spawning activity in this zone. In the light of such considerations, the presence of few and small larvae of anchovy in the central shelf and the opposite findings off Malta are in agreement with a net transport of newly hatched-larvae, removed from the spawning zone and growing along the journey towards the Maltese archipelago. Furthermore, the absence of the biggest size class in the central zone of the study area suggests the lack of a physical connection with the NW zone, where the spawning of the European anchovy was also detected. These findings are comfortably in agreement with those of Lafuente et al., (2002) and Cuttitta et al., (2003), which suggest a transport offshore linked to a synergy effect of the AIS and the upwelling system in the NW zone.

A different scenario emerged in 2011, showing warmer and nutrient-depleted surface waters in relation to inconsistent intensity and direction of the wind and weakened coastal upwelling. The higher density and the wider range of larval size of both types of small pelagic fish in Capo Passero are consistent with the reduced hydrodynamic conditions linked to the lower blowing of Mistral winds and the consequent weakening of the upwelling system and cold filaments formation. In this case, geostrophic and along-coast currents play a key role in determining the fate of the early life stage. In these conditions, Capo Passero assumes an important function as a retention area for eggs developed *in situ* and larvae gathered from the north-west, resulting



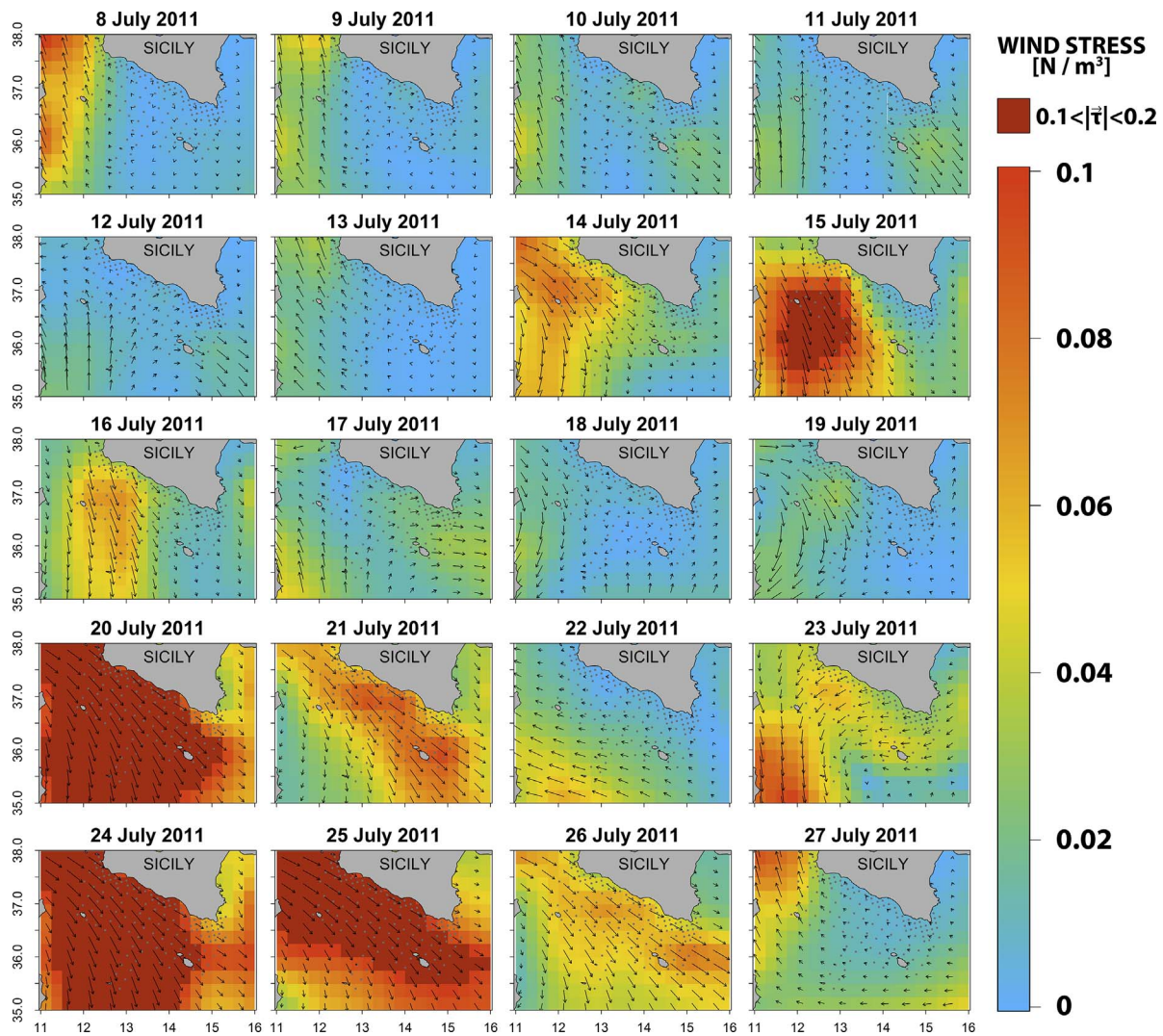


Fig. 9. Daily wind stress occurring from 8 June to 27 July 2011 in the Strait of Sicily. This period, temporally overlapped with ichthyoplanktonic data collection, showed only few and not persistent events of Mistral winds (from NW) in this period.

from along-shore advection (Lafuente et al., 2002, Falcini et al., 2015).

