Changes in hydrological properties of the Mediterranean Sea over the last 40 years with focus on the Levantine Intermediate Water and the Atlantic Water

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Outline

1 Introduction

The Mediterranean Sea is a semi-enclosed basin, with connection to the Atlantic Ocean and the Black Sea through the Gibraltar Strait and the Dardanelles/Marmara Sea/Bosphorus system, respectively. It is composed by two basins: the Eastern and Western Mediterranean (hereafter EMED and WMED), separated by the Sicily Strait (Bergamasco and Malanotte-Rizzoli, 2010).

The thermohaline properties of the Mediterranean Sea are dominated by several factors: evaporation, precipitation, river runoff, inflow from (outflow to) the Atlantic and Black Sea and heat exchange with atmosphere. Due to strong evaporation, the Mediterranean Sea is characterized by high salinity values and deep water formation, which exerts a significant influence on the local currents (Gačić et al., 2014), as well as on the North Atlantic deep water formation, and hence on the global climate (Poulain et al., 2007; Sarafanov et al., 2008).

Over the past few decades, some changes of the thermohaline properties in the two Mediterranean basins have taken place. In WMED, quasi-continuous warming and salinification signals were found in the deep water during the second half of last century, with the order of the trends being 10^{-3} °C/year and 10^{-3} year^{-1}, respectively (Rohling and Bryden, 1992; Bethoux and Gentili, 1999; Rixen et al., 2005; Vargas-Yáñez et al., 2010). In the intermediate depth, Sparnocchia et al. (1994) reported that the salinification and warming trends are 1.6×10^{-3} year^{-1} and 6.5×10^{-3}°C/year respectively in the Ligurian Sea over the period of 1950-1987, and similar trends (1.8×10^{-3} year^{-1} and 6.8×10^{-3}°C/year) of Western Intermediate Water in the Ligurian Sea from 1959 to 1997 were reported by Bethoux and Gentili (1999). In contrast to the WMED, there is no quasi-continuous and obvious thermohaline long-term trend in the East Mediterranean Deep Water (EMDW), but some abrupt changes occurred influenced by the Nile damming construction, the East Mediterranean Transient (the shift of EMDW formation site from the Adriatic Sea to Aegean Sea during the late 1980s and early 1990s), etc. (Skliris et al., 2007). However, from a re-analysis dataset, a significant warming can be found from 1980 to 2000 (Rixen et al., 2005).

These thermohaline changes of the intermediate and deep water are caused by changes in the near-surface level that propagate deeper through convection, advection and mixing processes. Therefore, the intermediate and deep water changes can be attributed to the anomalies of the upper levels characterized by the presence of two of the most important water masses in the Mediterranean Sea: the Atlantic Water (AW) and the Levantine Intermediate Water (LIW).

As one of the ways to compensate the loss of freshwater, the AW flows into the Mediterranean Sea through the Gibraltar Strait. The AW is characterized by the salinity minimum and its path, close to the surface, is towards the Levantine Sea. While flowing eastward, its salinity gradually increases through evaporation and mixing with the surrounding Mediterranean waters. Typically, the AW salinity is 36.2 at the Gibraltar Strait, then increases to 37.5 at the Sicily Strait and finally it approaches values around 38.6 in the Levantine Sea (Skliris, 2014). Moreover, recent studies have shown a strong salinification trend (~0.05 year^{-1}) in the AW outside the Gibraltar Strait during 2003-2007 (Millot, 2007; Soto-Navarro et al., 2012).

The LIW, which is mainly formed in the Levantine Sea, is characterized by the maximum of salinity underneath the AW, spreads at the intermediate depth across the Mediterranean Sea and finally exits through the Gibraltar Strait after mixing with some other waters (Menna and Poulain, 2010 for a brief review). Along its route towards the Atlantic Ocean, the LIW progressively sinks from a near-surface layer in the Levantine Sea to 300-350 m in the middle of the Mediterranean Sea and finally deeper than 350 m in the Western part of the basin (Notarstefano and Poulain, 2009). Moreover, the hydrological properties have also shown some changes. Rohling and Bryden (1992) reported that the LIW core salinity increased during 1909-1989, which was modified to a reduced salinification by Painter and Tsimplis (2003); Sparnocchia et al. (1994) reported that LIW core showed warming and salinification trends during 1950-1987.

In the last 10 years, abundant Argo data are available in the Mediterranean Sea thanks to several projects involving the use of autonomous profiling floats (Poulain et al., 2007). The amount of data collected by the Argo floats provides an opportunity to investigate recent hydrological changes of the AW and LIW. In this report, in addition to the Argo data, the in-situ data collected under various oceanographic campaigns between 1972 and 2010 (most of them are part of the MEDAR/MEDATLAS project) are also used.

Although the dataset, mostly the Argo data, are relatively abundant in the last 10 years, the hydrological properties of LIW and AW are still unclear. Hence, the first question we want to address is whether the salinity and depth of LIW and AW cores show significant trends in the last 10 years. Moreover, the hydrological properties of the AW and LIW are speculated to influence the intermediate and deep water in the Mediterranean Sea. Hence it is interesting to investigate whether the salinity and depth trends in last 10 years are different from the longer-term trends that are shown by the historical dataset and reported in the literature (Sparnocchia et al., 1994; Painter and Tsimplis, 2003), as the first step to attempt to explain, even monitor in some sense, the changes in the intermediate and deep water.

