Anonymous Referee #1

This manuscript describes the results of surveys of eggs and larvae south of Sicily in the summers of contrasted years 2010 and 2011. Differences in distribution, especially between Capo Passero and Malta, are attributed to differences in wind forcing resulting in a stronger offshore filament in 2010; the filament would advect larvae from the Cape to Malta. The attribution seems logical enough, and there is some back-up from Lagrangian modelling, although with only two cases one cannot be sure about the possible role of other factors not discussed here. The interest is rather limited, because the study is geographically localised and there is nothing particularly novel about the techniques used. It can have its place in the context of other papers in the region.

Many thanks for the positive and encouraging comment. We are aware of the fact that our analysis is geographically localized. However, we believe that this should not be considered as a limitation. From a marine biology perspective, motivations for conducting a Lagrangian connectivity analysis, like the one presented in this ms, may come even from regional areas, where it can be relatively easier to establish dynamical connections across the domain. On the other hand, every sub-basin may present its peculiarities, from a physical oceanography point of view, so that it is not obvious that extending the study to wider domains corresponds to gain in physical information, proportionally. Said that, in the revised version we stress how our findings (since supported by a general theory) can be applied to similar geographical regions where fate and distribution of small pelagic fish larvae are potentially affected by wind effects [See line 326-328]. Regarding the novelty of our technique, we point out that nobody else (with the exception of some co-authors of this ms in recent publications), to our knowledge, uses kinematic models of mesoscale turbulent dispersion coupled to a large-scale ocean circulation model. The use of a generic kinematic eddy model (i.e., a “kinematic simulation”) does not guarantee an accurate numerical simulation of Lagrangian turbulent trajectories in a regime where the locality hypothesis for particle dispersion is expected to hold (see Thomson and Devenish, 2005, for a critical discussion about the use of kinematic simulations of turbulence). Our kinematic model fulfills the basic theoretical requirements for this scope (see Lacorata et al., 2008 or Lacorata et al., 2014 for a full description of the method) and has the advantage to be suitable for any kind of scaling regime (the Richardson’s law is only an example). See line 151-187.

However, it does need considerable improvement in the description of what was actually done, particularly in respect of the models used.

We fully agree with this comment. In this revised version, as mentioned above, we improve the part dedicated to the description of our numerical simulations and the novelty of our technique. See line 151-187.

I think the authors should also consider the difference between years in terms of the direct wind forcing (leading to upwelling and possibly a filament off Capo Passero) as well as the wind-stress curl.

We actually performed such an analysis (Figure 6). In the revised version of the ms, however, we discuss with more details the role of Ekman transport (i.e., wind forcing and upwelling induce currents) and we explain better the link between this and the wind-stress curl (i.e., input of Potential Vorticity that triggers the offshore evolution of the filament). See line 222-236; 260-267; 270-298.

There are many places where the English usage should be improved, but much of this could be through the final copy-editing

English language has been carefully revised.

Page 2098. Line 12. “use” not “hire”. Lines 17-18. Does “more favourable” refer to Capo Passero in 2011 or Malta in 2010? Line 19. Omit “want to”.

Thanks of these corrections. We now specify that the more favorable condition is represented by an alongshore transport towards the recruiting area of Capo Passero. See Line 28-30.

Page 2099. Line 9. “pelagic fish”? “pelagic” is an adjective and needs to be followed by a noun, e.g. “fish”. Line 13 should read “. . sea, i.e. E. encrasicolus . .”. Line 23. “of” or “on”? At present with “of” this means effect of fish catch on abundance and northward expansion. Use “on” if you mean effect of abundance on fish catch.

Thanks. We corrected all these sentences.

Page 2100. Line 1. “chlorophyll-enriched”. Line 4. “pelagic fish” as above? Line 7. Put “. . .” around “connect the dots”. Lines 8-9. Not “i.e.”; the central Mediterranean is not the same as the Sicily Channel. Either “ . . central Mediterranean Sea and specifically the Sicilian Channel. . .” or omit “central Mediterranean Sea (i.e.”. Lines 17-19. I don’t think the current is due to upwelling, especially if “This current often gives rise to the cold filament.” I think the wind causes both the current and the upwelling.

Thanks for these corrections. We modified these sentences accordingly and, in particular, we clarified the sentence related to the cold filament. See line 78-87

Page 2101. Line 2. Any initial hypothesis should be stated in the introduction. If it only follows from the results, is it a hypothesis? Line 12. Insert “further” before “offshore”. Line 16. “hauled from within 5m of the bottom . .”. Lines 16-17. “. . at deep stations . .”. Line 17. Omit “on”. Line 21. Not “at binocular”. Do you mean “under a microscope”?

Thanks, we made all the suggested corrections. Regarding page 2101 Line 2 we have slightly changed the sentence. Indeed we believe that Lagrangian simulations have to be considered as numerical experiments that can be designed either to test an old hypothesis or to find out hints for a new one. In our case we want to verify the relationship between wind forcing, upwelling events, and Lagrangian transport variability. This framework allows us to reinforce the initial hypothesis and to pursue the potential vorticity analysis that, consequently, provides a mechanistic explanation regarding the link between wind effects and offshore transport of larvae. See line 97-99.

Page 2102. Line 4. Better ". . In particular, eggs were assigned a stage number". Line 5 end. "following". Lines 9, 11. Move "were obtained" from end of sentence to after "(TL, mm)". Line 11. Better ". . Then length classes at 1 mm intervals were". Lines 25, 26. Surely the wind stress does not suddenly decrease at 11 m/s.

Thanks, we made all corrections.

Page 2103. Section 2.3 is unclear and needs to say what was actually done. What is the main model? Its area (figures 3 and 4 show different extent)? Resolution? Open boundary conditions and forcing? Period(s) run? Line 13. "instances" seems the wrong word – is it referring to (i) and (ii)? Line 14. "scope" seems the wrong word – I cannot tell what it refers to. Lines 17-18. This implies that the total velocity is made up of such cells. Surely they are added to a larger-scale deterministic velocity (where from)?

