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Variability of water mass properties in the Strait of Sicily in summer period of 1998–2013

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Abstract

The Strait of Sicily plays a crucial role in determining the water mass exchanges and related properties between western and eastern Mediterranean. The presence of sills to the east and west of the Strait of Sicily and the complex seabed topography modulate the thermohaline circulation of the Mediterranean basin. An anti-estuarine circulation is mainly characterized, from a dynamic point of view, by a two-layer system: a surface layer composed of Atlantic Water (AW) flowing eastward, essentially dominated by mesoscale processes, and a subsurface layer composed of Levantine Intermediate Water (LIW) flowing in the opposite direction; the topography appears to play an important role. Furthermore, there are transition water masses with variable hydrological characteristics. The dataset here studied is a time series 16 years long (1998–2013), which highlights the high horizontal and vertical interannual variability affecting the study area. Strong temperature-salinity correlations, in the intermediate layer, for specific time intervals, could be linked to the reversal of sub-surface circulation in the Central Ionian Sea. Moreover, a long-term monitoring of the hydrographic properties of water masses across this strait allow the modelers to assess the performance of hydrological models of this area.

1 Introduction

The Strait of Sicily is a topographically complex region of the Central Mediterranean (CMED) comprising two sills separated by an internal deep basin; the eastern sill has a maximum depth of about 540 m, the western sill is composed of two narrow passages with a maximum depth of 530 m, and the central basin has trenches more than 1700 m deep (Gasparini et al., 2005). From a dynamic point of view, three main spatial and temporal scales characterize the CMED (Sorgente et al., 2011): (i) the mesoscale (characterized by horizontal scale less than few tens of kilometers and periods in the range from a few days to a few tens of days), (ii) the large Mediterranean basin scale including

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the thermohaline circulation, and (iii) the sub-basin scale (oceanographic phenomena characterized by diameters ranging between 200 and 300 km). The mesoscale structures (i), under the influence of wind stress, topography and internal dynamical processes generate boundary currents and jets which can bifurcate, meander and grow then forming ring vortices and filament patterns interacting with the large scale flow fields (Lermusiaux, 1999; Lermusiaux and Robinson, 2001). The thermohaline circulation (ii) in this area is antiestuarine and is mainly driven by the balance between the relatively fresh waters entering at the Gibraltar Strait and the negative fresh-water budgets over the whole Mediterranean basin (Sorgente et al., 2011). Specifically, the upper open conveyor belt consists of an eastward flow of low-salinity Atlantic Water (AW) and a subsurface layer (200–400 m) of westward-spreading saltier Levantine Intermediate Water (LIW), sporadically enriched by Cretan Intermediate Water (CIW). Two quasi-closed secondary cells are present in the eastern and in the western Mediterranean basins, which are responsible for the transformation of surface and intermediate waters into eastern and western Mediterranean deep waters (EMDW and WMDW) respectively. The role of the LIW is particularly important since it is the preconditioning agent for the formation of both the Adriatic Deep Water (AdDW) and WMDW (Gačić et al., 2013). At sub-basin level (iii), two main veins of the AW are known to flow in the Strait of Sicily: the Atlantic Tunisian Current (ATC – Sammari et al., 1999) in the south along the African coast and the Atlantic Ionian Stream (AIS – Robinson et al., 1999) in the north along the Sicilian coast. The AIS constitutes an energetic current mainly flowing eastward, able to force upwelling on the Adventure Bank (AB in Fig. 1) and along the southern Sicilian coast, especially during summer when such current is stronger. An important spatial variability exists in terms of shape, position and strength of permanent or quasi-permanent sub-basin gyres and their unstable lobes, meanders patterns, bifurcation structures and strength of permanent jets, transient eddies and filaments (Robinson et al.,1999; Sorgente et al., 2011; Basilone et al., 2013; Bonanno et al., 2013). The ATC, flowing along the Tunisian coast, shows a more clearly-marked path in winter (Sorgente et al., 2003, 2011; Béranger et al., 2004) than in summer.

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Further confirmation of the weakening of the ATC signal in summer is highlighted by Placenti et al. (2013), that found a more regular jet of the AIS than the ATC, which becomes unstable producing also small scale features (Gasparini et al., 2008). The intermediate and deep circulations in the Strait of Sicily are mainly represented by the LIW moving westward around the submarine mountains of the eastern Mediterranean before crossing the channel through the sills south of Malta at a depth ranging from 250 to 350 m (Placenti et al., 2013; Lemursiaux and Robinson, 2001). Interannual changes have been recorded in the outflowing dense water mass characteristics in the Sicily Channel (Gasparini et al., 2005). In particular, during the eastern Mediterranean Transient (EMT – Roether et al., 2007; Theocharis et al., 1999, 2002), a part of eastern Mediterranean Deep water (EMDW) has been uplifted and was able to overflow into the Tyrrhenian Sea (Klein et al., 2004). Such water mass, called transitional EMDW (tEMDW), is characterized at the bottom of the channel by a minimum potential temperature (Gasparini et al., 2005).

The classical view of a quasi-stable thermohaline circulation of the Mediterranean has recently been overruled. During the 1990s deep water formation in the Aegean sea took over from the Adriatic. Huge amounts of dense waters characterized by enhanced salinity and temperature were released for a few years, forming the EMT, significantly influencing the thermohaline structure and stratification of the entire eastern Basin (Borzelli et al., 2009; Gačić et al., 2013). The EMT induced changes have been communicated through the Strait of Sicily to the western Mediterranean basin (Gasparini et al., 2005). A significant warming and salinification of the whole water column has been observed also in the western Mediterranean, comparable to the EMT, both in terms of intensity and observed effects (Schroeder et al., 2008). Furthermore, it has been demonstrated that the upper layer circulation in the Ionian (Borzelli et al., 2009; Gačić et al., 2010), the thermohaline properties of the Adriatic deep water (AdDW – Gačić et al., 2010), and the salt distribution over the EM (Gačić et al., 2011) are interconnected through the Bimodal Oscillating System (BiOS – Gačić et al., 2010). In fact, during the last 24 years, it has been observed that the upper-layer circulation in the

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Ionian reversed on decadal time scales, from anticyclonic to cyclonic and vice versa. In particular, the anticyclonic mode represents a preconditioning mechanism for the dense water formation processes in the Aegean and eventually for EMT-like events (Demirov and Pinardi, 2002; Gačić et al., 2011). In this context, the Strait of Sicily is the most suitable region for observing the exchanges between the two basins and, more specifically, to follow how hydrographic modifications produced in one sub-basin can propagate into the other (Gasparini et al., 2005).

The main aim of this study is to examine the variability of thermohaline proprieties of the water masses flowing through the Strait of Sicily during the period 1998–2013. The entire time series is analyzed both in terms of horizontal and vertical spatial variability, and may improve the understanding on long-term variability and evolution of the Mediterranean circulation. The document also provides contributions that may allow the modelers to assess the performance of hydrological models of this area.