2 Data and Method

2.1 Argo data

For this work we used data collected from Argo floats between 2000 and 2014. Most of them are part of the Argo program in the Mediterranean Sea (MedArgo) whilst the US NAVY floats belong to the Argo equivalent NAVOCEANO program. The profilers are equipped with Sea-Bird CTD sensors (model SBE41CP) with accuracies of ±0.002° C, ±0.002 and ±2 dbar for temperature, salinity and pressure, respectively. Most of Argo floats fleet were programmed following the specifications of the MedArgo program (Poulain et al., 2007) with a cycle length of 5 days, a drifting depth of 350 m and a maximal profiling depth of 2000 m; the NAVY floats mission parameters were usually set to 1000 m and 1500 m for the parking and maximal profiling depth, respectively. The Argo data are transmitted by satellites, e.g. Iridium or Argos telemetry systems, to one of the Argo Data Assembly Centre (DAC), where they are processed and quality-controlled using a basic set of tests, and then sent to one of the Global Data Assembly Center (GDAC). We have downloaded the data from the Coriolis Data center IFREMER (a GDAC center) located in Brest (France) in NetCDF format. A delayed-mode quality control of pressure, temperature and salinity was applied in accordance to the *Argo*

Quality Control Manual (Wong, A., R. Keeley, T. Carval and the Argo Data Management Team, 2013), and in particular the Owens-Wong method was adopted (Owens and Wong, 2009) to check the salinity data. The Argo float salinity profiles were also qualitatively compared to a reference dataset (Notarstefano and Poulain, 2008; Notarstefano and Poulain, 2013) to remove the unfit profiles.

2.2 Other data

Another dataset was built combining the temperature and salinity profiles acquired under various oceanographic campaigns and the historical data of two datasets (MEDAR/MEDATLAS and CORIOLIS 2010 V1) that include measurements mainly collected by CTDs, XBTs, moorings and thermosalinographs. All these data have been collected from several sources, their different format has been uniformed and then a quality control procedure has been applied to remove any remaining outlier and spike.

2.3 Methods

The aim of this work is to analyse the variability of two main water masses of the Mediterranean Sea: the AW and LIW. The identification of the core of the AW and LIW is made possible through a salinity-signature approach, by looking for the salinity minimal and maximal values for the AW and LIW, respectively.

Before proceeding to the recognition of the water types, the data of each profile were sorted by depth classes. The data distribution should conform certain conditions, otherwise the profile was rejected. In particular the data of each profile must cover the range between 30 dbar and 600 dbar, in order to exclude both the coastal and the shallow profiles; in this way it was assured that the accepted profiles had enough observations in the water column.

Before the extraction of salinity minimum and maximum, the Mediterranean Sea was divided into 11 sub-basins as defined by the EU/MEDAR-MEDATLAS II project (Fig. 1). The EMED is composed by the Levantine Sea, Aegean Sea, Cretan Passage, Ionian Sea, Adriatic Sea and Sicily Channel, while the WMED includes the Tyrrhenian Sea, Liguro-Provençal Sea, Catalan

Sea, Algerian Sea and Alboran Sea. Moreover, it was supposed that the water was well mixed horizontally; hence each profile observation can present the thermohaline properties of associated sub-basin at a specific time.

The salinity minimum and maximum of each profile were extracted according to a specific criteria based on the typical mean depth of the AW and LIW respectively in the 11 sub-basins of the Mediterranean Sea (Fig. 1). Firstly, we divided the Mediterranean Sea into three areas: the western, central and eastern parts. Each part groups some sub-basins as reported in Table 1. Secondly, the depth range selected for choosing the salinity minimum and maximum varies in the three parts (see Table 1 for details) in order to be a representative layer of the two water masses (AW and LIW): in particular, the depth range for the salinity maximum selection is set deeper when moving westward, following the natural sinking path of the LIW; the salinity minimum that characterized the AW is searched in the near surface layer in all sub-basins, from the Gibraltar Strait to the Levantine Sea. In the last step of data selection, the minimum and maximum were selected and the associated depths were considered only if their difference was larger than 0.1, in order to have a clear distinct signal of the two water masses.

About 20000 profiles were selected, spatially well distributed in the various sub-basins of the Mediterranean Sea. In some areas there are scarcity of data mostly due to shallow water area (Northern Adriatic and Sicily Channel areas) or few deployment operations (Aegean and Alboran Seas).

The salinity and depth of LIW and AW cores exhibit a seasonal cycle, especially the values corresponding to near-surface waters. A weighted least-squared regression method was used to fit the seasonal cycles on a basis of monthly mean values of salinity and depth (the maximal and minimal salinity of each profile mentioned above and the associated depth), where the weights are the number of profiles in each month. The seasonal cycle extracted was in the form of

$$S_c = A\cos(\omega t - \varphi) \quad (1)$$

where A is the amplitude, ω is angle frequency and φ is the phase difference. The seasonal cycle was removed from the original observations when the regression was significant using the F test with 95% confidence interval.

Once the seasonal cycle was removed, the monthly mean of the salinity maximum (that is the LIW core signature) and minimum (that is the AW core signature) and the respective mean depth were computed in all the sub-basins. The long-term trends were then calculated by the weighted least-squared regression, where the weights are the number of profiles. Finally, a *t*-student test with 95% confidence interval was used to determine whether these trends are significant or not.

3 Results

The salinity and the depth of LIW and AW cores are investigated in each sub-basin of the Mediterranean Sea (Fig. 1). Trends over the last ten years (2004-2014) were computed and compared to longer-term trends (1972-2014, 1972-2004) in order to analyze any obvious difference.

3.1 Seasonal cycle

As introduced in Section 2.3, the weighted least-squared regression was used to fit the seasonal cycle of the salinity and depth of LIW and AW cores, where the number of profiles in each month was chosen as the weight. Tables 2-3 list the results of the regressions.