Thanks for this remark. This section has been revised by specifying the following information. The main model is the Ocean model provided by the Mediterranean Forecasting System (see, e.g., Tonani et al., 2008, for a detailed description of the Ocean model that is not necessary to repeat here). The Ocean model covers all the Mediterranean basin. Horizontal and vertical spatial resolution are, respectively, 1/16 x 1/16 degree (6.5 km) and 72 vertical layers ranging from 1.5 m to 5000 m depth. Daily re-analysis velocity fields are used for the large-scale circulation while a 2D kinematic eddy field and a 3D convective cell field are added to the main model to compensate the lack of, respectively, effective mesoscale turbulent dispersion and vertical mixing in the mixed layer (see Palatella et al., 2014, and Lacorata et al., 2014, for more details about this type of modelling techniques). The boundary conditions are open (if meant relative to the Sicily Channel sub-domain), with rebound conditions of the Lagrangian particles against the coasts (an accurate modelling of the circulation in proximity of coastal boundaries is outside the capabilities of the Ocean model we have used). Wind forcing is provided by ECMWF data every six hours. Period of the simulation: from June, 1st to September, 30th for 2010 and 2011. All other corrections have been made and, moreover, we have specified where the larger-scale deterministic velocity field comes from: the total velocity in a given point is the sum of the Ocean model velocity (i.e. the MFS model) plus the kinematic model(s) velocity. See line 151-187

Line 13. "instances" seems the wrong word – is it referring to (i) and (ii)? Line 14. "scope" seems the wrong word – I cannot tell what it refers to.

We changed "both instances" with "these drawbacks". We also changed "Deterministic chaotic flows work…etc…(Palatella et al., 2014)" with "Deterministic chaotic flows are very suitable, at this regard, since they can generate trajectories that accurately (in statistical terms) simulate the typical small-scale turbulent motions that affect the dispersion of a tracer distribution at early stage (Palatella et al., 2014)." See line 170-187.

Page 2104. Lines 3-6. Are these sentences describing previous work or results of the present study? Line 9. Better “. . was greater than in 2011 . .”. Line 11. “. . The abundances differed between . .”? Line 14. Better “Analysis of egg stages revealed different spatial distributions . .”. Line 21. “. . eggs were found . .” (“exclusively” is redundant; “only” already gives the meaning). Line 23. Omit “was”. Line 26. “length” not “dimensional” – say what you mean. Also page 2105 line 2, page 2108 line 21. Line 27. “9” not “8”?

Thanks, we made all corrections. Regarding Section 3.1, the old line 3-6 (page 2104) refers to our results in this present study. There are no previous works that describe the spawning pattern in this specific area. See the new line 194-204.

Page 2105. Line 1. Omit “more”. Lines 2-3. “. . we recorded very few larvae.” (see figure 2, there is at least one). Line 6. “. . a smaller length range . .”. Line 8. Omit “coastal, upwelling induces” (as above). Line 13. “. . filament generated off Capo . .”. Section 3.2 The timings of the model results need to be treated carefully to be relevant to the cruise dates.

Thanks, we made all corrections. In Section 2.3 we spend some words regarding the timings of the model. Buoyant particles of the Lagrangian runs are emitted at constant rate in the period from June, 1st to September, 15th (for both years). So the dates we mentioned are consistent with the cruise samplings. See line 165-168.

Page 2106. Line 2. Where do these Eulerian velocity fields come from – what model run exactly? Line 20. “. . in 2010, when the Mistral wind blew steadily for”.

Thanks, we made all corrections. We make clear that the Eulerian velocity fields are from the Ocean model provided by the Mediterranean Forecasting System (Tonani et al., 2008). See line 151-169.

Page 2107. Line 1. “along . . filament.” I do not understand this. Line 3. “. . we use a surface cold filament model”. Rest of section. How does the effect of wind stress curl compare with the effect of the wind-forced coastal current and coastal upwelling? The supplementary figure S4 seems to show rather strong offshore Ekman transport on a few days. Line 19. Add “,” after “model”.

Thanks, we made all corrections. We now explain the link among the curl of wind stress, the wind-induced coastal current, and the coastal upwelling. We here use the PV model as a diagnostic tool to quantify the efficiency of the cold filament in delivering eggs and larvae offshore. Surely, the cold filament is generated by the coastal upwelling. However, the analysis of the wind stress curl quantifies the PV input that is needed to trigger the offshore evolution of the filament. See lines 222-236; 263-267; 270-273; 294-298.

Figure 5c should show 2011

The figure is now correct. Thanks and sorry for the mistake.

All the other minor comment were fully addressed

Anonymous Referee #2

Figure 1 is possibly misleading because the dots showing the location of the sampling stations can be confused with the dots showing the abundance of larvae.

Thanks for this comment. We modified this figure.

Also, the distribution appears very patchy, with concentrations at neighboring locations having little in common. Therefore, the real distribution is clearly undersampled and possibly gives a biased view of the real distributions. To gain confidence in the experimental data, more should be said about the total volume of water filtered at the different stations.

Thanks for this comment. In section 3.1 we remark that the distribution of eggs and larvae largely varies among sampling stations due to the spawning behavior of the adults. Indeed, as other small pelagic fish (e.g. *Sardina plichardus* or *Engraulis encrasicolus*), *Sardinella aurita,* spawns in a very localized areas during a brief lapse of time, generating a very patchy distribution within the study area. See line 191-193.

Very little is said about the actual lagrangian method and the numerical set-up. Section 2.3 gives general comments, references but does not provide any information about the real method used in this study.

We fully revise Section 2.3 by specifying the following information:

1) Method: we integrate numerically the evolution of Lagrangian trajectories in an Ocean model (i.e. the MFS model defined in the whole Mediterranean basin) to which a couple of supplementary kinematic velocity fields are added, in order to account for mesoscale turbulent dispersion, on one hand, and a basic vertical mixing in the mixed layer, on the other one. The role of the small-scale kinematic models of dispersion is to fit the numerical simulations of particle transport to observation, at least in terms of characteristic temporal and spatial scales (see for ex. Lacorata et al., 2014, or Palatella et al., 2014). This method is different from the common techniques that are based on the use of stochastic diffusion models (see Thomson 1987 and a plenty of other literature on this). Our kinematic modelling technique is based on deterministic chaos, namely chaotic Lagrangian trajectories generated by simple periodic velocity fields (essentially, multi-scale cellular patterns) to which specific space-time relationships can be assigned.

2) Velocity fields: the total velocity field applied to a Lagrangian particle, in a given point of the domain, is the sum of the Ocean model velocity field (MFS, i.e. the large-scale circulation model) plus the kinematic velocity field. The large-scale Ocean model is provided by the Mediterranean Forecasting System (MFS) in terms of daily output of reanalysis fields. Horizontal and vertical spatial resolution are, respectively, 1/16 x 1/16 degree (6.5 km) and 72 vertical layers ranging from 1.5 m to 5000 m depth. Details about the set up of the additional kinematic models can be found in Lacorata et al. (2014), and Palatella et al., (2014).

3) Buoyancy: numerical simulations assume neutrally buoyant passive particles.

4) Seeding strategy: 25600 particles at constant rate from June 1st to September 15th

5) Timespan: from June 1st to September 30th, 2010 and 2011.

See line 151-187.

Also, the strong statements made at lines 11-14 about the issues related to Lagrangian techniques should be substantiated with appropriate references or omitted.