2 Dataset and methods

The dataset here analyzed was acquired during several oceanographic surveys carried out in the period 1998–2013 (Table 1) on board the R/V *Urania* in the Strait of Sicily. Sampling stations are arranged on a regular grid of 4 nautical miles in inshore waters and 12 miles in offshore waters, to ensure maximum area coverage with a specific attention to the continental shelf along the southern coast of Sicily (Fig. 1). Since 2004 CTD profiles have been acquired also in the Maltese waters in the framework of the FAO MedSudMed Project "Assessment and monitoring of the fishery resources and the ecosystems in the Straits of Sicily" (http://www.faomedsudmed.org/). The sampling design in Fig. 1 shows the maximum area coverage in the Strait of Sicily; during some surveys such design was modified mainly due to bad weather conditions. The long–term variability in the hydrological characteristics of the Strait of Sicily has been analyzed on the basis of vertical profiles of conductivity ($\mathrm{s\,m^{-1}}$), temperature (°C), pressure (db) and salinity (PSU) obtained from the surface to the bottom by means of a CTD-rosette system, consisting of a CTD SBE 911 plus probe and a General Oceanics rosette with 24 12 L Niskin Bottles. The probes were calibrated before and after the cruise at NURC (NATO Undersea Research Centre) in La Spezia, Italy. The collected downcast data was quality-checked and processed in agreement with the Mediterranean and Ocean Data Base instructions (Brankart, 1994), using the Seasoft-Win32 software. The overall accuracies are within 0.001 °C for temperature, 0.001 $\mathrm{s\,m^{-1}}$ for conductivity, and 0.015 % of full scale for pressure. With the aim of characterizing water masses and their interannual variability, we divided the water column into three layers. Two of them, the surface (0–200 m) and the intermediate (200–500 m) layers, represent the two main water masses in the Strait of Sicily; a third layer (> 500 m) is considered for characterizing deeper water mass. Mean values of temperature, salinity and density (and s.d. in Table 2) are evaluated for the area with longitude in the range 11.5–15° E and latitude in the range 35–38° N. Such dataset allows to better evaluate the spatial variability of water mass in both horizontal and vertical directions, and the relative dynamics of circulation. Moreover, the main surface circulation features in the Strait of Sicily were evaluated by means of the altimeter products (Absolute Dynamic Topography) produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (http://www.aviso.oceanobs.com/duacs/). The circulation pattern (geostrophic velocity field) in the study area was evaluated in the periods of the oceanographic surveys (see Table 1).

3 Results and discussion

3.1 Hydrology

The θ-S diagram (Fig. 2) mainly highlights the presence of two highly stratified water masses: fresher AW in the upper layer, and an intermediate westward-flowing salty outflow LIW. A third layer of transition water masses (tEMDW) with variable hydrological

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characteristics is evident. Only in some stations, to the east of meridian 15° E, the presence of Ionian Surface Water (ISW) is recorded.

3.2 The surface layer

The surface layer (0–200 m) is known to be characterized by both intrannual and interannual high variability (Gasparini et al., 2005; Ismail et al., 2012). Our dataset, mainly constituted by CTD profiles acquired in the period between end of June and July (except in 1999; see Table 1), confirms a high variability of such water layer in terms of temperature, salinity and density (Table 2). The presence of a water mass of Atlantic origin is highlighted by the minimum in the vertical salinity profiles (S_{min}). In the Strait of Sicily and in the years considered in this study, the average value of salinity minimum varied between 37.22, observed during the survey "Bansic07", and 37.863 recorded in the survey "Bansic12" (Table 3). Potential temperature at depth of minimum salinity varied between 17.577 °C and 20.342 °C, values estimated during the "Bansic09" and "Bansic08" oceanographic surveys respectively. The high variability in temperature and salinity (Table 3) are the result of the complex circulation of surface water, that in the Strait of Sicily is mainly dominated by mesoscale processes. The analysis of the hydrological dataset evidences the presence of transition water positioned between AW and LIW: the western Intermediate Water (WIW in Fig. 2). The WIW is generated during the winter convection period in the north area of the western Mediterranean Basin as a result of surface cooling of the AW and mixing processes with LIW below (Conan and Millot, 1995; Gasparini et al., 1999; Ismail et al., 2012). Generally WIW forms a portion of the water column positioned between 100 and 200 m depth with the same flow direction of the AW (Millot, 1999). During the surveys in the Strait of Sicily it has been recognized with a clear signal in some stations in western part of the study area in autumn 1999 and in summer 2005 and 2009. Intermittent signal of the WIW in the Sicilian Channel has also been reported by Sammari et al. (1999), Lermusiaux and Robinson (2001) and Ismail et al. (2012). In the study area the WIW is characterized by a potential temperature between 14 °C and 14.2 °C, a salinity in the range 38–38.6

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and density lower than 28.8 $kg\,m^{-3}$; it forms a portion of the water column positioned between 100 and 200 m depth.

Ismail et al. (2012) singled out the presence of the Ionian Water between the AW and the top of the LIW in the western side of the Strait of Sicily, with an east-west direction. The analyzed dataset permits to recognize the Ionian Waters in the eastern part of the Strait of Sicily and, in particular, east of the 15° E longitude (Fig. 2). Moving westward the ISW signal is less marked, due to mixing with the surrounding waters.

The different mean values of S_{min} and T_{Smin} (Table 3 and Fig. 3) reflect the changes of the hydrological characteristics during the observation interval. From 1998 to 2007 mean values of S_{min} are characterized by moderate variability around 37.4. In the period 2007–2012 a positive trend is evident up to a mean value of ~ 37.7.

Mean values of S_{min} and T_{Smin} show large inter-annual variability. The trend reported in Fig. 3 changes slightly if data from the west Ionian Sea (15–15.5° E) is included.

3.2.1 Dynamics of surface circulation

The geostrophic velocity field, evaluated for the CMED by means of the AVISO altimeter products, permitted to highlight the two main streams of AW: ATC and AIS (Fig. 4). ATC is more intense in winter (Sorgente et al., 2011; Ismail et al., 2012), and AIS is more intense in the summer and typically characterized by high spatial variability (Garcia Lafuente et al., 2005). Both flows are considered as quasi-permanent or permanent features of the area (Béranger et al., 2004; Sorgente et al., 2011).

The estimated path of both streams was checked by using salinity profiles collected in the study area. In particular, for each oceanographic survey the cores of AIS and ATC were identified by minimum salinity values (S_{min}) at each transect perpendicular to the Sicily coast (e.g. Fig. 5). The pattern of salinity minimum (Fig. 6) shows a variety of segmented structures confirming the complex circulation of surface water, which is dominated by mesoscale processes (Gasparini et al., 2005). The interpretation of the density interfaces (not shown) and of geostrophic currents (Fig. 4) in the study period, highlights the presence of alternating cyclonic and anticyclonic structures along the central part of the southern Sicily coast (13.5–14° E); such alternation was also highlighted by Basilone et al. (2013) for the period 1998–2007. The anticyclonic pattern operates a push towards higher latitudes of the AW favoring the entry of fresh water along the Sicilian coast (Fig. 4). Nevertheless, in some years, even though such anticyclonic pattern is present, fresh AW does not reach the Sicilian coasts (Figs. 4 and 6). The observed variability of surface circulation at sub-basin scale highlights that the "Maltese Channel Crest", a summer mesoscale feature located north-west of Malta (Robinson et al., 2009; Sorgente et al., 2011), does not seem to be a permanent feature of the area, as proposed by previous studies (Béranger et al., 2004; Sorgente et al., 2011). The horizontal salinity patterns also show the presence of a thermohaline front to east of the Strait of Sicily (∼ 15° E), which indicates a sort of physical barrier to the dynamics of surface circulation.