For the LIW core salinity, only 4 sub-basins (the Aegean Sea, Adriatic Sea, Liguro-Provençal Sea and Catalan Sea) show statistically significant seasonal cycles, with amplitude ranging from 0.016 to 0.049. The associated determination coefficients (R^2, i.e. the ratio of explained variance and total variance) range from 0.08 to 0.2 (Table 2). The LIW core depth shows statistically seasonal cycle in more sub-basins, with the amplitude ranging from 14 to 44 dbar and the determination coefficient ranging from 0.03 to 0.2.

For the AW core salinity, all the sub-basins, except the Adriatic Sea, show statistically significant seasonal cycles, since the AW core is closer to the surface with respect to the LIW core and therefore interacts more with the atmosphere. The amplitudes of seasonal cycle change from 0.06 to 0.4, with the determination coefficients from 0.05 to 0.37 (Table 3). Similarly, the depth also shows significant seasonal cycles in most of the sub-basins, with the amplitude ranging from 2.1 to 18.7 dbar and the determination coefficient ranging from 0.16 to 0.6.

3.2 Trends

3.2.1 The Levantine Sea

In the Levantine Sea (the formation site of the LIW), the salinity of the LIW core has increased at a rate of 0.0042±0.0012 yr^{-1} from 1979 to 2014 (Fig. 2a). From 1979 to 2004, a salinification trend (0.0064±0.0026 yr^{-1}, statistically significant) can also be found, while in the last decade (2004-2014), the positive salinity trend seems to slow down, but the trend is not statistically significant (0.0057±0.0062 yr^{-1}), with high salinity from 2007 to 2011. The depth of the LIW core gradually increases (towards deeper values) at a rate of 0.88±0.53 dbar/yr from 1979 to 2014 (Fig. 2b). Before 2004, the depth slowly decreases (towards shallower values) at a rate of -2.4±1.3 dbar/yr and then there is an inversion with a faster increase (6.1±2.1 dbar/yr) after 2004, which means the LIW core deepened by about 60 dbar in the last 10 years.

Concerning the AW core, the salinity trends show an increase (0.0029±0.0019 yr^{-1}, Fig. 2c) from 1979 to 2014, where the salinification signal is mainly due to the positive trend before 2004 (0.0073±0.0039 yr^{-1}). After 2004, the salinity decreases insignificantly at a rate of -0.0035± 0.0095 yr^{-1}, with a relatively large value during 2007-2009 (Fig. 2c). The changes of the salinity between LIW and AW cores show similar patterns: a positive salinity trend from 1979 to 2004, as well as large values between 2007-2009 (the latter may be related to a decadal oscillation); more exactly, the salinity of LIW and AW core shows a correlation coefficient of 0.77 (statistically significant under 95% significance interval). The presence of similarity suggests that the salinity of LIW core and AW core may be physically correlated. For instance, transportation of the fresher AW to the Levantine Sea will decrease the salinity of the Levantine Surface Water (LSW) in summer. In the following winter, the salinity in the formation site of the

LIW (around Rhodos Gyre) will also decrease by the advection of the fresher LSW. Accordingly, the LIW will become fresher (Skliris, 2014). The exact physical processes dominating the similarity need further study. The AW core depth shows a positive trend (0.28± 0.18 dbar/yr, sinking) from 1979 to 2014 and a faster sinking trend (1±0.83 dbar/yr) in the last decade (Fig. 2d).

3.2.2 The Cretan Passage

In the Cretan Passage, the salinity of the LIW core exhibits statistically significant trend of 0.003 ±0.001 yr^{-1} in the whole period (1982-2014) considered by the analysis (Fig. 3a), which is mainly due to the salting trend of 0.011±0.0034 yr^{-1} after 2004. The salinity increases slowly (0.0035±0.0026 yr^{-1}) before 2004. The depth of the LIW core shows a positive trend (1.6±0.65 dbar/yr, Fig. 3b) between 1982 and 2014, but the largest positive contribution to this trend corresponds to the years after 2004 (3±2.4 dbar/yr). Before 2004, the trend is not significant.

The AW core salinity shows no statistically significant trend (Fig. 3c). The depth of AW core shows an increase trend of 0.35±0.33 dbar/yr for the whole period (Fig. 3d).

3.2.3 The Aegean Sea

In the Aegean Sea, the salinity of the LIW core shows a positive trend of 0.0052±0.002 yr^{-1} for the whole period considered with an increasing trend of 0.0061±0.0035 yr^{-1} before 2004 and a stronger salinification signal (0.021±0.01 yr^{-1}) after 2004 (Fig. 4a). The depth trend of the LIW core shows a significant trend (decrease, -7.6±5.1 dbar/yr) only after 2004 (Fig. 4b).

A decreasing trend of the AW core salinity (-0.094±0.061 yr^{-1}) is observed before 2004, followed by a positive trend (0.093±0.058 yr^{-1}) since 2004 (Fig. 4c). The result is that the trend for the whole period is not significant. There is not a significant trend for the AW core depth between 1972 and 2014, while the depth increases at a rate of 3±2.6 dbar/yr (Fig. 4d) only after 2004.

The above results should be interpreted with great caution, because the number of observations is low.

3.2.4 The Ionian Sea

The increasing trends of the LIW core salinity are statistically more robust thanks to the quantity of data available for the analysis (Fig. 5a). A significant increasing trend of 0.0059±0.00052 yr^{-1} for the whole period is observed, with positive trends of 0.0063±0.0019 yr^{-1} and 0.0095±0.0011 yr^{-1} before and after 2004, respectively. This salinification signals have a near-constant rate, with a small increment in the last 10 years. The LIW core depth shows a significantly negative trend of -1.5±0.55 dbar/yr for the whole period, -2.4±1.4 dbar/yr and -6.5±2 dbar/yr before and after 2004, respectively (Fig. 5b). The LIW core is becoming shallower at a faster rate in the last 10 years.

