Journal of Sea Research 115 (2016) 6–17

Contents lists available at ScienceDirect

Journal of Sea Research

journal homepage: www.elsevier.com/locate/seares

Different key roles of mesoscale oceanographic structures and ocean bathymetry in shaping larval fish distribution pattern: A case study in Sicilian waters in summer 2009

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ARTICLE INFO

Article history:
Received 2 October 2015
Received in revised form 20 March 2016
Accepted 23 April 2016
Available online 27 April 2016

Keywords:
Ichthyoplankton
Larval fish assemblages
Environmental conditions
Mesoscale oceanographic structure
Southern Tyrrhenian Sea
Strait of Sicily

ABSTRACT

Fish larvae data collected in year 2009 were used to examine the effects of particular environmental conditions on the structure of larval assemblages in two oligotrophic Mediterranean areas (the Southern Tyrrhenian Sea and the Strait of Sicily). For this purpose, relationships with environmental variables (temperature, salinity and fluorescence), zooplankton biomass, water circulation and bathymetry are discussed. Hydrodynamic conditions resulted very differently between two study areas. The Southern Tyrrhenian Sea was characterized by moderate shallow circulation compared to the Strait of Sicily. In this framework, distribution pattern of larval density in the Tyrrhenian Sea was mainly driven by bathymetry, due to spawning behavior of adult fish. There, results defined four assemblages: two coastal assemblages dominated by pelagic and demersal families and two oceanic assemblages dominated by mesopelagic species more abundant in western offshore and less abundant in eastern offshore. The assemblage variations in the western side was related to the presence of an anti-cyclonic gyre in the northern side of the Gulf of Palermo, while in the eastern side the effect of circulation was not very strong and the environmental conditions rather than the dispersal of species determined the larval fish communities structure. Otherwise in the Strait of Sicily the currents were the main factor governing the concentration and the assemblage structure. In fact, the distribution of larvae was largely consistent with the branch of the Atlantic Ionian Stream (AIS). Moreover, very complex oceanographic structures (two cyclonic circulations in the western part of the study area and one anti-cyclonic circulation in the eastern part) caused the formation of uncommon spatial distribution of larval fish assemblages, only partially linked to bathymetry of the study area. Typically coastal larvae (pelagic families: Engraulidae and Clupeidae) were mostly concentrated in the offshore areas and off Capo Passero, where the presence of a thermo-haline front maintained their position in an area with favourable conditions for larval fish feeding and growth.

1. Introduction

The studies on ichthyoplankton distribution, mainly of commercially important species, play an important role in ecology and evolution of fish populations (Moser and Smith, 1993; Neilson and Perry, 1990), because the spatial distribution of early life stages can be the major determinant of recruitment success and consequently of the adult population sizes (Boehlert and Mundy, 1993; Govoni, 2005; Moser and Watson, 2006; Sinclair, 1988). The early life history of the fish populations depends on several factors that affect mainly the spawning biomass of fish adults (Basilone et al., 2013; Giannoulaki et al., 2013; Somarakis et al., 2004) and the larval fish conditions (Riveiro et al., 2011), mainly due to feeding success (Pepin et al., 2014), to optimal habitat (Sabatés et al., 2006, 2007; Valavanis et al., 2008) and to predation (Litvak and Leggett, 1992; Steele and Forrester, 2002; Yin and Blaxter, 1987). Moreover, mesoscale oceanographic structures including geostrophic and wind influenced current regimes (wind-induced mixing of the surface layer, upwelling) play an important role in determining the patterns of abundance and distribution of larval fish populations. This is because they act as mechanisms of retention and concentration of fish larvae in recruiting areas creating oceanic conditions favorable for the growth and survival (Alemany et al., 2006; Falcini et al., 2015; Paris et al., 2007).

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http://dx.doi.org/10.1016/j.seares.2016.04.005
1385-1101/

In the past, the influence of these factors on larval distribution was widely analyzed in the Mediterranean Sea, a semi-enclosed basin of which environmental characteristics are sensitive to both basin scale and local effects (*e.g.* winds, topography) and fluctuations of fish populations are not exclusively linked to fishing activity, but rather significantly affected by ocean conditions (Falcini et al., 2015; Lloret et al., 2000). Extensive work has mainly covered the coastal waters of the north-western part of the Mediterranean Sea (Alemany et al., 2006; Alvarez et al., 2012; García and Palomera, 1996; Olivar et al., 2012; Olivar and Sabatés, 1997; Palomera and Olivar, 1996; Palomera and Sabatés, 1990; Sabatés, 1990, 2004; Sabatés and Olivar, 1996; Sabatés et al., 2007) and to a lesser extent the central (Cuttitta et al., 2003, 2004) and the eastern parts (Aegean Sea: Isari et al., 2008; Somarakis et al., 2011; Tsikliras and Koutrakis, 2011; Tsikliras et al., 2014; eastern Ionian waters: Granata et al., 2011; Tunisian waters: Koched et al., 2013; Zarrad et al., 2013). These studies carried out in the Mediterranean Sea showed that there was a clear bathymetric separation of larval fish assemblages, due to different spawning behavior of adults: inshore assemblages have a different composition from offshore ones (Alemany et al., 2006; Giordano et al., 2014; Granata et al., 2011; Sabatés and Olivar, 1996). Generally, bathy and mesopelagic families were characteristic members of the oceanic group, while the inshore species consist of pelagic and demersal (Beldade et al., 2006; Sabatés et al., 2003; Tsikliras and Koutrakis, 2011). However, this trend can be disrupted by peculiar mesoscale oceanographic structures, because currents, fronts and gyre can reshape the distribution of fish larvae with advection and concentration (Agostini and Bakun, 2002; Falcini et al., 2015; Sabatés et al., 2013). On the other hand, the environmental parameters that can affect the distribution of fish larvae, such as temperature and food availability, are strictly dependent on local conditions and vary considerably at reduced spatial scale (García Lafuente et al., 2002).

This is the case of spatial distribution of larval fish assemblages in two oligotrophic areas in the Mediterranean Sea with different and peculiar environmental conditions: southern Tyrrhenian Sea and Strait of Sicily. The southern Tyrrhenian Sea has high relevance as a probable nursery area for many commercially important pelagic and coastal fishes such as *Seriola dumerili*, *Xiphias gladius* and *Thunnus thynnus* and it is a habitat for mesopelagic fishes and squids, and plays a key role in deeper ecosystem energy flux (Bruno et al., 2001; Giordano et al., 2014; Granata et al., 2011). The Strait of Sicily is one of the main fishing sites in the Mediterranean (García Lafuente et al., 2002). It is a region characterized by a dominant hydrographic feature (the Atlantic Ionian Stream (AIS)) that has clear influence on the spawning strategy and the recruitment success of many fish species (García Lafuente et al., 2002, 2005; Mazzola et al., 2000, 2002).

In this paper, the different roles of hydrographic, physical, chemical and biological conditions in these two study areas during summer 2009 were showed, with the aim of determining what are the conditions in which the dynamics of transport and the chemical–physical and biological properties can be decisive in affecting the spatial composition of fish larvae in Mediterranean Sea.

2. Material and methods

2.1. Ichthyoplankton and oceanographic sampling

The two study areas are located in the southern side of the Tyrrhenian Sea and in the Strait of Sicily (Fig. 1).