3.3 The Intermediate layer

The θ-S diagram (Fig. 2) highlights the presence of an intermediate (200–500 m) westward salty Levantine outflow (LIW). In the eastern part of the area, from 15° E, the presence of Cretan Intermediate Water (CIW) is recorded during the 1999, 2000, 2001, 2006, 2012 and 2013 surveys (not shown). CIW and LIW are identified in the θ-S diagram (e.g. in Fig. 2), due to the deviation toward higher values of salinity, as observed also by Manca et al. (2006). In agreement with such authors, the CIW in the eastern part of the Sicily Channel is characterized by slightly higher levels of salinity, compared to LIW, with potential temperature of $\theta = 14.5$–$15\,^{\circ}\mathrm{C}$ and density of $\sigma < 29.1\,\mathrm{kg\,m^{-3}}$ (not shown). LIW enters the Strait of Sicily from the east through the large relatively deep passage between Malta and Libya (Manzella, 1994; Placenti et al., 2013). The LIW vein core is characterized by a maximum salinity located between 200 m and 350 m, as shown in Table 3, and in agreement with previous studies (Ismail et al., 2012). In the years 1998–2013 a general increase of salinity values in the LIW core, especially in 2007 and 2013, has been recorded, while temperature ($T_{S\max}$) and depth is more

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variable (Table 3 and Fig. 3). Mean values of S_{max} and T_{Smax} are in the ranges 38.73–38.86 and 13.95–14.57 °C (Fig. 3) respectively. Our dataset and the recorded trend are fully in agreement with those reported by Gasparini et al. (2005) for the common study period (1998–2004). Additional information on the Levantine Intermediate Water in the Strait of Sicily can be derived from the analysis of θ-S diagrams in the intermediate layer for the station 945 (see Fig. 7). A positive trend in salinity of LIW is evident in the period 1998–2007, except for 2006 when a slight decrease in salinity is recorded (Fig. 7a). Afterwards, in the period 2007–2011 a decrease in salinity can be observed (Fig. 7b). Starting from 2011, the system seems to switch towards higher salinity levels up to 2013. Salinity and potential temperature for the period 1998–2013 (Table 2), in the intermediate layer (200–500 m), are positively correlated with high values of the Spearman's correlation coefficient ($r = 0.71$, $p < 0.05$).

A possible hypothesis to explain the alternation of high and low values of salinity in the intermediate water layer in the Strait of Sicily could be linked to the reversal of upper layer circulation in the central Ionian Sea (BiOS – Gačić et al., 2010, 2013). An anticyclonic circulation in the Ionian Sea favours a more intense spreading of the AW into the Ionian with the weakening of its spreading into the Levantine (Gačić et al., 2011). In contrast, in case of cyclonic circulation there is a wider spreading of AW in the eastern basin that produces a dilution of LIW. Therefore, variations in salinity in the Strait of Sicily could be explained in terms of the thermohaline variability in native LIW, as proposed also by Gačić et al. (2013). Considering a travel time of the signal from Rhodes Gyre to the Strait of Sicily of 10–13 years (Gačić et al., 2013), the increase in salinity recorded in the LIW in the Strait of Sicily for the period 1998–2007 may be connected to the decrease of AW spreading in the Levantine basin (Gačić et al., 2013) observed between the mid-eighties and mid-nineties. The subsequent cyclonic phase could have caused the salinity decrease in the intermediate waters in the Strait of Sicily starting from 2008. Actually, in 2012 there was a further increase in salinity and temperature up to 2013 (Figs. 3–7), apparently out of phase with the BIOS model.

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3.4 The deepest layer

Even though the central basin, occupying a significant portion of the Strait, has a mean depth of about 800 m, in several trenches it can be deeper, reaching 1700 m (Gasparini et al., 2005). During the mid-1990s a significant volume of transient EMDW (tEMDW) is found below the LIW (Sparnocchia et al., 1999), which is the result of mixing between the LIW, the old EMDW and the new EMDW originated from the eastern Mediterranean Transient (EMT, Roether et al., 1996). These waters display lower temperatures and salinities than the LIW. The LIW and tEMDW exit the Strait of Sicily into the Tyrrhenian Sea as two independent veins adjacent to the western Sicilian slope. In the Strait of Sicily the tEMDW has a core characterized by a temperature minimum of 13.63 °C, a salinity of 38.73, and a density of 29.15 $kg\,m^{-3}$. In this bottom layer the potential temperature increased between 1998 and 2013 from 13.6 °C to 13.8 °C, as well as salinity from 38.72 to 38.77 (Fig. 7). In the deep layer salinity and potential temperature in the period 1998–2013 show high values of the Spearman's correlation coefficient ($r = 0.81$, $p < 0.05$). This coefficient increases up to a maximum of 0.9 if the correlation is performed in the years 1998–2007. The vertical structure of the water column (Fig. 8) for the period 1998–2013 helps us to understand the possible relationships between the BIOS and the changes in thermohaline properties of the intermediate and deep waters especially in the Strait of Sicily. The entire water column is characterized by an increase in salinity since 1998; especially between 2003 and 2004 there was a greater spread of salinity throughout the water column as shown in Fig. 2 of Gačić et al. (2013), reaching at the bottom the same values of 1992 (Gasparini et al., 2005). This phase is followed by a decrease in salinity up to 2010; then since 2011 there is a new salt phase that affects the entire water column characterized by the isohaline 38.78, which reaches the bottom. The density vertical section (Fig. 8) shows wide variation of density between 1998 and 2013. Specifically, the isopycnal 29.15 has a depth in the range 500–700 m in the years 2000, 2005 and 2010, while drops below 1000 m in the years 2004, 2008 and 2012. Such variability, characterized by a cyclicity of 4–5 years in the

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study period, could be linked to the shorter time-scale of the propagation of the salinity signal from the Strait of Sicily to the Algero-Provençal subbasin (4 yr), observed by Gačić et al. (2013).