The salinity of the AW core shows salinification trends of 0.011±0.003 yr^{-1} for the whole period, 0.0072±0.0093 yr^{-1} (not significant) before 2004 and 0.024±0.0099 yr^{-1} after 2004 (Fig. 5c). In the whole period from 1975 to 2014, the AW core deepens at a rate of 0.54±0.15 dbar/yr; however, trends are not significant both before and after 2004 (Fig.5d).

3.2.5 The Adriatic Sea

There are few observations in the Adriatic Sea with some temporal gaps. Anyway, according to these observations, the salinity of the LIW core shows a positive trend of 0.0061±0.0014 yr^{-1} for the whole period, 0.0053±0.0041 yr^{-1} before 2004 and 0.02±0.0087 yr^{-1} after 2004 (Fig. 6a), despite the fact that a strong decrease in salinity is observed between 2006 and 2010. The depth of the LIW core shows a shoaling trend of -1.9±1.5 dbar/yr, and a larger negative rate (-17±9.1 dbar/yr) occurs in the last 10 year (Fig. 6b).

The salinity of the AW core shows a positive trend (0.0071±0.0041 yr^{-1}) and its depth exhibits a positive trend (0.18±0.15 dbar/yr) for the whole period (Fig. 6cd).

3.2.6 The Sicily Channel

The Sicily Channel is a shallow sub-basin that connects the EMED and the WMED, hence the LIW and AW salinity fluctuations in this part of the Mediterranean Sea have been often used to monitor the exchange of salt and heat between the two basins (Schröder et al., 2006).

In the Sicily Channel, the salinity of the LIW core shows an increasing trend of 0.0015±0.0012 yr^{-1} in the whole period (Fig. 7a). The salinity seems to increase at a faster rate after 2004, which is, however, statistically insignificant. Moreover, no significant trend for the depth of the LIW core is found (Fig. 7b).

Also the salinity of the AW core shows a significant positive trend of 0.011±0.0042 yr^{-1} during 1978-2014 and 0.014±0.01 yr^{-1} during 1978-2004 (Fig. 7c). After 2004, the salinity trend becomes negative (not statistically significant). No significant trend of the AW core depth is found (Fig. 7d).

3.2.7 The Tyrrhenian Sea

After crossing the Sicily Channel, a LIW branch flows into the WMED through the Tyrrhenian Sea (Millot and Taupier-Letage, 2005), hence the salt transportation of the LIW in Tyrrhenian Sea has also been used to explain the thermohaline changes in the WMDW (Schröder et al., 2006).

There is a significant positive trend of the LIW core salinity of 0.0018±0.00053 yr^{-1} during the whole period; salinity increases at a faster rate after 2004 (0.0039±0.0012 yr^{-1}), while it seems to decrease (but not significantly) before 2004 (Fig. 8a). The depth trend of the LIW is significant only after 2004 with a rising rate of -5.3±2.4 dbar/yr (Fig. 8b).

The AW core salinity shows a positive trend of 0.0056±0.0037 yr^{-1} for the whole period, but the trends are not significant both before and after 2004 (Fig. 8c). No significant trend is found for the depth of the AW core (Fig. 8d).

3.2.8 The Liguro-Provençal Sea

The Liguro-Provençal Sea is the sub-basin where the formation of West Mediterranean Deep Water (WMDW) takes place (more specifically in the Gulf of Lions), and where the LIW is argued to contribute to the deep water formation (Marty and Chiavérini, 2010). Therefore LIW can influence the hydrological properties of WMDW. In this sub-basin, the salinity of the LIW core increases (at a rate of 0.0013±0.00032 yr^{-1}) in the whole period, mainly due to the contribution before 2004 (0.0023±0.00067 yr^{-1}, Fig. 9a). In the last 10 years, the previous salinity increase trend seems to vanish. The LIW core deepens before 2004 (2.5±1 dbar/yr) and then a fast rising is observed after 2004 (-4.3±2.7 dbar/yr); both the trends are statistically significant (Fig. 9b), but these two opposite trends result in an insignificant trend for the whole period.

The salinity of the AW core shows a positive trend (0.0028±0.0017 yr^{-1}) from 1972 to 2014, but a strong negative tend (-0.013±0.007 yr^{-1}) is observed in the recent 10 years (Fig. 9c). The AW core deepens (0.081±0.061 dbar/yr) in the whole period, but it shows rising trends both before 2004 (-0.15±0.11 dbar/yr, statistically significant) and after 2004 (statistically insignificant, Fig. 9d).

3.2.9 The Algerian Sea

In the Algerian Sea, the salinity of the LIW core shows a positive trend of 0.0013±0.00049 yr^{-1} for the whole period (Fig. 10a). Both the trends before and after 2004 are positive and confirm the salinification of the LIW in this sub-basin, but they are statistically insignificant. The depth of the LIW core shows a positive trend of 0.84±0.56 dbar/yr, mainly due to deepening observed from 1975 to 2004 (trend of 3.8±1.6 dbar/yr, Fig. 10b). The LIW core rises at a rate of -2.4±1.6 dbar/yr after 2004.

The Algerian Sea is next to the Alboran Sea and represents the sub-basin where the AW flows close to the Algerian coast (Millot and Taupier-Letage, 2005). Therefore the salinity of the AW core shows similar characteristics to those of the Alboran Sea. For instance, the salinity trend of the AW core for the whole period is 0.013±0.0045 yr^{-1} (Fig. 10c), which is similar to 0.02±0.007 yr^{-1} in the Alboran Sea (Fig. 12c). The salinity trend is 0.02±0.014 yr^{-1} before 2004, but this increase seems to slow down after 2004 (even though not statistically significant). The depth of the AW core increases for the whole period (0.12±0.1 dbar/yr), with a decrease in the recent 10 years (-0.49±0.31 dbar/yr, Fig. 10d).