We believe that these are general and objective considerations: no model has infinite resolution and therefore there will always be issues related to the scales of motion of the order of the grid step, and lesser. The same holds for the vertical motion in a coarsely resolved mixed layer. These drawbacks can be surely mitigated in sophisticated high-resolution models but not totally eliminated. In our case, we use a large-scale circulation Ocean model in order to study Lagrangian transport and dispersion (within a relatively large area). In dealing with finite resolution issues at a mesoscale (and lesser) level, we overcome such an issue by means of our kinematic modelling technique. In the revised version of Section 2.3 we stress this concepts in a clearer way. See line 170-187.

Please explain the sentence "This indicates that Sardinella aurita larvae did not find the ideal dynamics conditions (where ?) for a local recruiting and were delivered offshore". Please also clarify the scenario described on page 2105 (lines 8-13). Obviously, eggs are hatched near Capo Passero. Then, I do not understand how a coastal upwelling can induce a current transporting the eggs along the Sicilian coast and mix (? – current do not mix water masses) these eggs with in situ (where ?) spawning eggs when no eggs are found along the coast...Also why would only lavae larger than 8 mm be advected by the cold filament ?

Sorry, This paragraph was actually really confusing (and some parts were wrong). We now formulate our statements in a clearer and analytic way. See line 222-236.

Figure 3 and 4 do not support the idea of a transport of eggs/larvae from Capo Passero region to the western part of Malta: the main stream flows eastward of Malta. The arrow on figure 3 does not reflect the results of the Lagrangian simulation. It is therefore misleading.

This comment is not really clear. The arrow enlightens a particular branch of the Lagrangian particle trajectories that delivers a large amount of them to the east side of Malta around the 8th of July. We do not mention within the text the western part of Malta. Moreover, this is strongly supported by the Eulerian field (which is cruised averaged, and not a single snapshot) that shows the presence of a preferential path from Capo Passero to Malta in 2010 that does not occur in 2011. The reviewer can notice that July 2011 is characterized by weak currents (Fig. 4) and thus particles show a huge dispersion rather than a strong advection towards Malta. We now provide a clearer description of those results in line 243-249.

Figure 5 shows rather different Chl-a content in 2010 and 2011. Therefore, one cannot rule out the fact that the different distributions of Sardinella aurita might be due to different temperature conditions (a corrected figure 5c would help) and food web dynamics rather than the occurence or not of cold filaments transporting eggs and larvae offshore.

Figure 5 has been corrected. Food web dynamics are very unlikely since larvae behave like passive, advected particles. See line 303-309.

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) from ichthyoplanktonic data, collected during the 2010 and 2011 summer cruises. We also 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~~ use a potential vorticity (PV) model that takes into account the role of wind stress in generating those cold filaments that are 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, high-PV cold filament. Such a pattern is not found in the 2011 analysis, which indeed shows an

alongshore transport towards the recruiting area of Capo Passero and thus 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 fish 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).

The link among ocean currents, transport and distribution of small pelagic fish species, atmospheric ~~forgeing~~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 fishes 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 et al 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. 2006, Tsikliras and Antonopoulou, 2006, Sinovčić et al., 2004) with possible effects on~~f~~ 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 of *Sardinella aurita* are often associated with warm coastal and ~~enriched chlorophyll~~ chlorophyll-enriched 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 species (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 (central Mediterranean Sea)~~)~~. ~~The~~ This ~~Sicily Channel~~ 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, 1997). 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): blowing wind along the coastline creates offshore Ekman transport at the surface; consequently, water that are moved offshore are the replaced by deeper fluid that upwells and creates colder surface temperatures at the coast; the resultant sloping interface implies a cross-shelf pressure gradient that triggers a geostrophic, along-shore flow.

This wind-induced effect, moreover, ~~This current often gives rise~~is at the base of ~~to~~ the formation of cold filament that propagates offshore from the eastern Sicilian tip (i.e., Capo Passero; ~~Figure~~ Fig. 1) (Bignami et al., 2008~~; Falcini et al., 2015~~). These kind of jets are often related to instabilities formed at an upwelling front (Flament et al., 1985, Washburn and Armi, 1988, Wang et al., 1988, Strub et al., 1991 and Haynes et al., 1993), in particular, when a short-term wind bursts hit restricted areas of the near-shore sea surface (Bignami et al., 2008).

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 station were sampled in Bansic 10 e Bansic 11, respectively (~~Figure~~ Fig. 1). Systematic sampling is constituted by a regular grid of stations (1/10° × 1/10° along the continental shelf, and 1/5° × 1/5° further 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 from within 5 m ~~from~~ of the bottom to the surface, or from 100 m to the surface at~~d~~ deep stations. 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~~under a microscope 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) $Y_i = \frac{(10 \times d_i \times x_i)}{v_i}$, where Y_i is the number of larvae/eggs of each species under 10 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 m^3 and d_i is the maximum depth reached by net.

Eggs and larvae preserved in formaldehyde were used for the determination of the stage of development. In particular, eggs were assigned a stage ~~staging of eggs were performed assigning~~ number from 1 (stage after fecundation, with a single cell) to 11 (stage pre-hatching) following (Gamulin and Hure, 1955; Whitehead, 1988). We considered stage from 1 to 4 “early stage”, from 5 to 8 “middle stage” and from 9 to 11 “late stage”.

Larvae were photographed through binocular stereo microscope with integrated camera and total length (TL, mm)~~,~~ were obtained from the analysis of image performed with suitably calibrated software (Image Pro Plus 6.0, Image Cybernetics, RoperIndistries, SilverSpring, MD, USA)~~, were obtained~~. Then, length classes ~~length~~ of 1 mm of magnitude were considered.

2.2 The remote sensing dataset

We pair the biological dataset with remote sensing data for (Table 1): sea surface temperature (SST), chlorophyll-a concentration (Chl). From these daily satellite data we evaluated cruise-averaged spatial maps (for each environmental parameter) that were superimposed to the entire ichthyoplanktonic data set, for both 2010 and 2011 datasets. This allowed to first recognize the main hydrographic features that occurred at Sicily Channel sea surface and the relations between Sardinella eggs and larvae distributions and environmental datasets.