4 Conclusions

The analyzed dataset allowed to study the high interannual water masses variability in the Strait of Sicily. The obtained results, supported by a large dataset both in terms of area covered (sampling intensity) and time interval, highlighted how the Strait of Sicily is an important site for studying the effects of surface and intermediate water circulation at sub-basin scale. The interpretation of the density interfaces and of geostrophic currents in the surface water highlights the presence of alternating cyclonic and anti-cyclonic structures along the central part of the southern Sicily coast. Moreover, such observed variability of surface circulation points out that the "Maltese Channel Crest" is not a permanent feature of the area. At subsurface levels the presence of an intermediate westward-flowing salty outflow, composed by LIW with occasional intrusions of CIW in the easternmost part of the study area, is observed. The LIW is characterized by salinification (1998–2007), followed by a decrease in salinity up to 2011, while a new salt/warm phase is recorded up to 2013. This trend could be linked to the reversal of sub-surface circulation in the central Ionian Sea; in fact the increase in salinity recorded in the LIW for the period 1998–2007 may be connected to the decrease of AW spreading in the Levantine basin, observed between the mid-eighties and mid-nineties. The subsequent cyclonic phase could have caused the salinity decreasing in the intermediate waters in the Strait of Sicily starting from 2008. Moreover, the vertical structure evolution shows in deeper layers a wide variation of density between 1998 and 2013 probably linked to the shorter time-scale of propagation of the salinity signal (4–5 years) from the Strait of Sicily to the Algero-Provençal sub-basin.

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References

Basilone, G., Bonanno, A., Patti, B., Mazzola, S., Barra, M., Cuttitta, A., and McBride, R.: Spawning site selection by European anchovy (Engraulis encrasicolus) in relation to oceanographic conditions in the Strait of Sicily, Fisheries Oceanography, 22, 309–323, 2013.

Béranger, K., Mortier, L., Gasparini, G. P., Gervasio, L., Astraldi, L., and Crépon, M.: The dynamics of the Sicily Strait: a comprehensive study from observations and models, Deep-Sea Res. Pt. II, 51, 411–440, 2004.

Bonanno, A., Zgozi, S., Cuttitta, A., El Turki, A., Di Nieri, A., Ghmati, H., Basilone, G., Aronica, S., Hamza, M., Barra, M., Genovese, S., Falco, F., Knittweis, L., Mifsud, R., Patti, B., Bahri, T., Giacalone, G., Fontana, I., Tranchida, G., and Mazzola, S.: Influence of environmental variability on anchovy early life stages (Engraulis encrasicolus) in two different areas of the Central Mediterranean Sea, Hydrobiologia, 701, 273–287, doi:10.1007/s10750-012-1285-8, 2013.

Borzelli, G. L. E., Gačić, M., Cardin, V., and Civitarese, G.: Eastern Mediterranean transient and reversal of the Ionian Sea circulation, Geophys. Res. Lett., 36, L15108, doi:10.1029/2009GL039261, 2009.

Brankart, J. M.: The MODB local quality control, Technical Report, University of Liege, Liege, 5 pp., 1994.

Conan, P. and Millot, C.: Variability of the northern current off Marseilles, western Mediterranean Sea, from February to June 1992, Oceanol. Acta, 18, 193–205, 1995.

Demirov, E. and Pinardi, N.: Simulation of the Mediterranean Sea circulation from 1979 to 1993 – Part I: The interannual variability, J. Marine Syst., 33–34, 23–50, doi:10.1016/S0924-7963(02)00051-9, 2002.

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Gačić, M., Borzelli, G. L. E., Civitarese, G., Cardin, V., and Yari, S.: Can internal processes sustain reversals of the ocean upper circulation? The Ionian Sea example, Geophys. Res. Lett., 37, L09608, doi:10.1029/2010GL043216, 2010.

Gačić, M., Civitarese, G., Eusebi Borzelli, G. L., Kovaèeviæ, V., Poulain, P.-M., Theocharis, A., Menna, M., Catucci, A., and Zarokanellos, N.: On the relationship between the decadal oscillations of the northern Ionian Sea and the salinity distributions in the eastern Mediterranean, J. Geophys. Res., 116, C12002, doi:10.1029/2011JC007280, 2011.

Gačić, M., Schroeder, K., Civitarese, G., Cosoli, S., Vetrano, A., and Eusebi Borzelli, G. L.: Salinity in the Sicily Channel corroborates the role of the Adriatic–Ionian Bimodal Oscillating System (BiOS) in shaping the decadal variability of the Mediterranean overturning circulation, Ocean Sci., 9, 83–90, doi:10.5194/os-9-83-2013, 2013.

Garcia Lafuente, J., Vargas, J. M., Criado, F., Garcia, A., Delgado, J., and Mazzola, S.: Assessing the variability of hydrographic processes influencing the life cycle of the Sicilian Channel anchovy, Engraulis encrasicolus, by satellite imagery, Fish. Oceanogr., 14, 32–46, 2005.

Gasparini, G. P., Zodiatis, G., Astraldi, M., Galli, C., and Sparnocchia, S.: Winter Intermediate Water lenses in the Ligurian Sea, J. Marine Syst., 20, 319–332, 1999.

Gasparini, G. P., Ortona, A., Budillon, G., Astraldi, M., and Sansone, E.: The effect of the eastern Mediterranean Transient on the hydrographic characteristics in the Strait of Sicily and in the Tyrrhenian Sea, Deep-Sea Res. Pt. I, 52, 915–935, 2005.

Gasparini, G. P., Bonanno, A., Zgozi, S., Basilone, G., Borghini, M., Buscaino, G., Cuttitta, A., Essarbout, N., Mazzola, S., Patti, B., Ramadan, A. B., Schroeder, K., Bahri, T., and Massa, F.: Evidence of a dense water vein along the Libyan continental margin, Ann. Geophys., 26, 1–6, doi:10.5194/angeo-26-1-2008, 2008.

Ismail, S. B., Sammari, C., Gasparini, G. P., Béranger, K., Brahim., M., and Aleya, L.: Water masses exchanged through the Channel of Sicily: evidence for the presence of new water masses on the Tunisian side of the channel, Deep-Sea Res. Pt. I, 63, 65–81, 2012.

Klein, B., Manca, B. B., and Roether, W.: The evolution of the intermediate water masses of the eastern Mediterranean, Rep. Int. Comity Mediterr. Sea, 37, 111 pp., 2004.

Lermusiaux, P. F. J.: Estimation and study of mesoscale variability in the Strait of Sicily, Dynam. Atmos. Oceans, 29, 255–303, 1999.

Lermusiaux, P. F. J. and Robinson, A. R.: Features of dominant mesoscale variability, circulation patterns and dynamics in the Strait of Sicily, Deep-Sea Res. Pt. I, 48, 1953–1997, 2001.