3.2.10 The Catalan Sea

Positive trends of the LIW core salinity are found for the whole period (0.0022±0.00041 yr^{-1}) and before 2004 (0.0053±0.0017 yr^{-1}, Fig. 11a). The trend after 2004 is negative, but not statistically significant. The depth trend is significant only after 2004, with a negative rate of -5.3 ±5.1 dbar/yr (Fig. 11b).

The salinity of the AW core shows a positive trend of 0.011±0.0031 yr^{-1} for the whole period (Fig. 11c). The depth shows a positive trend (0.2±0.095 dbar/yr) for the whole period, with a negative trend (-0.45±0.43 dbar/yr) after 2004 (Fig. 11d).

3.2.11 The Alboran Sea

Even though the Alboran Sea is important to monitor the water exchange between the Atlantic and the Mediterranean, there are still few profiles available, due to a scarcity of projects focused on that area and the marginality of that sea. Given the existing observations, a robust salinification signal is found for the LIW core (0.002±0.0016 yr^{-1} before 2004, 0.0017±0.0011 yr^{-1} after 2004 and 0.002±0.00039 yr^{-1} for the whole period, Fig. 12a). A quasi-monotonical salinification of the LIW core is observed from 1981 to 2014, which is consistent with the results of Potter and Lozier (2004), who reported that the Mediterranean outflow water core salinity increases at a rate of 0.028/decade from 1950 to 2000. The trend of the LIW core depth is not significant before 2004 (Fig. 12b). However, there is an abrupt rising of the LIW core in the recent 10 years with a rate of -13±4.7 dbar/yr.

The salinity of the AW core increases in the whole period (0.02±0.007 yr^{-1}, Fig. 12c). The salinification between 2003 and 2007 (Millot, 2007; Soto-Navarro et al., 2012) cannot be observed due to the rare observations. No significant trend of the depth of AW core in the Alboran Sea is found (Fig. 12d).

4 Summary

The results described above are summarized in Figs. 13-14 and Tables 4-7. The LIW core exhibits an accelerating salinification trend in the Ionian Sea, Adriatic Sea, Aegean Sea and Cretan Passage in the recent 10 years with respect to before (Fig. 13a). In the Alboran Sea, the trend after 2004 is close to that from 1972-2004, suggesting that the salinification trend reported in previous studies has continued in the recent 10 years. Moreover, if we do not take the statistical significance into account, all the sub-basins in EMED except the Levantine Sea, show that the salinification trend of LIW core is at larger rate in the recent 10 years with respect to before, while the salinification trend is at a lower rate in all the WMED sub-basins except the Tyrrhenian Sea in recent 10 years (Table 4).

The trends of LIW core depth in the various sub-basins show interesting results. In the Ionian Sea the depth shows a faster decrease (rising) trend after 2004 (Fig. 13b) with respect to before. In the Liguro-Provençal and Algerian Sea, the trends move from positive before 2004 to negative after 2004. In the Levantine Sea, the trends move from negative before 2004 to positive after 2004. Moreover, the majority of the sub-basins show negative depth trends (rising) in the last 10 years. When the statistical significance is not taken into account, all the sub-basins, except the Levantine Sea and the Cretan Passage, show negative depth trend differences (the difference of the trends between 2004-2014 and 1972-2004), meaning that the positive trends (sinking) are slowing down or the negative trends (rising) are accelerating (Table 5).

Few significant trends of the AW core salinity are found. In the Levantine Sea, Sicily Channel and Algerian Sea, the salinification trends disappear in the recent 10 years. In the Liguro-Provençal Sea, a decreasing trend is shown only in the recent 10 year. In the Ionian Sea, a positive trend after 2004 is observed with respect to the insignificant trend before 2004. In the Aegean Sea, a strong shift occurs, but it is doubtful due to the lack of observations. Table 6 shows that the accelerating salinification trends concentrate in EMED and the decelerating ones in WMED in recent 10 years with respect to before.

There are not clear trends of the depth of AW core. In the Algerian and Catalan Sea, a significant negative trend occurs during 2004-2014 with respect to insignificant trends before 2004 (Fig. 14b). In the Aegean Sea, a faster deepening of the AW occurs in the last 10 years, but it is doubtful due to the lack of observations. If the statistical significance is neglected, the trends of accelerating sinking or decelerating rising concentrate in EMED, with the opposite ones mainly in WMED, in recent 10 years with respect to before (Table 7).

5 Conclusions

In this report, the salinity and depth changes of the LIW and the AW cores are investigated using the Argo, MEDAR/MEDATLAS, and CORIOLIS datasets. A trend analysis in the 11 sub-basins is performed for three periods (1972-2014, 1972-2004 and 2004-2014), in order to investigate: 1) whether the salinity and depth of the LIW and AW cores show significant trends in the last 10 years; 2) whether these trends are significantly different from those corresponding to previous years (1972-2004) and found in the literature.

Considering the quality of dataset and statistical significance, the main conclusions are as follows:

1) In the Levantine Sea, the salinification trend of LIW core between 1972-2004 vanishes in the last 10 years. The depth trend of LIW core moves from negative value (toward the surface) during 1972-2004 to positive value during 2004-2014. The salinity of LIW and AW cores shows similar characteristics of changes with a correlation coefficient of 0.77 (statistically significant under 95% significance interval), suggesting that the salinity variations of the LIW core may correlate physically with the AW core salinity.
2) In the Ionian Sea, the salinity of LIW core increases quasi-monotonically in the last 40 years and the depth rises, but with a gap in around 2004.
3) In the Liguro-Provençal Sea, the increase of LIW core salinity before 2004 vanishes after 2004. The depth of LIW core changes from positive trend (sinking) before 2004 to negative trend (rising) after 2004.