We also analyze wind stress ($\vec{\tau}$) and Ekman transport ($\vec{m}$) from remote sensing. These quantities are 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

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

where ρ_{air} is the air density and the dimensionless friction coefficient $C_d = 0.0012$ for $0 < |\vec{U}_{wind}| < 11$ m ~~/~~s^{-1} and $C_d = 0.00049$ for $|\vec{U}_{wind}| \geq 11$ m s^{-1} (Large and Pond, 1981; McClain and Firestone, 1993). Ekman transport is then calculated as (Pickett and Paduan, 2003)

$$\vec{M} = (\rho_{water} f)^{-1} \vec{\tau} \times \hat{k}, \qquad (2)$$

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

2.3 The Lagrangian simulations

Modern Lagrangian modelling techniques have been developed recently to simulate tracer trajectories ~~advected by~~from Eulerian velocity fields~~marine currents~~~~from available velocity fields~~. ~~, such as those provided by the Mediterranean Forecasting System (MFS) (Tonani et al., 2008). The main model w~~We here ~~have~~ used the model ~~is~~ provided by the Mediterranean Forecasting System (MFS; ~~see, e.g.,~~ Tonani et al., 2008~~, for a detailed description of the Ocean model~~) as Eulerian input. ~~The~~ Its domain covers all the Mediterranean basin;~~.~~ the ~~Horizontal~~ horizontal ~~and vertical spatial resolution are, respectively,~~ is 1/16 x 1/16 degree (~ 6.5 km)~~ and~~ ; 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~~ daily re-analysis velocity fields from the MFS model are- used for the large-scale circulation while a 2D kinematic eddy field and a 3D convective cell field are added to the main model in order to ~~to~~ compensate the lack of~~, respectively,~~ effective mesoscale turbulent dispersion and vertical mixing in the mixed layer, as discussed below (Lacorata et al., 2008, 2014; Palatella et al., 2014). The boundary conditions 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 proximity of coastal boundaries is outside the capabilities of the Ocean model we ~~have~~ used). ~~Wind forcing is provided by ECMWF data every six hours.~~ The period covered by the simulation goes from June, 1st to September, 30th , for both 2010 and 2011. We assumed a source of passive neutrally buoyant particles emitting at constant rate in the period from June, 1st to September, 15th . The total number of numerical trajectories analyzed in each run is 25600.

As mentioned above~~Broadly speaking~~, there are two main issues related to the simulation of transport and mixing of particles in~~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~~ these two ~~instances~~ aspects~~drawbacks~~ are treated by adopting a kinematic Lagrangian modelling strategy. ~~:~~ Conservative~~Deterministic~~ ~~deterministic~~ chaotic flows are exploited to ~~work very efficiently at this scope, since they can~~ generate trajectories that accurately simulate (at least at a low order moment level~~in terms of statistics~~) the typical small-scale turbulent motions affecting~~, which in turn affect~~ the dispersion of a given tracer distribution~~ at early stage~~ (Lacorata et al., 2008, 2014; Palatella et al., 2014). At this scope~~In order to capture such a dispersion~~ the kinematic velocity fields are~~is~~ composed by 2D or 3D 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 unrealistic ~~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). –Such a pioneering approach represents a novelty, since it uses a kinematic model for mesoscale turbulent dispersion as coupled to a large-scale ocean circulation model (see ~~D~~details ~~about~~on ~~the~~ the kinematic model set up ~~of the kinematic models~~, the 3D vertical mixing model, and the 2D mesoscale turbulence model ~~are the same as~~ in Palatella et al., 2014~~, for the 3D vertical mixing model, and as in~~ and Lacorata et al., 2014~~, for the~~) ~~2D mesoscale turbulence model~~.

3 Results

3.1 Spatial distribution pattern of eggs and larvae

Spatial analysis of early life stages of *Sardinella aurita* showed a very patchy distribution among sampling stations. As other small pelagic fish, this discontinuous pattern typically reflects the spawning behaviour of adults, characterized by brief spawning events in a localized point of the study area.

From Icthtyoplankotonic data ~~have revealed~~we found that the main ~~principal~~ spawning and retention areas ~~of~~ for the *Sardinella aurita* ~~i~~, on ~~n~~ the Italian side of the Sicily Channel ~~(Figures 1). T~~is the south-eastern part of the Sicilian coastal zone, i.e., off Capo Passero~~, has been identified as the main spawning area for this species~~ (~~Figure~~ 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 greater than ~~higher~~

~~with respect to~~in ~~the~~ 2011 (mean of 36.65 against 14.13 eggs/10m^2 in survey 2010 and 2011; mean of 22.83 against 9.38 larvae/10m^2 in survey 2010 and 2011). Malta zone showed the largest fluctuations of abundance between the two years~~The main abundance differences between 2010 and 2011 in Malta zone~~ (~~Figure~~ 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 (~~Figure~~ Fig. 1).

Analysis of egg stages revealed different spatial distributions ~~Analysis of staging of eggs revealed a different spatial distribution~~ of stage in the south-eastern part of the Sicily Channel. In 2010, the area~~s~~ off Capo Passero was characterized by the presence of ~~all~~ different egg stages ~~in~~ with similar ~~amounts~~ concentrations (early stage: 36%; middle stage: 38%; late stage: 26%)~~.~~ ~~Otherwise, in~~while, in ~~-~~the region off Malta, we observed a predominance of middle and late stage (i.e., early stage: 20%; middle stage: 53%; late stage: 27%). ~~Differently~~On the other hand, in 2011 we observed a dominance of late stage eggs off Capo Passero (early stage: 7%; middle stage: 31%; late stage: 62%). For this year, ~~we also recognize that~~ *Sardinella aurita* eggs ~~are~~ were~~exclusively~~ found only off Capo Passero, with exception of one eggs of stage 6 (middle stage) on Adventure Bank; no eggs were therefore found off Malta~~, 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 Figure 2. In 2010 the zone off Capo Passero was characterized by a ~~dimensional~~ length range of 3 - 9 mm while, in the zone off Malta, we observed larvae ~~longer than 8 mm~~that range from ~~(range~~ 2 ~~–~~to 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 2011 showed a ~~more~~ different pattern: off Capo Passero we observe larvae that belong to a wide ~~dimensional~~ length range (from 2 to 11 mm) while, around Malta, we ~~-~~ recorded very few larvae~~did not record any larvae~~.

These evidences set some hypotheses regarding~~mark~~ ~~a~~ the joint action ~~of~~ between *in situ* spawning ~~(early stage)~~ and eggs/larvae advection due to mesoscale, coastal oceanographic structures. In 2010, the presence of i) several stages of *Sardinella aurita* eggs off Capo Passero; ii) middle to late stages off Malta; ~~and a~~ iii) small length~~less dimensional~~ range of larvae ~~in the southeast coast of Sicily~~off Capo Passero; and iv) a larger range off Malta ~~could be the mutual effect of~~ suggest an offshore advection of eggs and larvae from Capo Passero to Malta, reasonably due to wind-induced effects. Such a mechanism seems not to be active in 2011. Conversely, these results should be explained by the lack of durable oceanographic structures able to remove early life stages of *Sardinella aurita* from the spawning area (i.e., off Capo Passero), a counter hypothesis that might not be realistic in such a dynamic region. We therefore pursue the idea that the offshore transport occurring in 2010 likely delivered *Sardinella aurita* larvae far from the ideal recruiting area of Capo Passero.