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Manzella, G.: The Seasonal variability of the water masses and transport through the Strait of Sicily, Coast. Estuar. Stud., 46, 33–45, 1994.
Millot, C.: Circulation in the western Mediterranean Sea, J. Marine Syst., 20, 423–442, 1999.
Placenti, F., Schroeder, K., Bonanno, A., Zgozi, S., Sprovieri, M., Borghini, M, Rumolo, P., Cerrati, G.,Bonomo, S., Genovese, S., Basilone, G., Haddoud, D. A., Patti, B., El Turki, A., Hamza, M., and Mazzola, S.: Water masses and nutrient distribution in the Gulf of Syrte and between Sicily and Libya, J. Marine Syst., 121–122, 36–46, 2013.
Robinson, A. R., Sellschopp, J., Warn-Varnas, A., Leslie, W. G., Lozano, C. J., Haley, P. J., Anderson, L. A., and Lermusiaux, P. F. J.: The Atlantic Ionian Stream, J. Marine Syst., 20, 129–156, 1999.
Roether, W., Manca, B. B., Klein, B., Bregant, D., Georgopoulos, D., Beitzel, V., Kovacevich, V., and Luchetta, A.: Recent changes in eastern Mediterranean deep waters, Science, 271, 333–335, 1996.
Roether, W., Klein, B., Manca, B. B., Theocaris, A., and Kioroglou, S.: Transient eastern Mediterranean deep waters in response to massive dense-water output of the Aegean Sea in the 1990s, Prog. Oceanogr., 74, 540–571, 2007.
Sammari, C., Millot, C., Taupier-Letage, I., Stefani, A., and Brahim, M.: Hydrological characteristics in the Tunisian–Sardinia–Sicily area during spring 1995, Deep-Sea Res. Pt. I, 46, 1671–1703, 1999.
Schroeder, K., Taillandier, V., Vetrano, A., and Gasparini, G. P.: The circulation of the western Mediterranean Sea in spring 2005 as inferred from observations and from model outputs, Deep-Sea Res. Pt. I, 55, 947–965, 2008.
Sorgente, R., Drago, A. F., and Ribotti, A.: Seasonal variability in the Central Mediterranean Sea circulation, Ann. Geophys., 21, 299–322, doi:10.5194/angeo-21-299-2003, 2003.
Sorgente, R., Olita, A., Oddo, P., Fazioli, L., and Ribotti, A.: Numerical simulation and decomposition of kinetic energy in the Central Mediterranean: insight on mesoscale circulation and energy conversion, Ocean Sci., 7, 503–519, doi:10.5194/os-7-503-2011, 2011.
Sparnocchia, S., Gasparini, G. P., Astraldi, M., Borghini, M., and Pistek, P.: Dynamics and mixing of the eastern Mediterranean outflow in the Tyrrhenian basin, J. Marine Syst., 20, 301–317, 1999.

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Theocharis, A., Nittis, K., Kontoyiannis, H., Papageorgiou, E., and Balopoulos, E.: Climate changes in the Aegean Sea influence the eastern Mediterranean thermohaline circulation (1986–1997), Geophys. Res. Lett., 26, 1617–1620, 1999.
Theocharis, A., Klein, B., Nittis, K., and Roether, W.: Evolution and status of the eastern Mediterranean Transient (1997–1999), J. Marine Syst., 33–34, 91–116, 2002.

Table 1. Sampling period and name of the oceanographic surveys carried out in the Strait of Sicily.

Date	Cruise name
23 Jun 1998–13 Jul 1998	Mago98
14 Oct 1999–29 Oct 1999	Juvenile99
24 Jun 2000–11 Jul 2000	Ansic00
5 Jul 2001–26 Jul 2001	Ansic01
10 Jul 2002–1 Aug 2002	Ansic02
10 Jul 2003–4 Aug 2003	Ansic03
17 Jun 2004–8 Jul 2004	Ansic04
6 Jul 2005–25 Jul 2005	Bansic05
29 Jul 2006–11 Aug 2006	Bansic06
28 Jun 2007–17 Jul 2007	Bansic07
25 Jun 2008–14 Jul 2008	Bansic08
3 Jul 2009–22 Jul 2009	Bansic09
25 Jun 2010–14 Jul 2010	Bansic10
08 Jul 2011–26 Jul 2011	Bansic11
4 Jul 2012–23 Jul 2012	Bansic12
26 Jun 2013–16 Jul 2013	Bansic13

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Table 2. Number of stations for each layer and average values and standard deviations of salinity, potential temperature (°C) and density ($kg\,m^{-3}$) for each survey. In the layer 0–200 m are also included transitional waters.

Cruise Layer 0–200 m	Number of Stations	Salinity PSU	Pot. Temp. °C	Density $kg\,m^{-3}$	Cruise Layer 200–500 m	Number of Stations	Salinity PSU	Pot. Temp. °C	Density $kg\,m^{-3}$	Cruise Layer 500–bottom	Number of Stations	Salinity PSU	Pot. Temp. °C	Density $kg\,m^{-3}$
Mago98	170	37.982	16.153	27.985	Mago98	45	38.730	13.905	29.094	Mago98	26	38.735	13.679	29.147
S.D.		0.437	2.363	0.870	S.D.		0.040	0.143	0.057	S.D.		0.006	0.046	0.005
Juvenile99	185	38.246	16.951	27.969	Juvenile99	70	38.767	13.951	29.113	Juvenile99	33	38.739	13.652	29.155
S.D.		0.393	3.554	1.074	S.D.		0.017	0.14	0.031	S.D.		0.018	0.109	0.009
Ansic00	303	38.172	15.919	28.174	Ansic00	85	38.776	13.998	29.109	Ansic00	16	38.762	13.729	29.157
S.D.		0.43	2.507	0.868	S.D.		0.001	0.108	0.031	S.D.		0.007	0.053	0.005
Ansic01	421	38.241	16.764	28.01	Ansic01	96	38.785	14.093	29.096	Ansic01	42	38.769	13.781	29.151
S.D.		0.444	3.101	0.994	S.D.		0.032	0.21	0.057	S.D.		0.01	0.066	0.008
Ansic02	275	38.139	16.791	27.943	Ansic02	94	38.788	14.077	29.102	Ansic02	42	38.763	13.752	29.153
S.D.		0.519	2.933	1.033	S.D.		0.013	0.169	0.038	S.D.		0.018	0.148	0.018
Ansic03	286	38.273	16.751	28.034	Ansic03	77	38.79	14.212	29.074	Ansic03	44	38.776	13.908	29.129
S.D.		0.455	3.688	1.184	S.D.		0.017	0.171	0.041	S.D.		0.011	0.067	0.009
Ansic04	234	38.147	16.199	28.008	Ansic04	84	38.803	14.146	29.098	Ansic04	42	38.785	13.891	29.139
S.D.		0.575	2.535	1.055	S.D.		0.013	0.169	0.039	S.D.		0.009	0.078	0.011
Bansic05	220	38.146	16.014	28.13	Bansic05	72	38.805	14.05	29.121	Bansic05	40	38.785	13.839	29.151
S.D.		0.487	2.97	0.973	S.D.		0.018	0.147	0.031	S.D.		0.009	0.079	0.01
Bansic06	242	38.189	17.089	27.882	Bansic06	51	38.793	14.012	29.119	Bansic06	23	38.764	13.76	29.152
S.D.		0.408	3.836	1.147	S.D.		0.03	0.249	0.037	S.D.		0.013	0.085	0.008
Bansic07	209	38.007	16.816	27.843	Bansic07	57	38.824	14.183	29.107	Bansic07	27	38.796	13.878	29.151
S.D.		0.559	2.56	0.988	S.D.		0.024	0.247	0.078	S.D.		0.015	0.053	0.012
Bansic08	153	38.031	16.586	27.919	Bansic08	49	38.807	14.227	29.094	Bansic08	27	38.773	13.989	29.133
S.D.		0.511	2.543	0.952	S.D.		0.019	0.183	0.037	S.D.		0.012	0.04	0.007
Bansic09	170	38.106	15.993	28.111	Bansic09	58	38.797	14.078	29.107	Bansic09	32	38.772	13.826	29.144
S.D.		0.516	2.52	0.915	S.D.		0.018	0.167	0.036	S.D.		0.009	0.061	0.005
Bansic10	236	38.005	16.074	27.934	Bansic10	79	38.792	14.065	29.106	Bansic10	29	38.78	13.835	29.146
S.D.		0.472	2.178	0.915	S.D.		0.032	0.15	0.041	S.D.		0.009	0.064	0.006
Bansic11	157	38.17	16.062	27.992	Bansic11	52	38.781	14.157	29.078	Bansic11	25	38.792	13.871	29.148
S.D.		0.334	2.715	1.024	S.D.		0.055	0.144	0.063	S.D.		0.008	0.063	0.007
Bansic12	202	38.393	16.723	28.143	Bansic12	56	38.824	14.268	29.087	Bansic12	36	38.788	13.912	29.137
S.D.		0.39	3.341	1.052	S.D.		0.023	0.199	0.041	S.D.		0.014	0.095	0.01
Bansic13	235	38.080	16.666	27.924	Bansic13	50	38.829	14.237	29.097	Bansic13	25	38.800	13.929	29.142
S.D.		0.438	2.749	0.886	S.D.		0.015	0.188	0.036	S.D.		0.012	0.086	0.009