Oceanographic data and ichtyoplanktonic samples were collected during two oceanographic surveys on board of the O/V Urania: Bansic 2009 carried out in the period 04–21 July 2009 in the Strait of Sicily and MedSudMed 2009 carried out from 26 July to 3 August 2009 in the Southern Tyrrhenian Sea. The sampling was made on a station

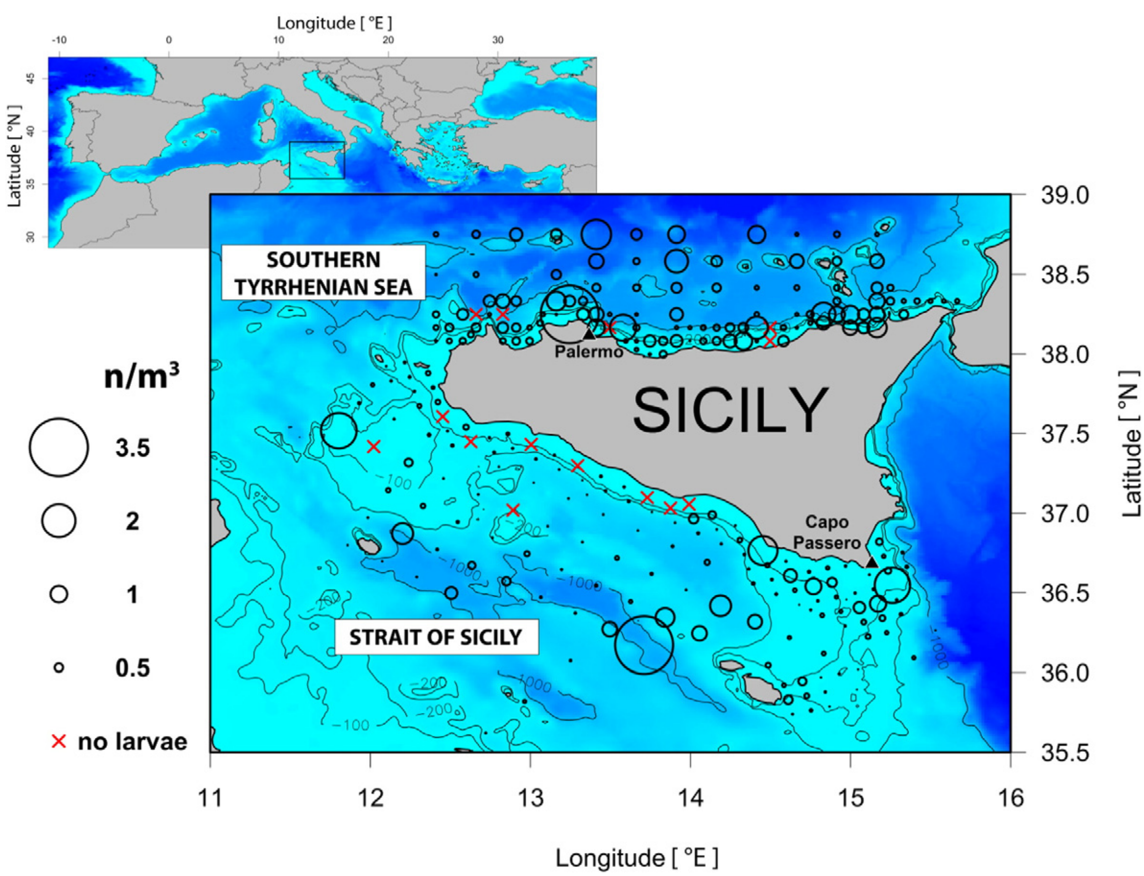

Fig. 1. Larval fish distribution in the study areas. The circle dimension is proportional to the total larval fish abundance.

Table 1
Analysis of deviance for GAM covariates of the final model fitted on total larval fish abundance.

Selected variables	Degree of freedom	F	p-value
Tyrrhenian Sea			
Zooplankton	1	23.71	4.15e−06
Temperature	1	6.50	0.0124
Fluorescence	3.19	3.03	0.0251
Strait of Sicily			
Salinity	1.28	6.52	0.0046
Zooplankton	1	3.07	0.0001
Temperature	3.54	3.66	0.0078

grid of 4 × 4 nautical miles within the 200 m bathymetry and a grid of 12 × 12 nautical miles for the off-shore areas over the 200 m bathymetry. In each station ichthyoplankton samples were collected by means of a Bongo40 net, which is composed by two coupled nets with the inlet mouth diameter of 40 cm and mesh size 200 μm. The plankton oblique tows were carried with a constant speed of 2 knots lasting from 12 to 15 min out to a depth of 100 m, wherever possible, because this layer characterizes the majority of the fish larvae in the study areas (Olivar et al., 2001, 2014; Sabatés et al., 2008). The larval fish collecting procedure was conducted during day and night, because, during the summer, fish pelagic larvae are more concentrated in the surface layer during the night and more dispersed along the column water during the day (Olivar et al., 2001; Sabatés et al., 2008), whereas the opposite occurs at least for most abundant mesopelagic species larvae (Olivar et al., 2014).

The filtered water volume of each mouth was measured by a calibrated flow-meters (type G.O. 2030). The samples were stored in formaldehyde at 4% buffered with borax. Fish larvae were sorted from the rest of the plankton and identified to the family taxonomic level. Taxonomic identification was based on Bertolini et al. (1956); Costa (1999); Moser and Ahlstrom (1996) and Tortonese (1970). The number of fish larvae from each sample was standardized to n/m^3 according to Perez Ruzafa et al. (2004).

In all the stations, continuous vertical profiles of temperature, salinity and fluorescence were obtained from the surface to the bottom by means of a multiparameter probe SEABIRD mod. 9/11 plus mounted on a General Oceanics rosette equipped with 24 Niskin Bottles. The probes were calibrated before and after the cruise at the NURC (NATO Undersea Research Centre) in La Spezia, Italy. Each parameter has been calculated as the average of the values for each meter of the layer from surface to 50 m depth, that corresponds about to the average thermocline calculated in the study areas.

The circulation features were evaluated by means of the altimeter products (Absolute Dynamic Topography) and geostrophic velocity field, produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (http://www.aviso.oceanobs.com/duacs/). The period selected to evaluate the circulation pattern was 15 July–14 August 2009 for the Tyrrhenian Sea and 01–31 July 2009 for the stations in Strait of Sicily.

Since results of this study about the larval fish distribution in Strait of Sicily suggested a relationship with offshore wind-induced currents, the influence of wind on surface circulation was evaluated by means of satellite wind stress ($\vec{\tau}$) and Ekman transport ($\vec{m}$) from ocean surface 6-hourly wind data ($\vec{U}_{wind}$), provided by the Cross-Calibrated Multi-Platform project (25 × 25 km, http://podaac.jpl.nasa.gov).

Wind stress was obtained as:

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

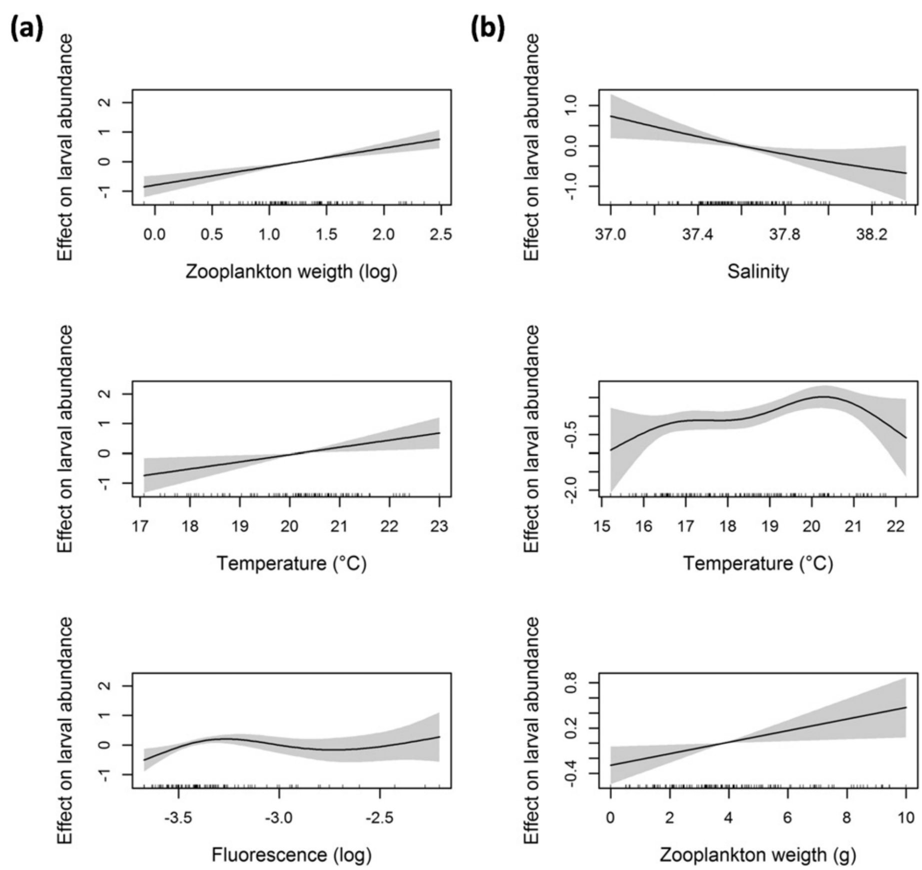

Fig. 2. (a) Plots of the smoothing response of the generalized additive model for larvae abundance in the Tyrrhenian Sea. (b) Plots of the smoothing response of the generalized additive model for larvae abundance in the Strait of Sicily. Black thick line indicates the value of the GAM smoothing response and grey area represents the 95% confidence intervals.

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

Ekman transport was calculated as:

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

where ρ_{water} ρ_{water} is the water density, f the Coriolis parameter, and $\hat{k}$ is the vertical unit vector (Pickett and Paduan, 2003).

Finally, the Ekman transport $\vec{M}$ was spatially represented in daily maps corresponding to survey period (from 4 to 21 July 2009).

2.2. Data analysis

A generalized additive model (GAM; Hastie and Tibshirani, 1986) for each study area was applied on total larval fish abundance and environmental parameters to define the factors that influenced larval fish concentration. Fluorescence and zooplankton weight of the Tyrrhenian Sea were transformed into natural logarithm in order to achieve uniform distribution for GAM application. The quasi-Poisson error distribution with the log link function was used and the natural cubic spline smoother was applied for smoothing the GAM fitting. The selection of the final model was performed by minimizing the Generalized Cross-Validation (GCV) and maximizing the level of explained deviance (0–100). All first-order interactions of the main effects were tested. Validation graphs (*e.g.* residuals *versus* fitted values, QQ-plots and residuals *versus* the original explanatory variables) were then observed to detect the existence of any pattern and possible model misspecification.

Afterwards, the stations were classified according to their species composition similarity by hierarchical clustering using the Bray-Curtis distance measure (Bray and Curtis, 1957) and Ward's linkage as grouping method (Ward, 1963). Only dominant families, defined as those with total density > 0.5 individuals per m^3, and the stations with presence of fish larvae were used in order to avoid problems, *e.g.* biasing or dominating the ordination. No scaling of the data was preventively carried out for the taxonomic dataset of the Tyrrhenian Sea, while the density values of the Strait of Sicily were transformed into square root, because some larval fish taxa exhibited a large variance and they could be decisive in determining the main sources of information. Analysis of similarities (ANOSIM) was performed to test the significance of differences in groupings separated in the cluster analysis (Clarke, 1993). Levels of occurrence, abundance of species and geographical distinctness among species and station groups were then used as subjective criteria to fine-tune the identification of clusters.

A Principal Coordinate Analysis (PCoA; Gower, 1966) was performed on Bray–Curtis dissimilarity of the larval fish assemblages to describe relationships among clusters and to show their general spatial pattern. The equilibrium circle (Legendre and Legendre, 1998) was used to select the families, that significantly contributed to the axes shown in the ordination graph. Specifically, they must have vectors outside of the equilibrium circle. The first and second dimensions of the PCoA were mapped to reveal gradients and patchiness.

A distance-based redundancy analysis (dbRDA), based on the Bray–Curtis dissimilarities and limited to 2 axes, was performed to explore which group of habitat variables best explained the spatial variation observed in larval fish assemblage structure (McArdle and Anderson, 2001). Environmental variables were standardized to obtain comparable scales (Clarke and Warwick, 1994). Distance based redundancy analysis (dbRDA) biplots were generated to visually display the direction and magnitude of the relationships between habitat factors and larval fish families (Legendre and Anderson, 1999). All the statistical analyses were carried out using statistical software R (R 3.0.1; R Core Team, 2013).

3. Results

3.1. Larval fish abundance

In the 109 stations in the Tyrrhenian Sea, total fish larvae density ranged between ~0.027 n/m^3 and ~1.941 n/m^3 (mean 0.296 n/m^3; standard deviation 0.243). The station with the most concentrated density was in the western coastal side of the study area in the gulf of Palermo. In general, ichthyoplankton showed a patchwork distribution with no difference between offshore and coastal area (KW = 0.791; p-value > 0.05) and with higher concentrations of larvae in the eastern coastal side compared to the western coastal side (KW = 5.237; p-value < 0.05) (Fig. 1).

In the 150 stations in the Strait of Sicily total fish larvae density ranged between ~0.011 n/m^3 and ~3.572 n/m^3 (mean 0.433 n/m^3; standard deviation 0.561). Largest abundance values were found in the eastern part of the study area (KW = 5.868; p-value < 0.05), over the continental shelf area separating Sicily coasts from Maltese Islands (Fig. 1).

The generalized additive model for the Tyrrhenian Sea indicated the zooplankton weight, the temperature and the natural logarithm of fluorescence as the most important factors to explain the variability of larval fish abundance. The explained deviance by the model was 34.2% of the

Table 2
Larval fish families recorded in Tyrrhenian Sea and the Strait of Sicily. Ecological group (B: bathypelagic fish, P: pelagic fish, M: mesopelagic fish, D: demersal fish), abundance (number of fish larvae for each family) and percentage of total abundance (number of fish larvae for each family/total number of fish larvae) are reported.

Family	Ecological group	Abundance Tyrrhenian Sea	Percentage Tyrrhenian Sea	Abundance Strait of Sicily	Percentage Strait of Sicily
Ammodytidae	D	14	0.617	2	0.077
Apogonidae	D	3	0.132	1	0.039
Blennidae	D	1	0.044	7	0.270
Bothidae	D	24	1.057	35	1.352
Bramidae	P	2	0.088	1	0.039
Callionymidae	D	5	0.220	20	0.773
Carangidae	P	10	0.441	31	1.198
Centracanthidae	P	7	0.308	17	0.657
Centriscidae	D	1	0.044	1	0.039
Cepolidae	D	6	0.264	1	0.039
Clupeidae	P	238	10.485	557	21.522
Congridae	D	2	0.088	20	0.773
Coproidae	D	1	0.044	0	0.000
Cynoglossidae	D	1	0.044	0	0.000
Engraulidae	P	132	5.815	1127	43.547
Evermannelidae	B	0	0.000	5	0.193
Gadidae	D	4	0.176	37	1.430
Gobidae	D	110	4.846	153	5.912
Gonostomatidae	B	848	37.357	195	7.535
Labridae	D	25	1.101	60	2.318
Myctophidae	M	387	17.048	124	4.791
Ophichthidae	D	1	0.044	2	0.077
Ophidiidae	D	1	0.044	0	0.000
Paralepidae	M	113	4.978	14	0.541
Phosichthyidae	B	207	9.119	23	0.889
Pomacentridae	P	32	1.410	14	0.541
Scombridae	P	18	0.793	22	0.850
Scophthalmidae	D	0	0.000	2	0.077
Scorpaenidae	D	3	0.132	12	0.464
Serranidae	D	25	1.101	27	1.043
Soleidae	D	0	0.000	3	0.116
Sparidae	D	34	1.498	57	2.202
Sternoptychidae	B	1	0.044	1	0.039
Stomiatidae	P	1	0.044	0	0.000
Stomiidae	B	1	0.044	0	0.000
Synodontidae	D	4	0.176	0	0.000
Trachinidae	D	1	0.044	9	0.348
Trichiuridae	M	1	0.044	1	0.039
Triglidae	D	0	0.000	5	0.193
Tunnidae	P	6	0.264	2	0.077
Total		2270		2588	

total deviance (Table 1). The relationship between larval fish abundance and zooplankton weight and temperature was linearly increasing, indicating a positive effect on abundance for zooplankton values higher than about 4.40 g and temperature values higher than 20.5 °C. The effect of fluorescence values was increasing until 0.04 mg L^{-1} and almost absent for higher values (Fig. 2a).