Finally we point out that, for both years, the wide distribution of egg stages off Capo Passero also suggests that this location - in addition to its in situ spawning eggs - receives eggs that are released all along the Sicilian coast and transported by coastal currents (Agostini and Bakun, 2002; Cuttitta et al., 2006; Falcini et al., 2015).

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 (~~Figure~~ Fig. 3~~;~~ and in Supplement~~ary Information~~). These simulations confirm the presence of a narrow filament that dynamically connects 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 eastern sector of Malta in a few days (i.e., ~ 50 km in 5 days that corresponds to a surface current of ~10 cm/s) by a particular branch of the Lagrangian trajectories. In particular, we observe two events with this intensity: one around ~~the~~ June 10^{th} ~~of June~~ and the second in~~at~~ between ~~the~~ June 30^{th} ~~of June~~ and ~~the~~ July 8^{th} ~~of July~~. The 2011 shows a similar pattern, although there is no evidence of a Lagrangian preferential path that connects Capo Passero to the eastern side of Malta and, for the whole July, the southward advection is much weaker with respect to the 2010 case. The comparison between these two scenarios is further stressed by the MFS Eulerian velocity fields (Tonani et al., 2008), averaged through the two oceanographic surveys (~~Figure~~ 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 (~~Figure~~ 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 µg/l) with compared to the 2011 (mean SST=25.08; mean Chl = 0.042 μg/l). In particular, in 2010 maps evidenced a cold and Chl-rich structure that protrudes offshore from the Capo Passero (~~Figure~~ Fig. ~~6A~~6a, ~~B~~b). Such a structure is characterized by a SST ≈ 23.20°C and a Chl ≈ 0.07 μg/l, 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 and~~,~~ Chl-rich filament, we find a comforting agreement from wind stress and Ekman transport maps (Supplement~~ary Information~~). Between the 30th of June and the 8th of July 2010 a significant Ekman transport likely induced the formation of an upwelling induced coastal current (~~Figure~~ Fig. 6). Although the 2011 is also characterized by strong wind events, it does not record the same persistency that we observe in 2010, when the Mistral wind blew steadily for ~~the 2010, where the Mistral wind steadily blown for~~ 8 days (see in the Supplement~~ary Information~~). The different wind pattern that we observe for the two years is better investigated in the next section.

4 The surface cold filament model

Based on our results, we reasonably hypothesize that the particularly strong Mistral wind pattern, and thus front instabilities related to~~the offshore~~ the coastal Ekman ~~transport~~layer occurred during the summer spawning in 2010, triggered the southward transport of *Sardinella aurita* larvae and eggs ~~along the~~from Capo Passero, along the~~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~~-~~ use a surface cold filament model ~~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~~ potential of~~to~~ these cold filaments and jets to propagate offshore and to maintain their coherent structure based on their potential vorticity (PV). These jets, indeed, are generated by a strong PV 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 ($\vec{\tau}$), is described by

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

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 (3~~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:~~.~~

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

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 $(\nabla \times \vec{\tau})_z$) we observe in~~ the~~ 2010 – with respect to the 2011 – marks the strong role of the wind stress in "loading" PV to the ~~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 a filament~~s or jets~~ (Bignami et al., 2008).

We therefore point out that Ekman transport due to Mistral wind was particularly active for both years (Supplementary Information), thus generating a cold coastal current that efficiently transported eggs and larvae to Capo Passero from the whole Sicilian coast. However, only the 2010 case was characterized by a high PV input able to trigger the filament that delivered eggs and larvae offshore (i.e., around Malta).

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 (i.e., PV inputs due to wind bursts blowing over shallow, coastal areas) lead to cross-shore transport of *Sardinella aurita* larvae from the spawining/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~~ length 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~~year, the presence of a cold, chlorophyll-rich filament that delivered the larvae to Malta form 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 that PV in 2010, relative to 2011~~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. Our findings can indeed be easily applied to those geographical regions where fate and distribution of small pelagic larvae are potentially affected by wind effects (e.g., Gulf of Tunis, northeast Spanish coast, the northern Aegean Sea, and California Current System). 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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Figure Captions

Figure 1. Map of the study area (i.e., Sicily Channel) showing the sampling stations. Bathymetry is indicated by contours~~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 (upper panels) and eggs (~~down~~lower panels) 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 2. Frequency histograms of the total lengths (TLs) measured off Adventure Bank, Capo Passero, and Malta during the two Bansic 2010 and 2011 cruises.

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.

Figure 4. Cruise averaged Eulerian velocity fields for the two Bansic 2010 and 2011 cruises: 25 June to 14 July 2010 and 8 to 27 July 2011, respectively.

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

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

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

Supplementary Information

S1. Maps of daily wind stress for the Bansic 2010 cruise

S2. Maps of daily wind stress for the Bansic 2011 cruise

S3. Maps of daily Ekman transport for the Bansic 2010 cruise

S4. Maps of daily Ekman transport for the Bansic 2011 cruise

S5. Animated gif showing the Lagrangian transport of *Sardinella Aurita* during the Bansic 2010 cruise.

S6. Animated gif showing the Lagrangian transport of *Sardinella Aurita* during the Bansic 2011~~0~~ cruise.

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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: multimission 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