4) In the Alboran Sea, the salinity of LIW core increase quasi-monotonically in the last 40 years, suggesting the salinification of the outflow towards the Atlantic in the second half of last century has continued in the last 10 years.
5) In the Algerian Sea, the salinification of AW core is close to that of Alboran Sea during 1972-2014, likely due to the effect of Algerian Current. The depth of LIW core moves from positive trend (sinking) during 1972-2004 to negative trend (rising) during 2004-2014.

If the statistical significance is not taken into account, 1) most of the EMED sub-basins show larger rate of the salinification trend of LIW core salinity in the recent 10 years with respect to before, with the smaller rates mainly in WMED sub-basins; 2) in the majority of the sub-basins, LIW cores rise faster or sink slower in the last 10 years with respect to before; 3) the accelerating salinification trends of AW cores concentrate in the EMED and the decelerating ones in the WMED in the last 10 years with respect to before; 4) the accelerating sinking (or decelerating rising) trends of AW core depth concentrate in EMED, with the opposite ones in WMED, in the last 10 years with respect to before.

Although LIW is an important factor influencing the thermohaline circulation of the Mediterranean Sea, however the long-term trends of LIW core salinity has not been well studied in the past few decades, and only a few of papers on this issue can be found (summarized in Table 8). Rohling and Bryden (1992) reported salinification in the Eastern Ionian Sea (0.0046 yr^{-1}) and Western Levantine Sea (0.0021 yr^{-1}) from 1960 to 1990, but later on these results were corrected by Painter and Tsimplis (2003) to -0.002 yr^{-1} and 0.003 yr^{-1}, respectively, both of which differ from our results: 0.006 yr^{-1} in the Ionian Sea and 0.006 yr^{-1} in the Levantine Sea from 1972 to 2004. In the Balearic Sea, Sparnocchia et al. (1994) reported a salting trend of 0.0011 yr^{-1} from 1950 to 1987, which is close to 0.00084 yr^{-1} in Rohling and Bryden (1992), but differs from our result (0.005 yr^{-1}) in the Catalan Sea from 1972 to 2004. In the Ligurian Sea, Sparnocchia et al. (1994) found a salinity trend of 0.0021 yr^{-1} from 1950 to 1987, which is close to the trend of 0.002 yr^{-1} in the Liguro-Provençal Sea from 1972 to 2004 in this report. Sparnocchia et al. (1994) reported that the LIW core became fresher in the Alboran Sea at a rate of -0.00079 yr^{-1} from 1950 to 1987, however our results show a salinity trend of 0.002 yr^{-1} from 1972 to 2004, which agrees with Potter and Lozier (2004), who found an increase trend (0.003 yr^{-1}) of the salinity in the Mediterranean overflow water from 1950 to 2000. For the salinity of

AW core, only Sparnocchia et al. (1994) discussed the long-term trend, and reported that no obvious trend could be found. The trend difference between the previous studies and our report results from several factors: the source and covering period of the dataset, the geographical definition of sub-basins, the quality control method, the way to remove the seasonal cycle and the calculation of the long-term trend, as discussed by Vargas-Yáñez et al. (2010).

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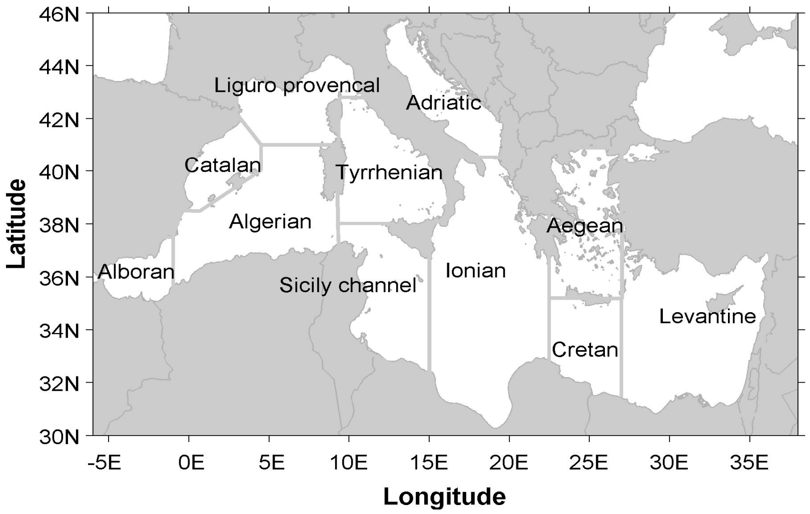

Fig. 1. Sub-basins studied in the Mediterranean Sea.