Affecting both temperatures and food availability conditions, the occurrence of either one or the other scenario could be highly relevant in terms of eggs production as well as of growth and mortality rates of the early life stages. Indeed, enhanced food conditions linked to the

blowing of intense and prolonged Mistral winds (i.e. the 2010 scenario) could influence the nutritional condition and hence the reproductive potential of adult fish (Roy et al., 1989; Quatey and Maravelias, 1999), which feeds on zooplankton and are strictly linked to areas characterized by high primary productivity (Ben-Tuvia, 1960; Regner, 1996;

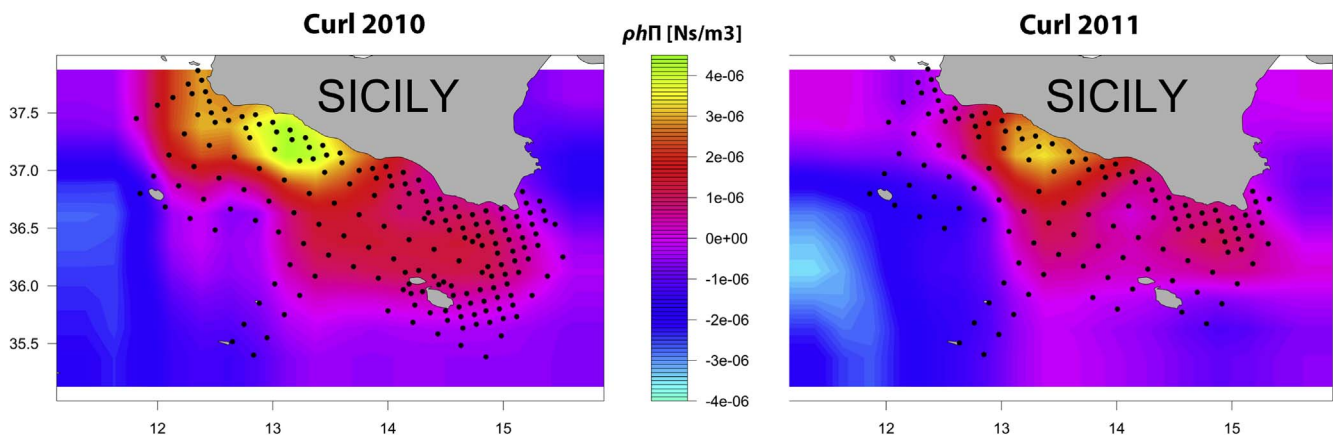


Fig. 10. Integral of the curl of wind stress  $\phi\Pi$  (N s/m³) (see Eq. (3)) performed throughout the Bansic 2010 (25 June–14 July) and Bansic 2011 (8–27 July) cruises showing the more intense potential vorticity increase that occurred in 2010. Such a potential vorticity input led to the offshore propagation of the cold filament.

Sabatés et al., 2009). Regarding early life stages, on the one hand the food availability could reduce mortality rates linked to starvation at larval stage, affecting the number of exogenous feeders. On the other hand, the lower temperature, by reducing the metabolic rate, could induce slower growth rate and crucially limit the energy consumption and the foraging events at larval stage (Blaxter, 1982; Houde, 1989). There is no explanation of just how food availability and temperature might tune the survival of the early life stage of these species and additional studies are needed. However, our study has shed some light on the main mesoscale oceanographic dynamics occurring in the Sicily Channel, which affect the surrounding environment of larvae, control dispersion and hence tune the mortality rates of the early life stages. Affecting the strength of recruitments, the dynamics of the upper layer in this zone could be a crucial aspect to take into account in the framework of populations dynamics and fishery management of this species, as well as other species that here spawn planktonic stages.

## 6. Conclusions

The dynamics of the marine surface layer plays a fundamental and, in many ways, unpredictable role as far as the life and evolution of pelagic species are concerned. In the early life stage, fish larvae move passively, as advected by currents. 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 modelling of velocity fields and Lagrangian transport, as well as by a deep understanding of the physical processes that rule the fate and dispersion of larvae.

We adopted this approach considering spatial distribution of the planktonic stages of *Engraulis encrasicolus* and *Sardinella aurita* collected over two years characterized by opposite environmental conditions. We pointed out how the occurrence of Mistral winds in the summer can modify the fate of the planktonic stage of this species. We can conclude that by affecting temperature, food availability and dispersion of the early life stage, the wind is a crucial aspect to take into account in order to assess the recruitment and the consequent biomass fluctuations of small pelagic fish in this marine system.

Moreover, we detected a connection due to the advection of planktonic reproductive stages between Maltese and Sicilian waters, which are identified as different Geographical Sub-Areas (GSA) from the General Fisheries Commission for the Mediterranean (GFCM). In this framework, the adoption of common management strategies could be a successful approach in the context of sustainable fisheries and resources exploitation. This approach is strongly advised in the studies addressed to the implementation of predictive models that could provide useful information in others similar systems. Our findings can indeed be easily applied to those geographical regions where the fate and distribution of small pelagic larvae are potentially affected by wind effects (e.g., Gulf of Tunis, north-east Spanish coast, the northern Aegean Sea, and California Current System). We believe that our approach, together with the use of operational oceanographic tools, can lead to very interesting and useful results for a sustainable fishery management. Moreover, it provides some insight into the potential of remote sensing and Lagrangian techniques, which, coupled with biological observations, allows us to clarify the dispersion dynamics involved during the planktonic stage of small pelagic species.

The expected benefits for fisheries management in strategic areas, in the Mediterranean, as well as other ocean basins, will consist in providing major and more detailed information about preferential sources and recruitment areas, with the aim of better estimating and possibly regulating the amount of future biomass.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.pocean.2018.02.009>.

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