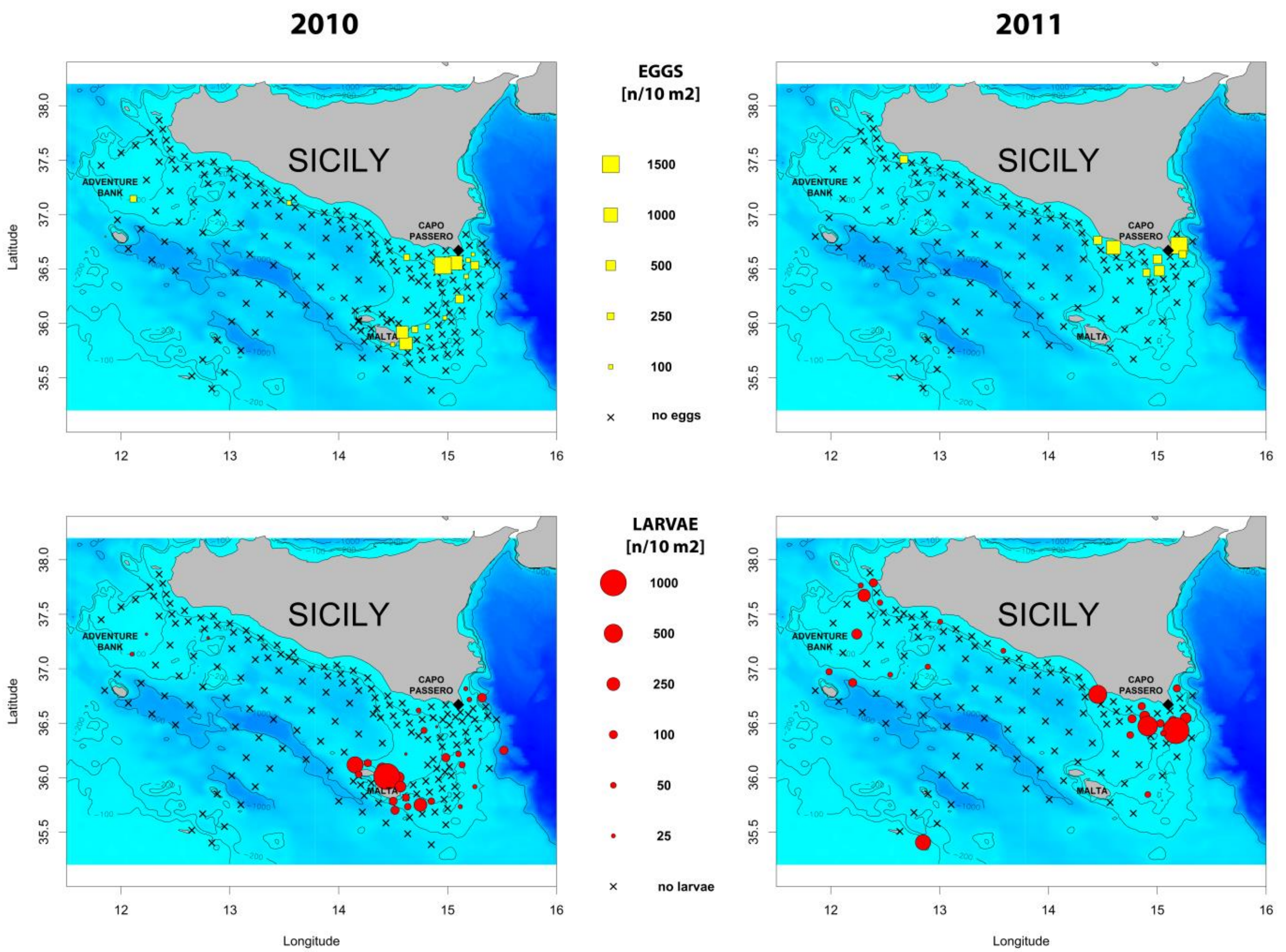

Figure 1**.** Map of the study area (i.e., Sicily Channel) showing the sampling stations. Bathymetry is indicated by contours~~are indicated contours~~ and by background colors, from cyan (shallower) to blue (deeper). The isobaths of 100, 200 and 1000 m are shown. Red circles and yellow squares represent larval (upper panels) and eggs (~~down~~lower panels) 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).

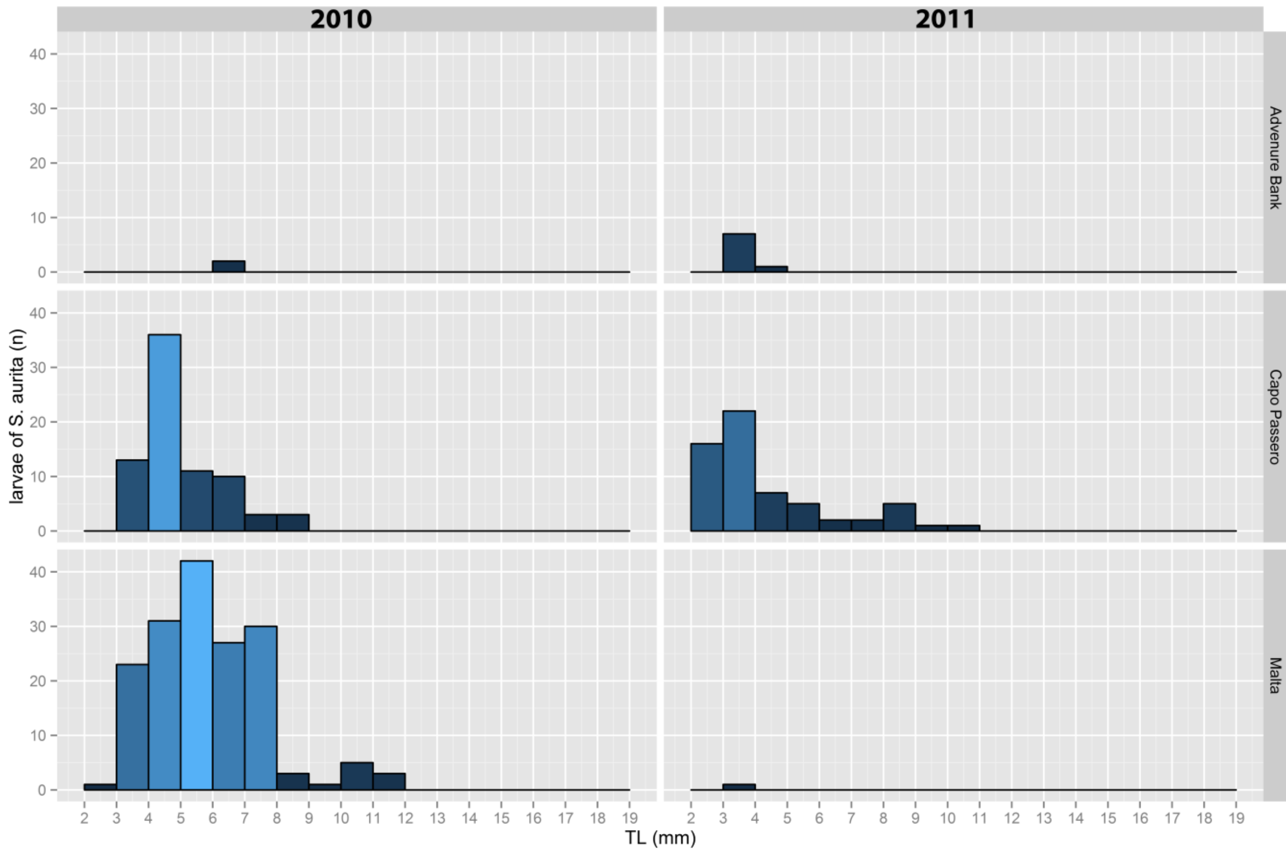

Figure 2**.** Frequency histograms of the total lengths (TLs) measured off Adventure Bank, Capo Passero, and Malta during the two Bansic 2010 and 2011 cruises.