The selected parameters for the best model to explain the larval fish abundance in the Strait of Sicily were salinity, zooplankton weight and temperature. The explained deviance by the model was 42.5% of the total deviance (Table 1). The higher larval fish abundance was associated with the lowest salinity values (<37.6) and with optimal temperature in the range 19–21 °C. The effect of the zooplankton on larval fish abundance was linearly increasing and positive for zooplankton values higher than 4 g (Fig. 2b).

3.2. Larval fish composition

A total of 2270 fish larvae from 36 families in the southern Tyrrhenian Sea and 2588 fish larvae from 34 families in the Strait of Sicily were identified (Table 2). The three most abundant families accounted for 64.89% of the total catch in the Tyrrhenian Sea. They were Gonostomatidae (37.36%), Myctophidae (17.05%) and Clupeidae (10.48%). Except Phosichthyidae (9.12%), Engraulidae (5.81%) and Gobidae (4.85%), all other 30 families comprised <2% of the total number of larvae collected. In the Strait of Sicily, the most abundance families were Engraulidae (43.55%) and Clupeidae (21.52%), and except Gonostomatidae (7.53%), Gobidae (5.91%), Myctophidae (4.79%), Labridae (2.32%) and Sparidae (2.20%), all other families comprised <2% of the total larvae.

Four larval fish assemblages were defined by the Bray–Curtis dissimilarity index for sample from Tyrrhenian Sea and five assemblages from Strait of Sicily, as suggested by their respective dendrograms (Fig. 3 a and b). The clusters differed substantially in family composition and abundance, presenting distinct assemblage structures in both sampling areas. The ANOSIM analysis showed significant dissimilarity between families assemblages obtained from cluster analysis in Tyrrhenian Sea (Global R = 0.6625; $p < 0.001$) and in the Strait of Sicily (Global R = 0.5523; $p < 0.001$).

The families that significantly contributed to the axes shown in the ordination graph of PCoA applied on data from Tyrrhenian Sea were Gonostomatidae, Myctophidae, Gobidae, Engraulidae and Clupeidae. The first dimension of the PCoA well discriminated two groups: the lower values characterized clusters 1 and 2 and families Gonostomatidae and Myctophidae and the higher values characterized clusters 3 and 4 and families Engraulidae, Gobidae and Clupeidae (Fig. 4a). This dimension showed a strong coastal–offshore gradient, indicating that the first assemblage (clusters 1 and 2 with mesopelagic families) was mainly present in the offshore area unlike families belonging to the second assemblage (clusters 3 and 4 with neritic families) located in coastal areas (Fig. 4b). The second dimension of the PCoA discriminated larvae of clusters 1 and 3 with small pelagic families from larvae of cluster 2 with mesopelagic families (Fig. 4a). This dimension showed different values in specific areas. In particular, higher values (clusters 1 and 3 with neritic families) were found in the Gulf of Palermo and in the easternmost part of the study area (Fig. 4c). Otherwise, negative values (cluster 2, mesopelagic fish larvae), were present in the offshore zone and in central-east coastal zone with exception of areas from 14.75° and 15° of longitude (Fig. 4c).

The families that significantly contributed to the PCoA axes defined by data from Strait of Sicily were Clupeidae, Engraulidae, Gobiidae, Labridae, Bothidae, Myctophidaedae. The first dimension of the PCoA discriminated two groups: the lower values characterized clusters 1 and 4 and families Clupeidae and Engraulidae and the higher values clusters 2 and 5 and families Gonostyomatidae and Myctophidae (Fig. 4d). This dimension showed the presence of the second assemblage (clusters 2 and 5 with mesopelagic families) in the western

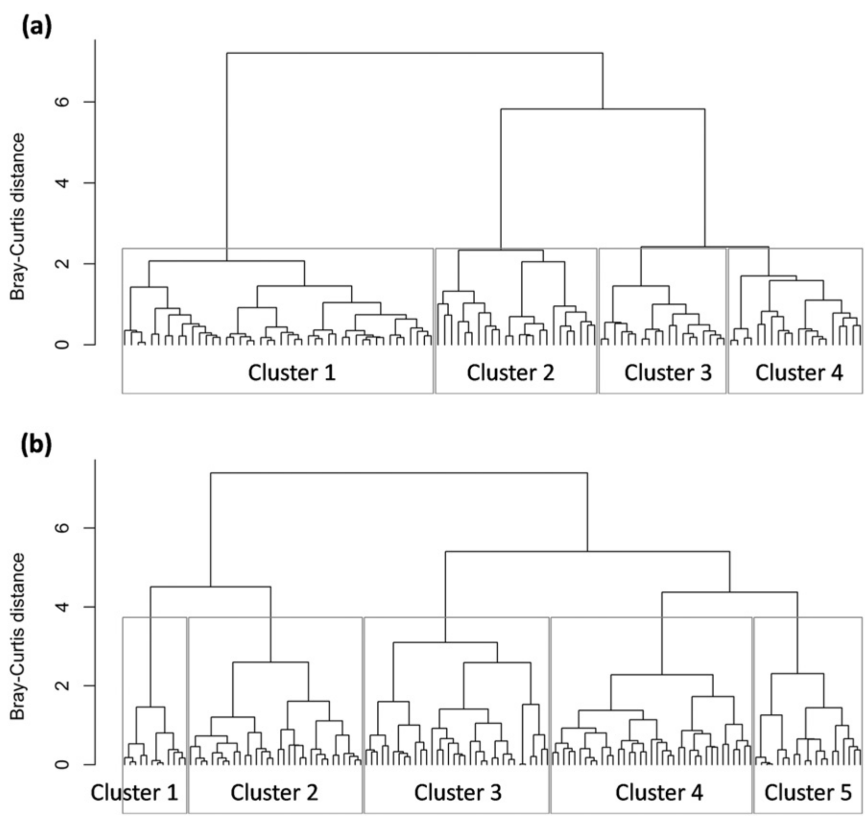

Fig. 3. Dendrograms generated by hierarchical cluster analyses with Bray–Curtis distance and Ward's grouping method applied on larval families composition in the southern Tyrrhenian Sea (a) and Strait of Sicily (b).