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Table 3. Average values (±SD) of minimum salinity (S_{min}), potential temperature of minimum salinity ($T_{S_{min}}$, °C), depth of minimum salinity (m), maximum salinity, temperature (°C) and depth (m) at the LIW core (maximum salinity).

Survey	S_{min} Mean ±SD	$T_{S_{min}}$ Mean ±SD	Depth of MAW core ±SD	S_{max} ± SD	$T_{S_{max}}$ ± SD	Depth of LIW core ±SD
Mago98	37.368 ± 0.213	18.946 ± 1.935	21.1 ± 10.5	38.736 ± 0.03	13.953 ± 0.09	317.8 ± 58.7
Juvenile99	37.629 ± 0.140	17.929 ± 0.960	31.6 ± 6.50	38.767 ± 0.02	14.009 ± 0.07	304.7 ± 55.0
Ansic00	37.439 ± 0.140	17.876 ± 1.380	19.8 ± 7.80	38.781 ± 0.01	14.048 ± 0.07	305.3 ± 49.8
Ansic01	37.452 ± 0.121	19.397 ± 2.149	19.6 ± 6.80	38.779 ± 0.02	14.177 ± 0.16	296.9 ± 62.4
Ansic02	37.286 ± 0.207	18.949 ± 1.570	25.4 ± 11.7	38.795 ± 0.01	14.215 ± 0.09	273.1 ± 41.6
Ansic03	37.460 ± 0.277	20.180 ± 1.877	18.4 ± 7.20	38.796 ± 0.01	14.336 ± 0.08	295.8 ± 53.7
Ansic04	37.312 ± 0.156	18.425 ± 1.764	26.5 ± 17.2	38.809 ± 0.01	14.303 ± 0.10	266.8 ± 47.2
Bansic05	37.492 ± 0.163	17.650 ± 1.993	22.1 ± 9.30	38.816 ± 0.01	14.268 ± 0.09	243.4 ± 36.9
Bansic06	37.567 ± 0.086	19.627 ± 2.041	19.4 ± 10.5	38.808 ± 0.01	14.300 ± 0.13	220.7 ± 36.1
Bansic07	37.220 ± 0.184	20.000 ± 1.764	17.1 ± 8.90	38.863 ± 0.02	14.577 ± 0.19	234.8 ± 68.3
Bansic08	37.381 ± 0.097	20.342 ± 2.094	19.2 ± 9.70	38.832 ± 0.01	14.499 ± 0.06	222.4 ± 27.7
Bansic09	37.421 ± 0.168	17.577 ± 1.586	24.0 ± 10.5	38.815 ± 0.01	14.363 ± 0.06	214.9 ± 32.0
Bansic10	37.371 ± 0.171	19.514 ± 1.756	20.2 ± 12.0	38.804 ± 0.03	14.242 ± 0.09	263.4 ± 51.7
Bansic11	37.607 ± 0.129	20.297 ± 2.221	20.0 ± 8.90	38.808 ± 0.03	14.208 ± 0.06	337.5 ± 52.7
Bansic12	37.863 ± 0.403	19.187 ± 1.974	18.3 ± 7.20	38.835 ± 0.01	14.499 ± 0.11	253.9 ± 28.8
Bansic13	37.580 ± 0.118	17.360 ± 1.848	34.2 ± 16.5	38.842 ± 0.02	14.463 ± 0.10	245.2 ± 32.4

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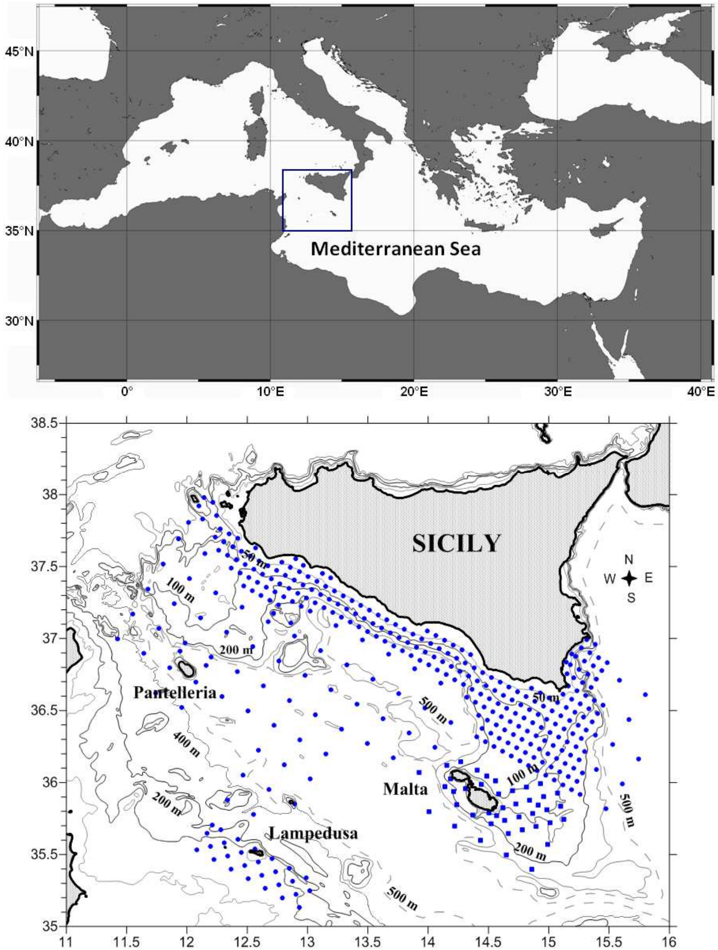

Fig. 1. The study area in the Strait of Sicily and the overall sampling design adopted in the period 1998–2013 (blue dots); the Maltese waters are investigated since 2004 (blue squares).