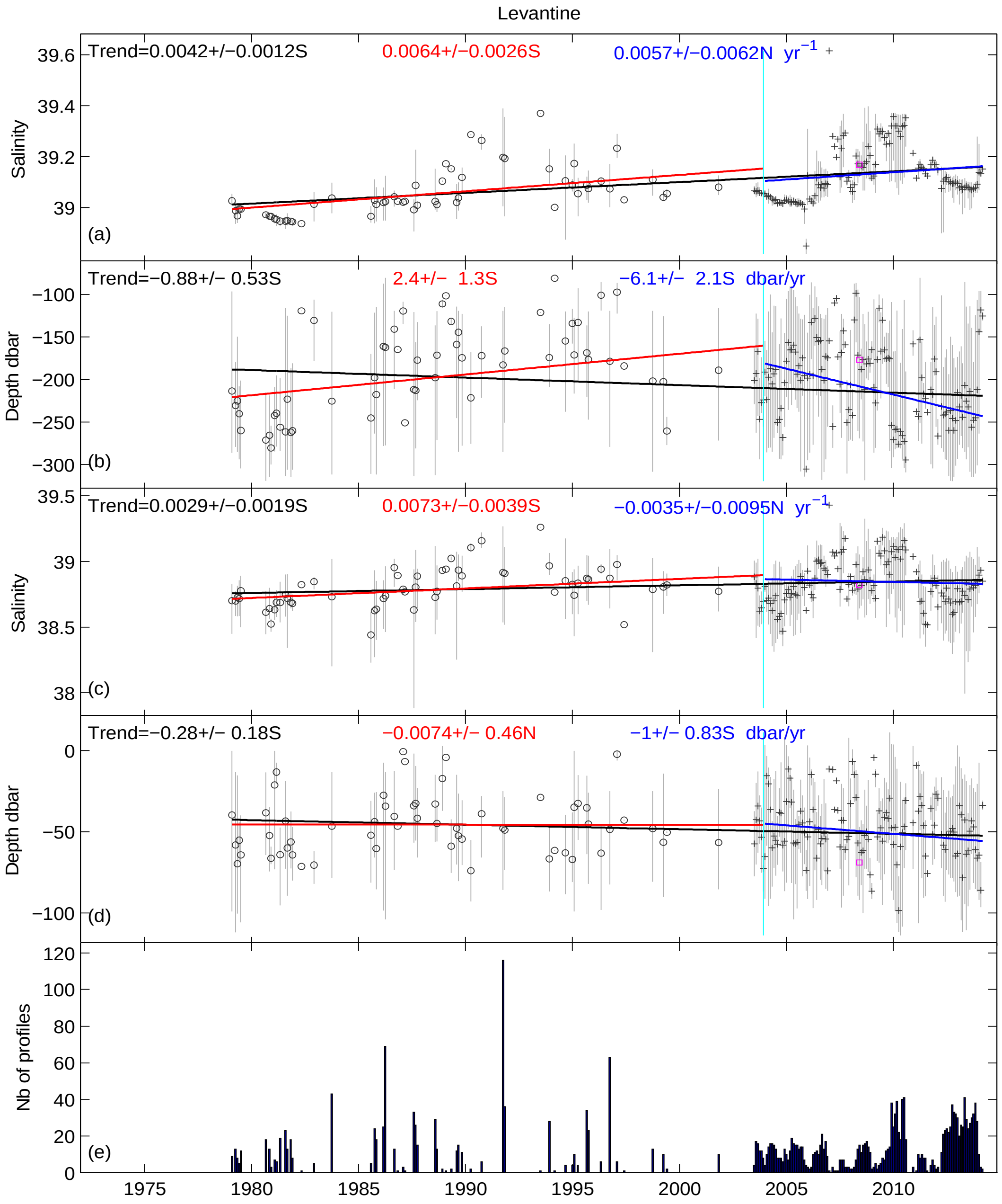

Fig. 2. Salinity and depth trends of LIW (ab) and AW (cd) cores and the number of profiles in each month (e) in the Levantine Sea, with black (red, blue) lines and numbers denoting the trends during 1972-2014 (1972-2004, 2004-2014), S (N) for the significant (insignificant) trends in the numbers, circles (crosses, purple squares) for the monthly mean values in each month with only non-Argo (only Argo, both Argo and the other) dataset, gray lines for the maximum and minimum values in each month and cyan lines denoting the year of 2004. Note that the monthly mean, maximum and minimum values are calculated after the removal of seasonal cycle.