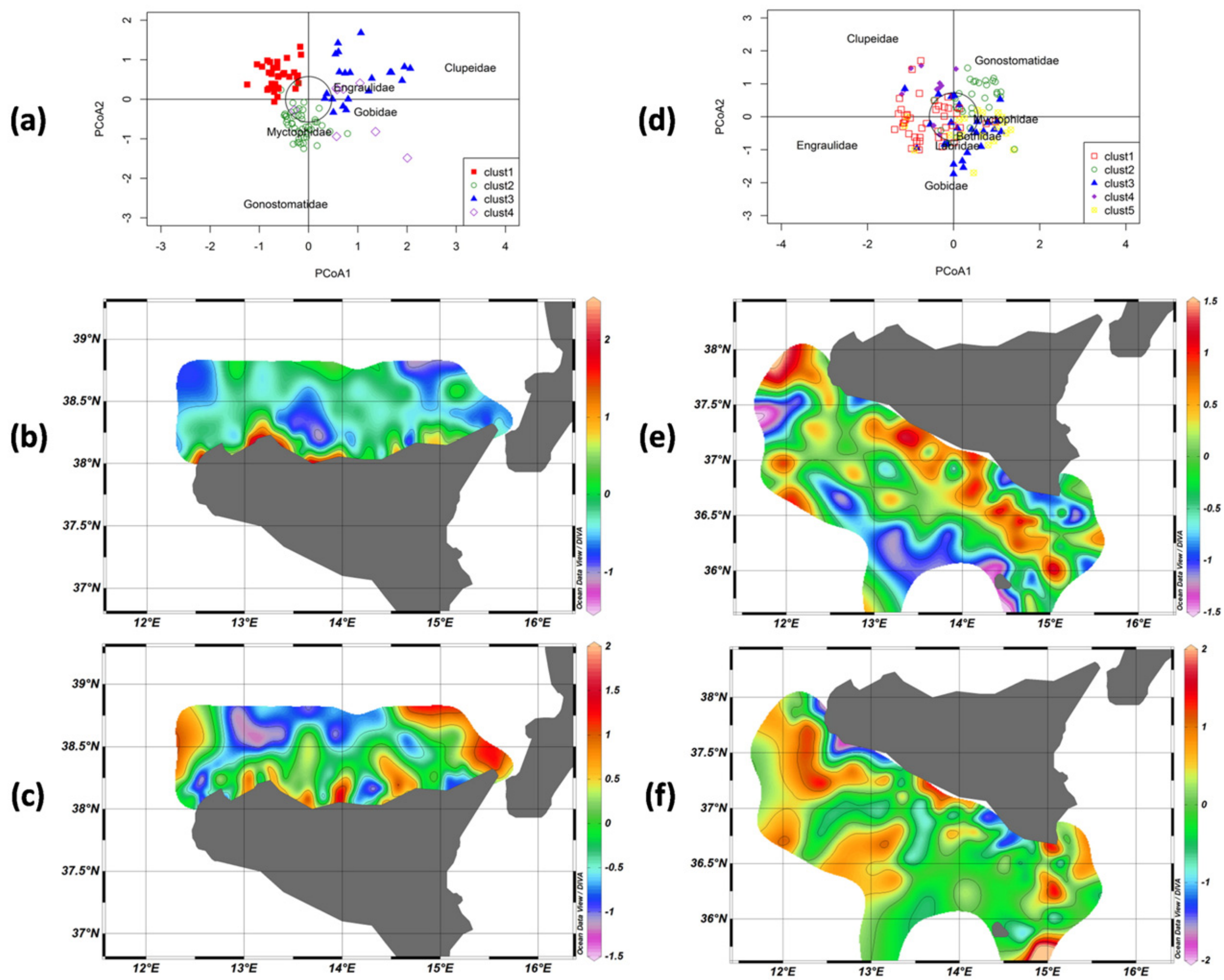

Fig. 4. (a) Bivariate plot of first and second principal coordinates on larval fish composition in the Tyrrhenian Sea. The equilibirum circle was added to a PCoA ordination diagram; (b) geographical distribution of the first principal coordinates on larval fish composition in the Tyrrhenian Sea; (c) geographical distribution of the second principal coordinates on larval fish composition in the Tyrrhenian Sea; (d) bivariate plot of first and second principal coordinates on larval fish composition in the Strait of Sicily. The equilibirum circle was added to a PCoA ordination diagram; (e) geographical distribution of the first principal coordinates on larval fish composition in the Strait of Sicily; (f) geographical distribution of the second principal coordinates on larval fish composition in the Strait of Sicily.

coastal area up to 14.5° of longitude, while the first assemblage (clusters 1 and 4 with small pelagic families) was dominant in the eastern coastal area and offshore (Fig. 4e). The second dimension of the PCoA discriminated larvae from cluster 5 with families Bothidae, Labridae and Gobiidae (lower values) from larvae from clusters 2 and 4 with families Clupeiade and Gonostomatodae (higher values) (Fig. 4d). This dimension showed lower values in the central area (from 13° to 15° of longitude) and higher values in the remaining areas (Fig. 4f).

3.3. Environmental parameters

3.3.1. Tyrrhenian Sea

The surface waters dynamics evidenced the presence of an anticyclonic eddy in the Tyrrhenian Sea located in the area from longitude 13°E to 14.5°E (Fig. 5a). This structure involved a sub-surface section of the water column until about 300 m of depth (Fig. 5b) and it was particularly evidenced by the isopycnal line 29 kg m^{-3} that in the middle sank from 200 m to 300 m.

The areal distribution of the parameters (temperature, salinity, fluorescence and zooplankton weight) showed the variability of the sub-surface layer. The isosurface of temperature (Fig. 6a) showed the presence of colder water in the western area of the study area and simultaneously an increase of temperature in the central area due essentially to the presence of anti-cyclonic eddy that generated a flexion of isotherms (not shown), such as of isopycnal lines (Fig. 5b). The salinity (Fig. 6b), fluorescence (Fig. 6c) and zooplankton (Fig. 6d) minimum values were in correspondence with this eddy. The zooplankton isosurface (Fig. 6d) showed higher values in the entire area further to the west and in the coastal eastern side.

3.3.2. Strait of Sicily

Geostrophic velocity field showed that the surface circulation was mainly affected by the eastward flow of AIS, which was characterized by its typical meandering path that borders the eastern coast of Sicily and reached maximum values of ~44 m s^{-1} in the core (Fig. 5a). Moreover satellite images (Fig. 5a) and density interfaces (Fig. 5c) showed the presence of two cyclonic structures in western side of the Strait of Sicily and a modest and superficial anti-cyclonic structure in eastern part. Specifically, the isopycnal 28.5 was about 50 m depth in the western part of Sicily and sank to about 120 m depth in the eastern part (Fig. 5c). Analysis of temperature and salinity data in the layer 0–50 m evidenced colder (16–18 °C) and saltier (37.75–38 PSU) water in coastal zone, especially in the Adventure Bank (western part of the study area) (Fig. 6a and b). The Bank was also characterized by higher fluorescence (Fig. 6c) and zooplankton (Fig. 6d) values. This may indicate the presence of wide coastal upwelling phenomena, generated by wind. Daily Ekman transport maps ($\vec{m}$) showed a clear transport of water from coastal to offshore zone for most of the days during the survey (Fig. 7). Indeed moderate ($4 < \vec{m} < 8$ m^2 s^{-1}) and intense ($\vec{m} > 8$ m^2 s^{-1}) values of cross-shore