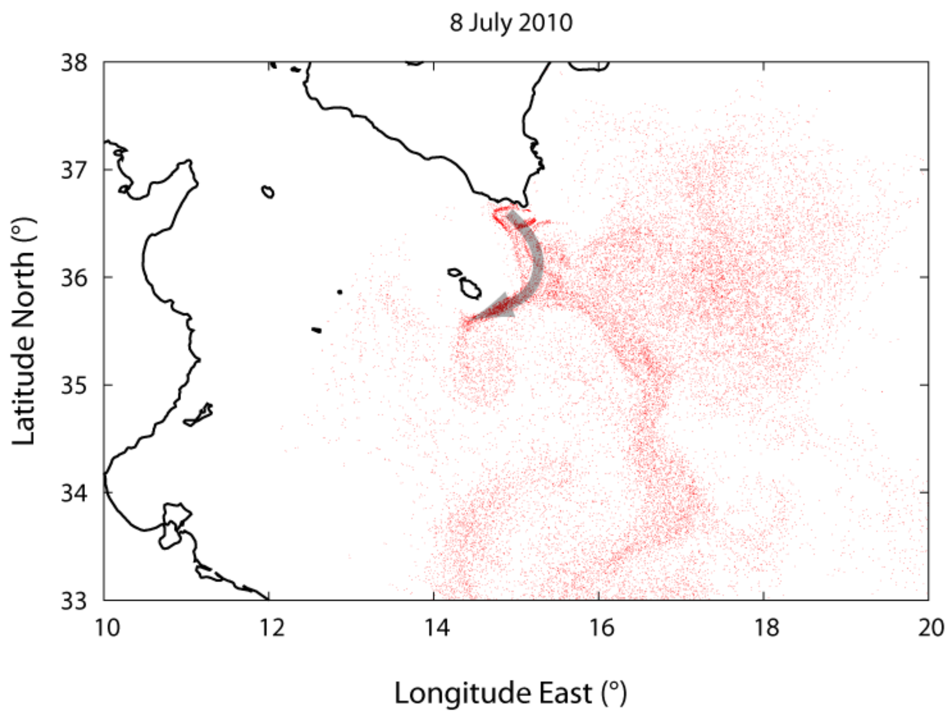

Figure 3**.** Lagrangian run snapshot on 8 July 2010 showing the net transport of Sardinella Aurita larvae (red dots) from Capo Passero to Malta that occurs along the cold filament forming off Capo Passero. The grey arrow highlights the net transport of larvae.

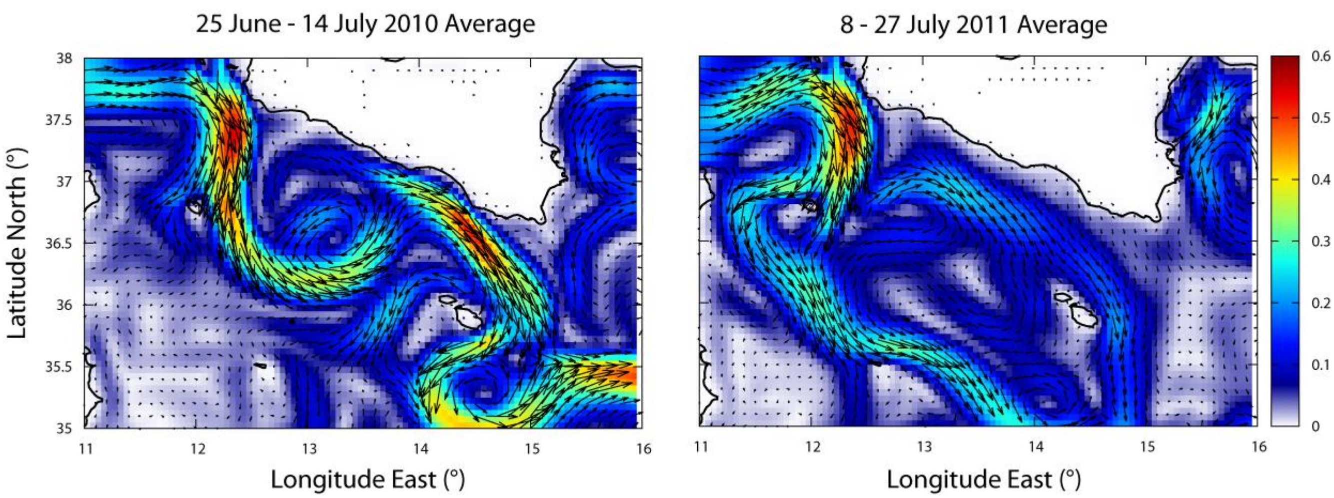

Figure 4**.** Cruise averaged Eulerian velocity fields for the two Bansic 2010 and 2011 cruises: 25 June to 14 July 2010 and 8 to 27 July 2011, respectively.