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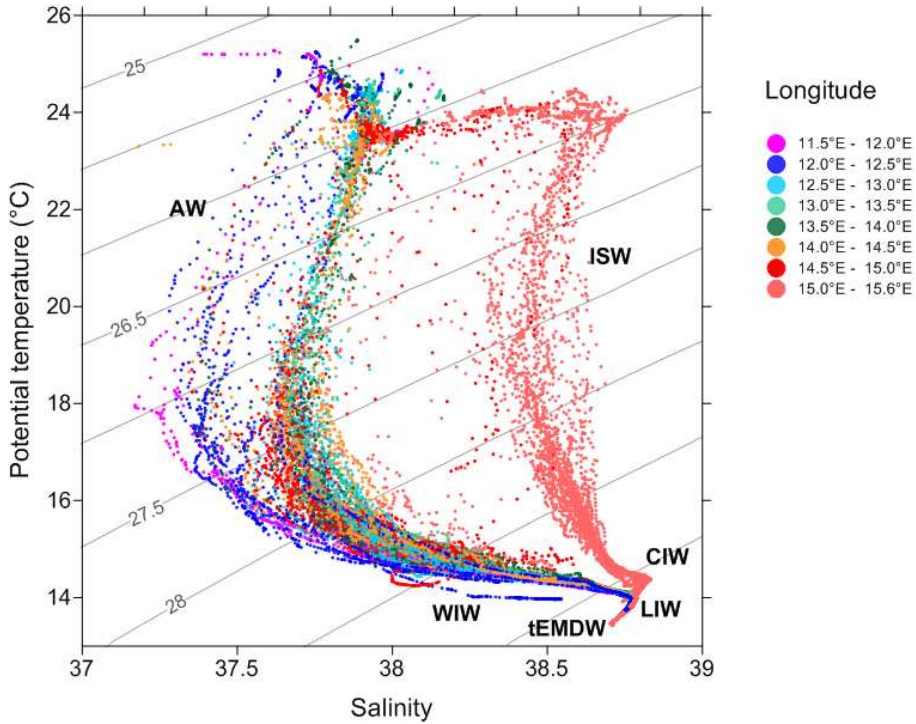

Fig. 2. θ-S diagram for the survey carried out in October 1999 (Strait of Sicily and west Ionian sea). The colors refer to longitude of the 185 stations.

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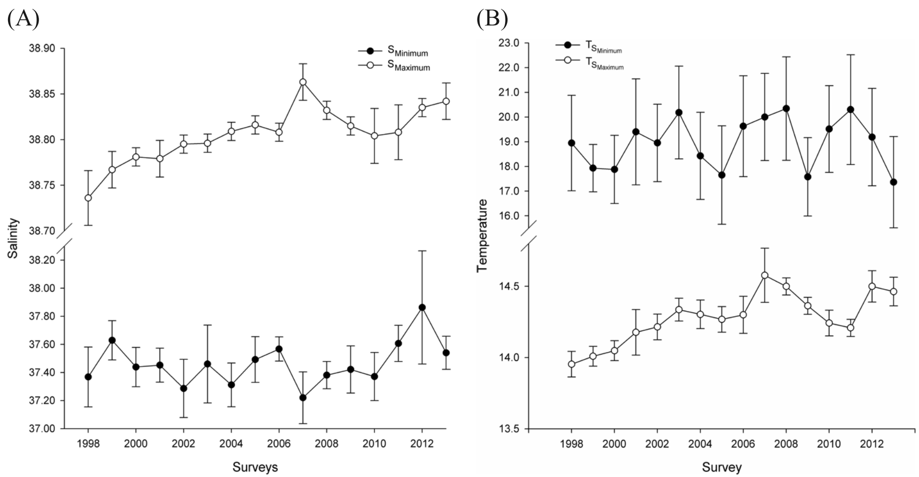

Fig. 3. (A) Mean values of salinity minimum and salinity maximum recorded in the period 1998–2013. **(B)** Mean temperatures recorded at depth of salinity minimum and salinity maximum.

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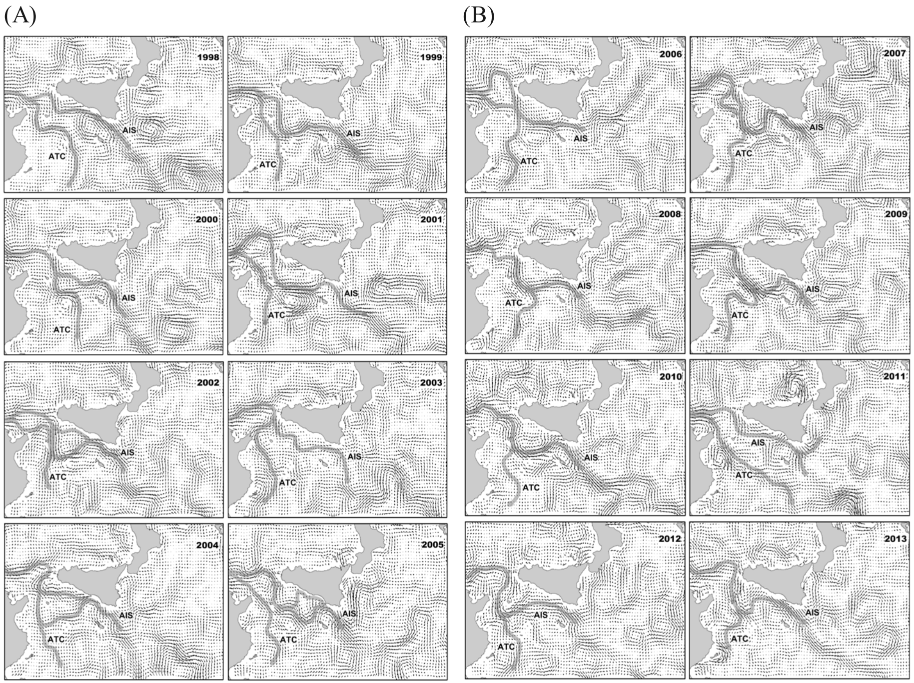

Fig. 4. Mean geostrophic velocity field (Absolute Dynamic Topography by Aviso) estimated in the period of each survey. The patterns of the main circulation streams (ATC and AIS) are evaluated by the Aviso altimeter products.