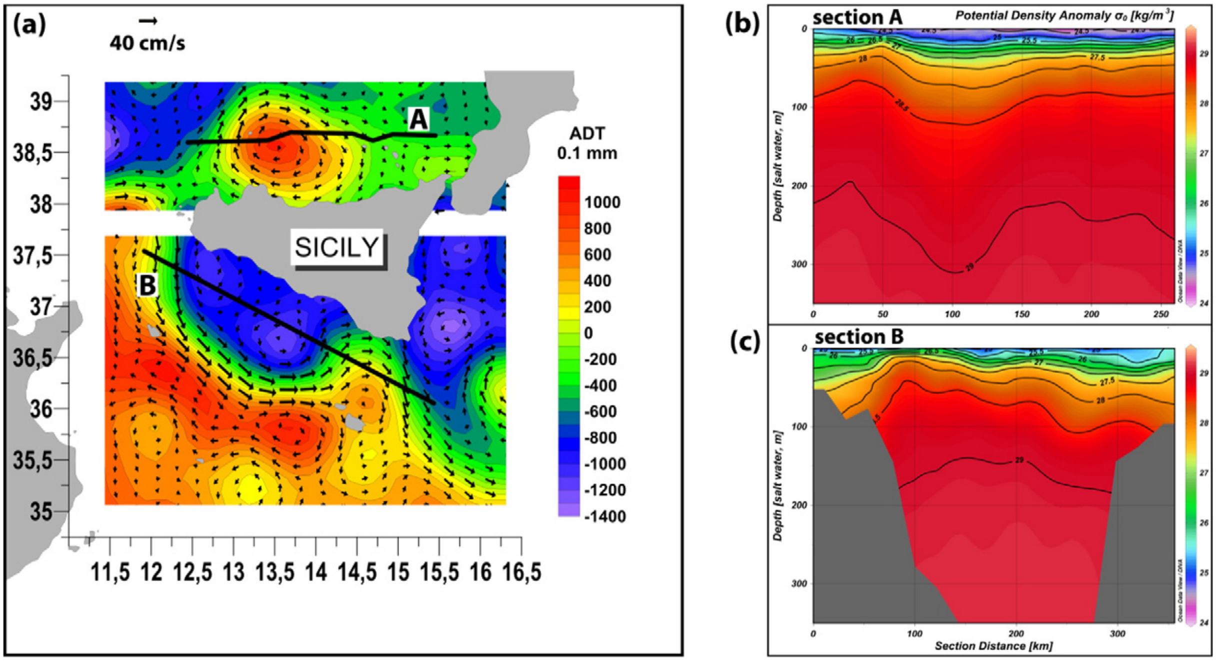

Fig. 5. (a) Absolute Dynamic Topography (ADT) and mean geostrophic velocity field by Aviso; (b) vertical section of density profiles across the transect A (Fig. 5a) in the upper 350 m; (c) vertical section of density profiles across the transect B (Fig. 5a) in the upper 350 m.

transport were evident in 11 over 18 analyzed days while in the other days the transport is weak or absent, especially in the coastal zone.

Moreover, a marked thermo-haline front was present in the easternmost part, beyond 15° of longitude and high zooplankton values were found in the western area adjacent to this front (from 13.5 to 14.5° of longitude; Fig. 6d).

3.4. Correlation between larval fish assemblages and environmental variables

The dbRDA provided an ordination that was constrained by some environmental variables. Results of the routine for the Tyrrhenian Sea showed that only the first two axes were significant which explained 77.20% of the overall variability. All environmental parameters, except the salinity, were significant. The biplot of the first two dbRDA axes (Fig. 8a) revealed a separation among clusters based on the environmental parameters. The first RDA axis revealed a separation between cluster 1, negatively correlated to temperature, zooplankton weight and fluorescence from cluster 2 positively correlated to the same parameters. The second axis identified neritic families (cluster 4) positively correlated with fluorescence and zooplankton weight and negatively correlated with temperature.

Results of the dbRDA for the Strait of Sicily showed that the first two axes were significant explaining the 63.41% of the overall variability. All parameters were significant. The first RDA axis revealed a separation between the first assemblage with small pelagic larvae (clusters 1 and 4) and the second assemblages (clusters 2 and 5). The second RDA axis separated clusters 3 and 5, positively correlated with zooplankton weight and salinity, from clusters 2 and 4, positively correlated with fluorescence and temperature (Fig. 8b).

4. Discussion

This study aims to examine the responses of larval fish assemblages to different hydrodynamic conditions, in order to clarify the role that mesoscale oceanographic structures, such as gyres, fronts and currents, can play compared to different chemical, physical and biological conditions. These factors can contribute to the survival and distribution of fishes at early development stages and consequently to the recruitment of marine fish populations.

The southern Tyrrhenian Sea is a typically oligotrophic area but little is known about the effects of physical forcings on the biology and ecology of fish populations (Azzaro et al., 2003; Carrada et al., 1992; De Domenico, 1979; Giordano et al., 2014). Open southern Tyrrhenian Sea is considered as an important spawning area for the swordfish (*Xiphias gladius*; Romeo et al., 2009) and the Atlantic blue fin tuna (Sinopoli et al., 2004). Moreover, a previous study showed that it is a relevant nursery area for the short-finned squid *Illex coindetii* (Perdichizzi et al., 2011), which represents an important prey for several adults fish species.

Our results in Tyrrhenian Sea generally permitted the identification of two main larval fish assemblages, separating a group of shallower stations where most larvae belonged to neritic families and another group of deeper stations where mesopelagic families were dominant. This bathymetric separation confirmed a study on ichthyoplankton composition carried out in June 2006 that covered only the eastern coastal side of southern Tyrrhenian Sea, from Cape Cefalù to Cape Rasocolmo. In fact, this study showed that in this region three main assemblages can be distinguished: shore fish larvae (Labridae, Serranidae) which dominate in coastal areas, larvae found over the continental shelf (Sparidae, Scorpaenidae, Bothidae, Mullidae, Engraulidae, Gobiidae, Trachinidae, Blennidae) and larvae of meso- and bathypelagic species, which mainly over slope and open waters (Gonostomatidae, Myctophydae, Sternoptychidae). This inshore–offshore gradient was explained with respect to the hydrographic features and structures determined by the surface circulation path (Giordano et al., 2014). Moreover, these results were very similar in terms of species composition and distribution to what found in nearby areas in the Mediterranean Sea (Alemany et al., 2006; Sabatés and Olivar, 1996). However, mesopelagic larvae (*e.g.* Myctophidae), which presented an irregular distribution, were abundant not only offshore but also in coastal stations. This situation could be linked to larval fish transport by oceanographic structures characterizing the southern Tyrrhenian Sea and affecting strictly the habitat (García Lafuente et al., 2002). There, the main feature observed was the presence of an anti-cyclonic gyre in the northern side of the Gulf of Palermo, which was characterized by warmer and less salty water, with low values of linked-productivity