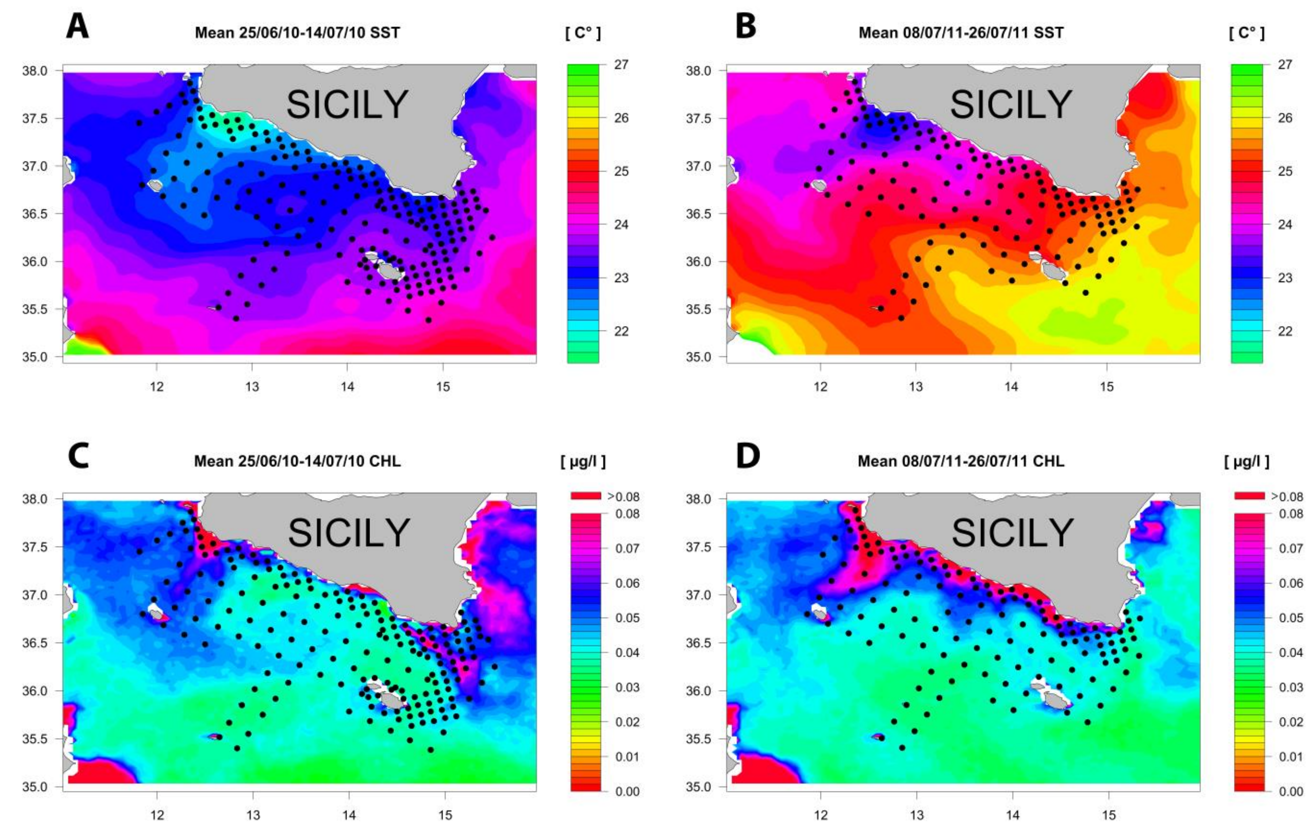

Figure 5**.** Cruise averaged Sea Surface Temperature (aA, cC) and Chlorophyll concentration (bB, dD) for the two Bansic 2010 and 2011 cruises.

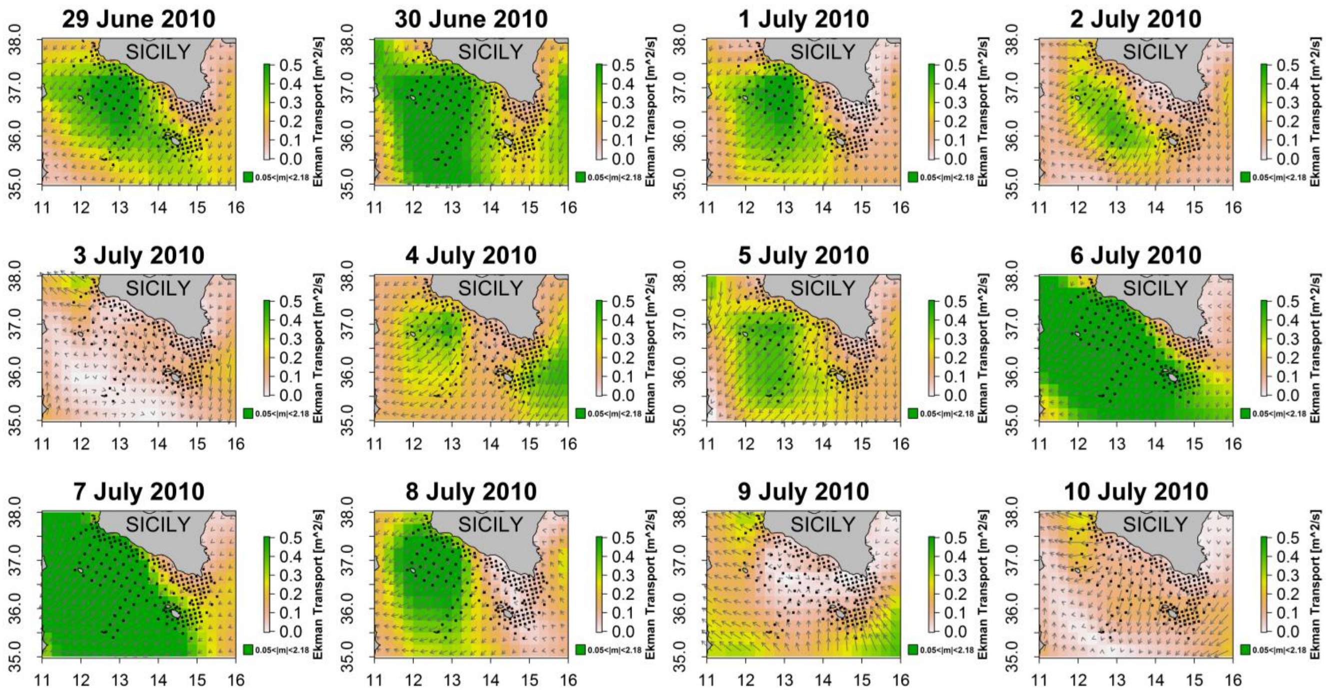

Figure 6**.** Daily Ekman transport during the Bansic 2010 cruise, from 29 June to 10 July.

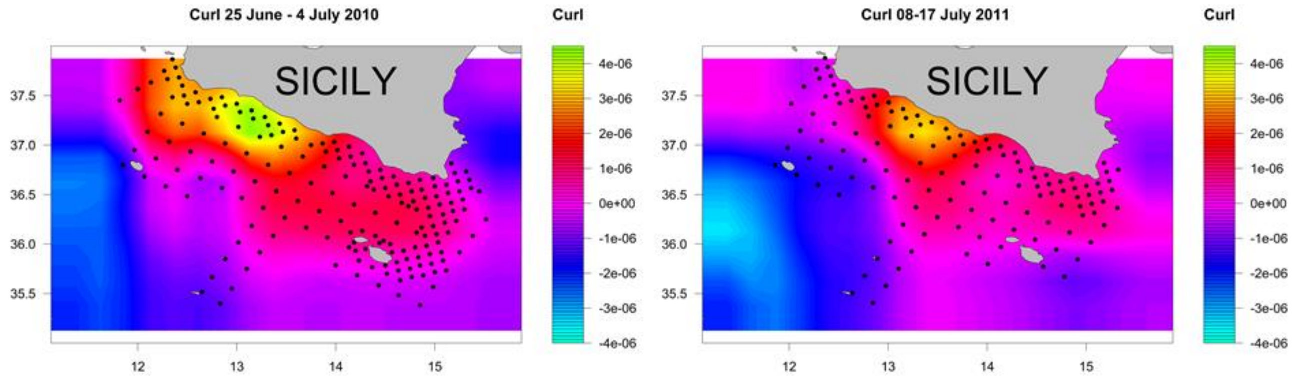

Figure 7**.** Integral of the curl of wind stress $\rho h\Pi$ (Ns/m^3) (see Eq. 4) performed throughout the Bansic 2010 (25 June to 14 July) and Bansic 2011 (8 to 27 July) cruises showing the more intense potential vorticity increase that occurred in 2010. Such a potential vorticity input led to the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