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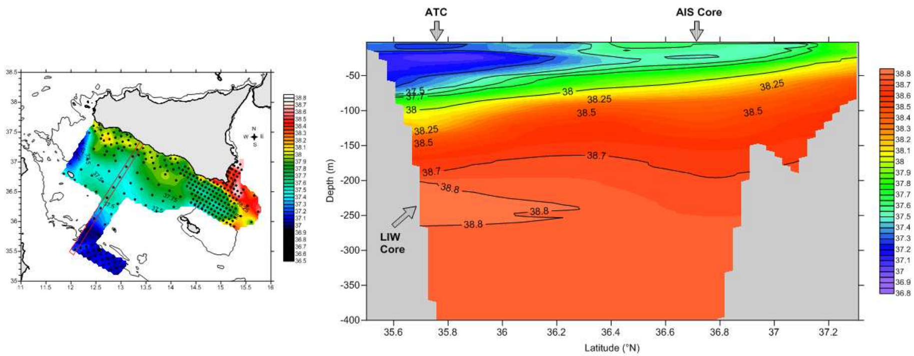

Fig. 5. Surface salinity map estimated in the oceanographic survey "Ansic 03" (left side). Salinity section (right side) and position of the main water masses along the selected transect (red box in the map) 250 km long.

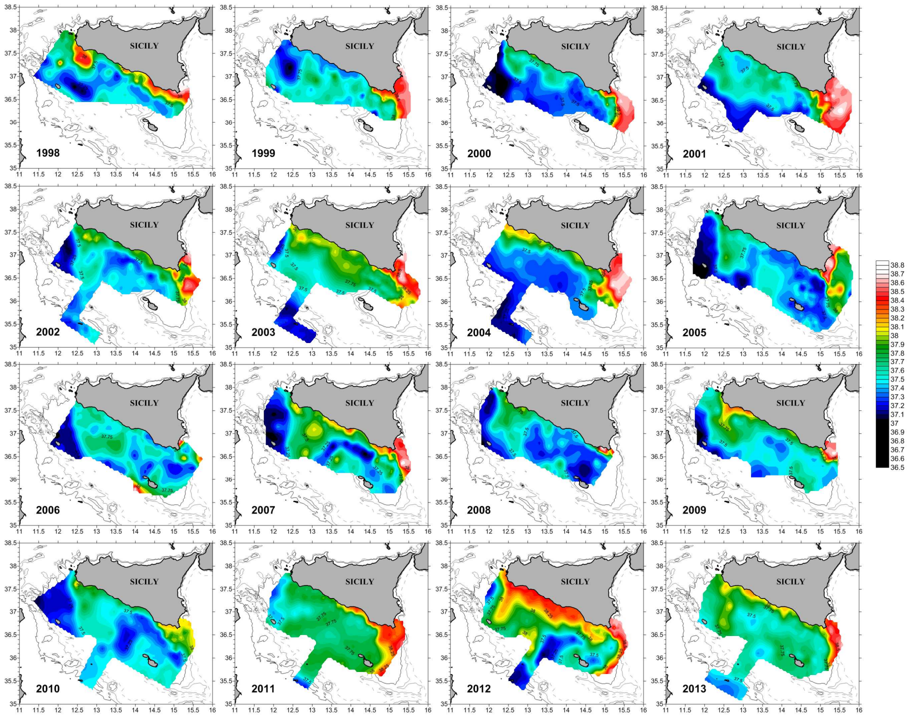

Fig. 6. Horizontal distribution of the minimum in the vertical salinity profiles (S_{min}) in the Strait of Sicily and western Ionian 1998–2013.

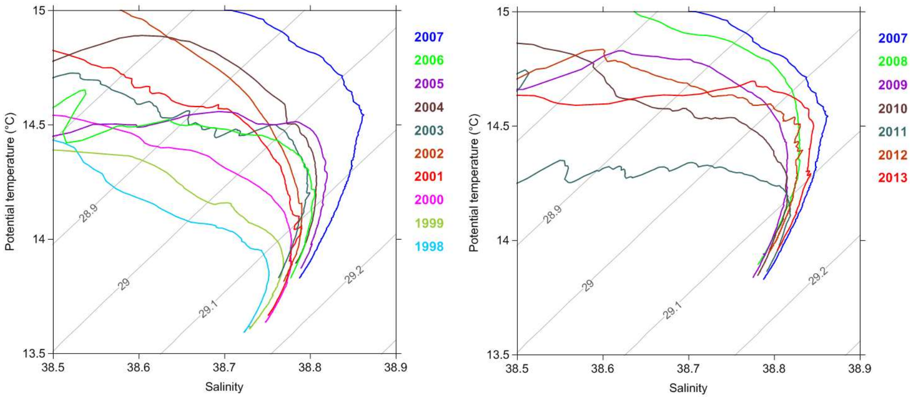

Fig. 7. Θ-*S* diagrams of the intermediate layer in the Strait of Sicily – Station 945.

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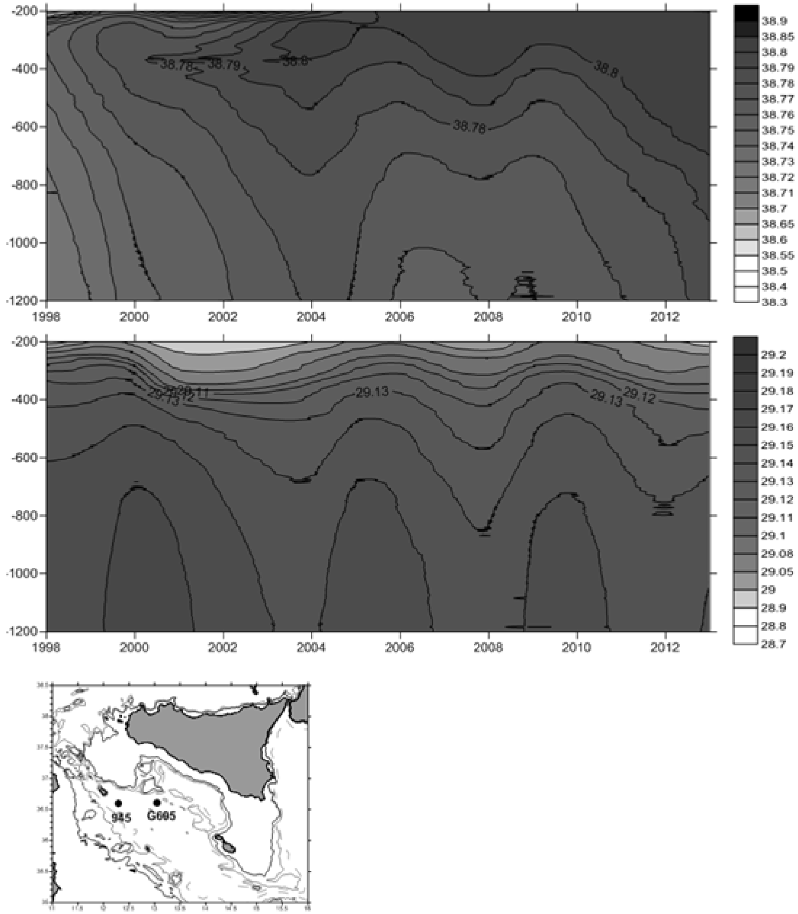

Fig. 8. Salinity (above) and Density in the layer 200–1200 m. The period 1998–2002 is recorded in the station 945 (1200 m) while the period 2003–2013 in the station G605 (1700 m).

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