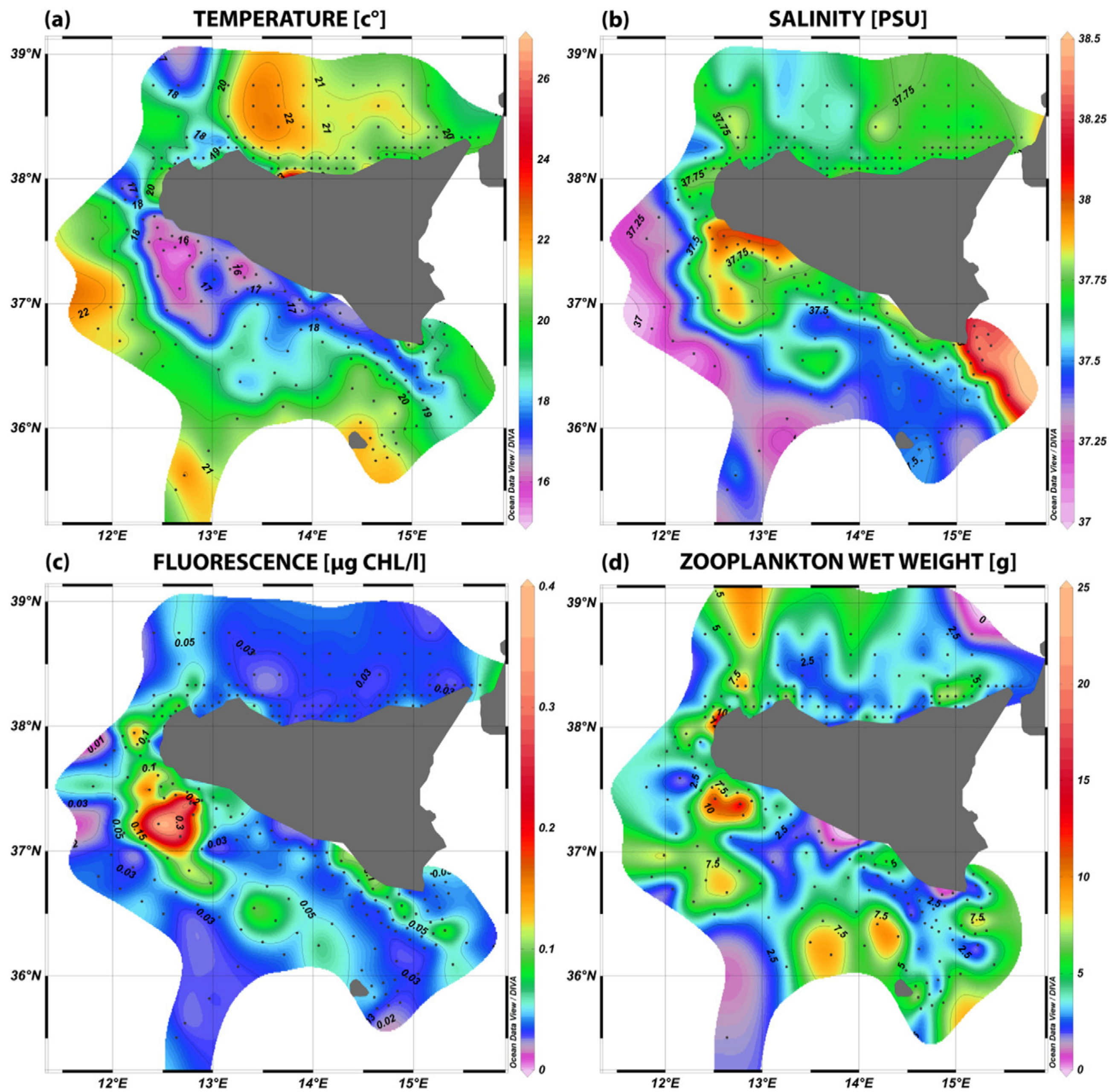

Fig. 6. Horizontal distribution pattern of mean values of temperature (a), salinity (b) and fluorescence (c) salinity in the layer 0–50 m and of total zooplankton weight (d).

parameters (fluorescence and zooplankton weight) in the core. This structure generated a near-coast accumulation area, exhibiting the maximum larval fish concentration. Specifically, the anti-cyclonic eddy could have acted as mechanisms of retention and concentration of different larval fish taxa, especially belonging to Clupeidae, Engraulidae and Gobiidae families and facilitated the transport inshore of mesopelagic larvae. In fact, it was shown that the dynamics of anticyclonic flow patterns imply convergence and downwelling (Bakun, 1996), with associated opportunities for concentrating small organisms in convergent frontal formations (Agostini and Bakun, 2002). The occurrence of mesopelagic species in neritic zones, where the spawning is not present, was observed also in other areas of the Mediterranean Sea, particularly in the Balearic Sea (Alemany, 1997), in the northern Aegean Sea (Koutrakis et al., 2004; Tsikliras et al., 2009) and in Costa Brava (Palomera and Olivar, 1996). Conversely, the eastern side of Tyrrhenian Sea was an area with apparently more stable hydrodynamic conditions. In this area, the larval fish assemblages were more regular, corresponding to the absence of relevant mesoscale oceanographic forcings. The environmental conditions rather than the dispersal of species could have partially determined the structure and dynamics of the eastern communities. In fact, larvae belonged to demersal and pelagic families were mainly concentrated in the coastal part, characterized by higher surface temperature values and mesopelagic larvae could be found mainly offshore as well as total zooplankton, with lower density values compared to the western offshore areas.

A different situation was found in the Strait of Sicily, which was also classified as an oligotrophic area (Malanotte Rizzoli et al., 1997; Van Wambeke et al., 2002). It was characterized by a very complex sea circulation that can have strongly influenced the spawning strategy and the recruitment success of many fish species (Cuttitta et al., 2003, 2015; Fortibuoni et al., 2010; Garofalo et al., 2010). In particular, many studies (Basilone et al., 2013; Cuttitta et al., 2015; Falcini et al., 2015; García Lafuente et al., 2002) have focused on the influence of oceanographic factors on the ecology and reproductive biology of

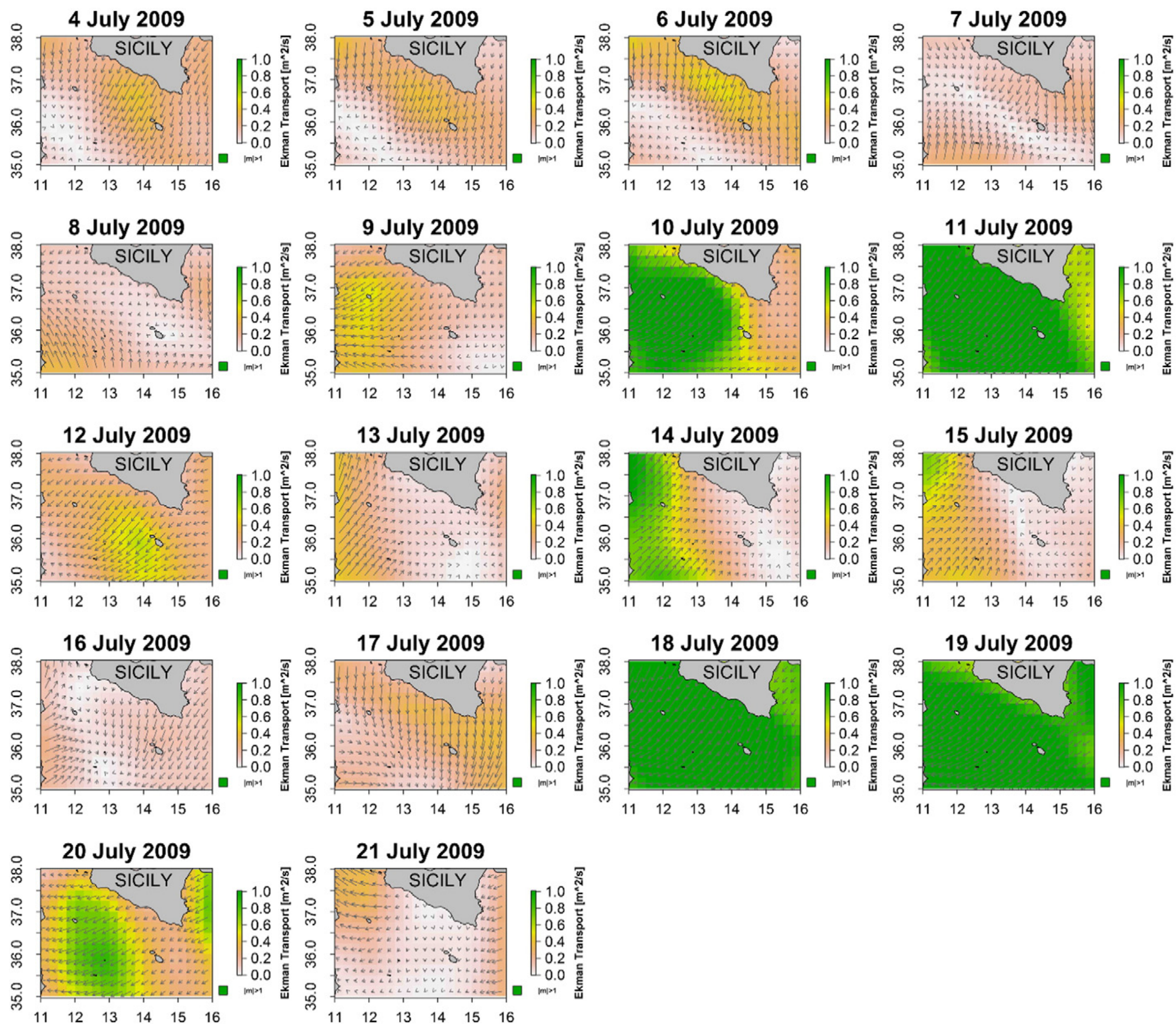

Fig. 7. Daily Ekman transport ($m^2\ s^{-1}$) during the cruise (Bansic 09) in Strait of Sicily. Arrows and colors indicate the direction and the intensity of the transport respectively.

the European anchovy (*Engraulis encrasicolus*), which is the target species of fisheries along the southern coast of Sicily, representing one of major fish resource in terms of economic importance (Patti et al., 2005, 2012). In this study, the influence of the circulation pattern in the Strait of Sicily on the distribution of fish larvae was very clear and it can be considered the main factor governing the larval fish retention and shaping the observed assemblages. In fact, the distribution of total larvae was largely consistent with the branch of the AIS, running roughly parallel to the southern Sicilian coast. AIS was able to advect the larvae towards a retention area at the south-easternmost corner of Sicily (off Capo Passero). Here, the presence of a thermo-haline front, as evidenced by temperature and salinity fields, allowed the larvae to maintain their relative position in an area with enhanced trophic condition, so probably providing more favourable conditions for larval fish feeding and growth (García Lafuente et al., 2002, 2005; Mazzola et al., 2002). As support of this finding, our results showed that this area was characterized by the mixing of all clusters. This happened because AIS transport and the thermo-haline front conveyed there the larvae belonged to families different from ecological point of view (demersal and small pelagic together with meso and bathypelagic fish larvae). In addition, the spatial extension of AIS path may have had important consequences on the predominant hydrological phenomena occurring in the region, such as the offshore extension of coastal upwelling (García Lafuente et al., 2005). In summer 2009, the flow of the stream moved further offshore (Bonanno et al., 2014) and so the study area showed a broader upwelling extension centred in the western zone on Adventure Bank and expanded eastward, modifying surface temperature, salinity and linked-productivity parameters (fluorescence and zooplankton weight). This feature was confirmed by the analysis of Ekman transport, which showed that strong and persistent transport of water induced by Mistral (NW) and Westerly winds and directed offshore was detected during the survey. These winds could have played a key role in shaping larval fish distribution pattern, because they could have modulated the capacity of advection of fish larvae offshore, similarly to what observed by Falcini et al. (2015) for the anchovy larvae in year 2004. In fact, in correspondence with these processes, typically neritic larvae (pelagic families: Engraulidae and Clupeidae) were found in the offshore stations.

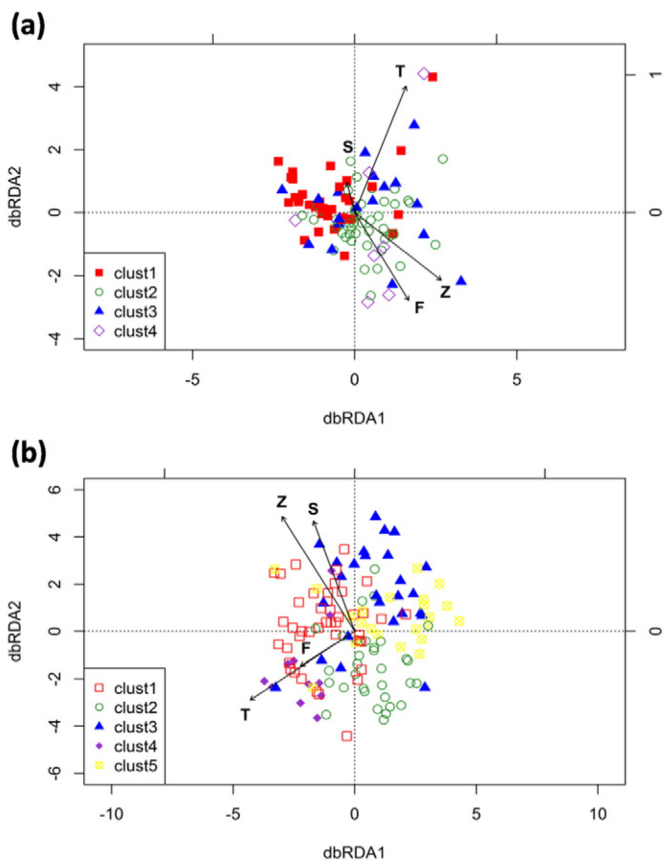

Fig. 8. Db-RDA ordination graph for the first two axes for the larval fish composition using Bray-Curtis distance and the CTD parameters (T: temperature; S: salinity; F: fluorescence; Z: zooplankton weight) as a constraining variable for the southern Tyrrhenian Sea (a) and for the Strait of Sicily (b).

Therefore, in contrast to the findings for the southern Tyrrhenian Sea, complex mesoscale oceanographic structures (*e.g.* AIS pathway, coastal upwelling, gyres and fronts), that interacted synergistically, were able to drive the mainly patterns of distribution of fish larvae in the Strait of Sicily. This evidence was supported also by the analysis of significance of environmental parameters affecting larval fish distribution. Indeed, only salinity and zooplankton weight were found to determine the taxonomic composition, discriminating small pelagic fish larvae species from larvae belonging to Gonostomatidae family. The association between salinity and zooplankton is mostly linked to the features of AIS surface currents, characterized by relatively low salinity values and able to transport zooplankton along its path off southern Sicilian coasts (Patti et al., 2005).

5. Conclusions

This case study evidenced the need to assess specific environmental conditions driving the dynamics of development of fish larvae and consequently the recruitment success of marine populations in a framework of efficient monitoring plans. The results underlined the different roles of mesoscale oceanographic structures compared with chemical, physical and biological parameters in shaping the spatial pattern of larval fish distribution in the central Mediterranean Sea in a case study of Summer 2009. In the Southern Tyrrhenian Sea more stable hydrodynamic conditions were observed. In this framework, although the anticyclonic eddy in the central part of the study area was able to transport part of mesopelagic larvae (*e.g.* mainly Myctophydae) in a restricted portion of the northern Sicilian coast, bathymetry and environmental conditions played a key role in determining larval fish distribution. Conversely, in the Strait of Sicily the distribution of early life stages of fish marine species was highly dependent on marked hydrodynamic features (current speed up to ~44 cm/s). In this context, larval fish distribution showed complex spatial patterns, not associated with bottom depth as found in other similar studies in Mediterranean (Alemany et al., 2006; Giordano et al., 2014; Granata et al., 2011; Sabatés and Olivar, 1996) but with mesoscale oceanographic structures (*e.g.* surface currents, gyres and fronts), as reported in different cases by Bakun (2006); Basilone et al. (2013); Palomera (1992) and Sabatés et al. (2001). These structures conveyed the larvae in retention areas with conditions favorable for their survival and growth (Cushing, 1990). Additionally, it was important to underline the effect of Mistral (NW) and Westerly winds in modulating the process linked to upwelling and the transport of neritic fish larvae offshore, as described by Falcini et al. (2015) about dispersion of anchovy larvae in year 2004.

Acknowledgments

The study was supported by the project "*Piano ICT per l'eccellenza nella Sicilia occidentale del settore innovazione imprenditoriale a partire dalla ricerca marina* (*ICT-E3*)", financed by the Region of Sicily. We thank Mr. Emanuele Gentile and Mr. Vincenzo Lubrano, Masters of the R/V Urania, and all of their crew for their collaboration and assistance during the oceanographic surveys and the technicians of the laboratories of IAMC-CNR U.O.S Capo Granitola for their help with ichthyoplanktonic sorting.

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