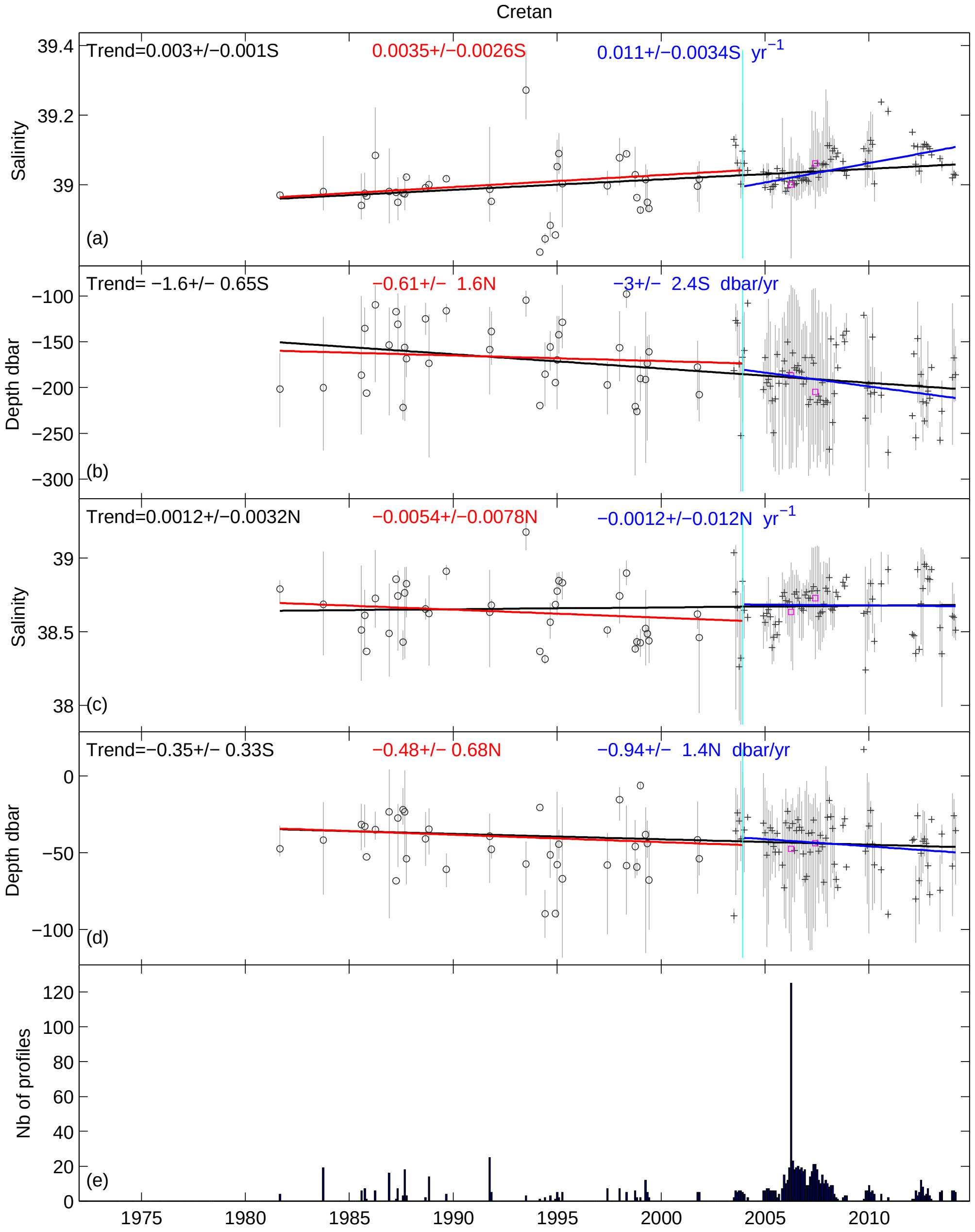

Fig. 3. The same to Fig. 2, but for the Cretan Passage.

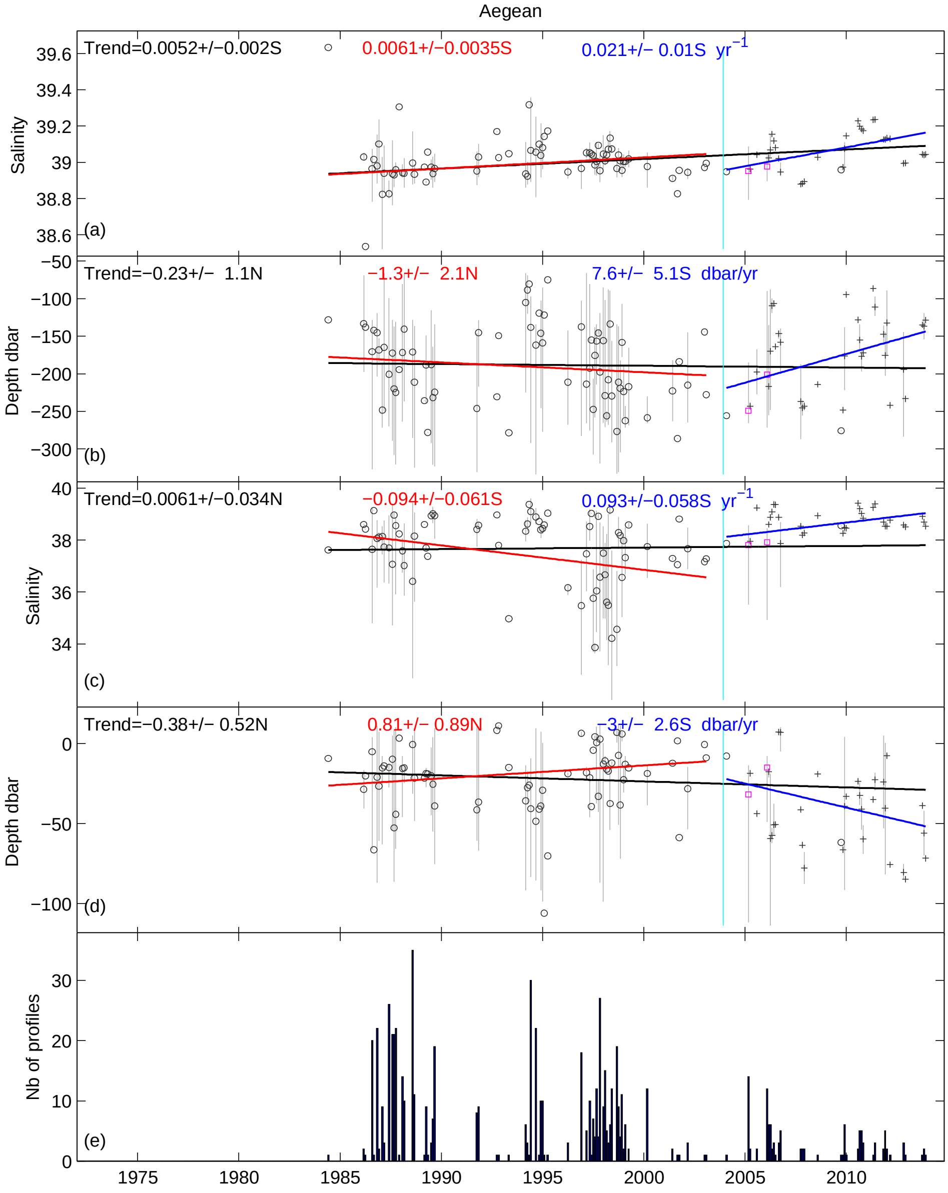

Fig. 4. The same to Fig. 2, but for the Aegean Sea.

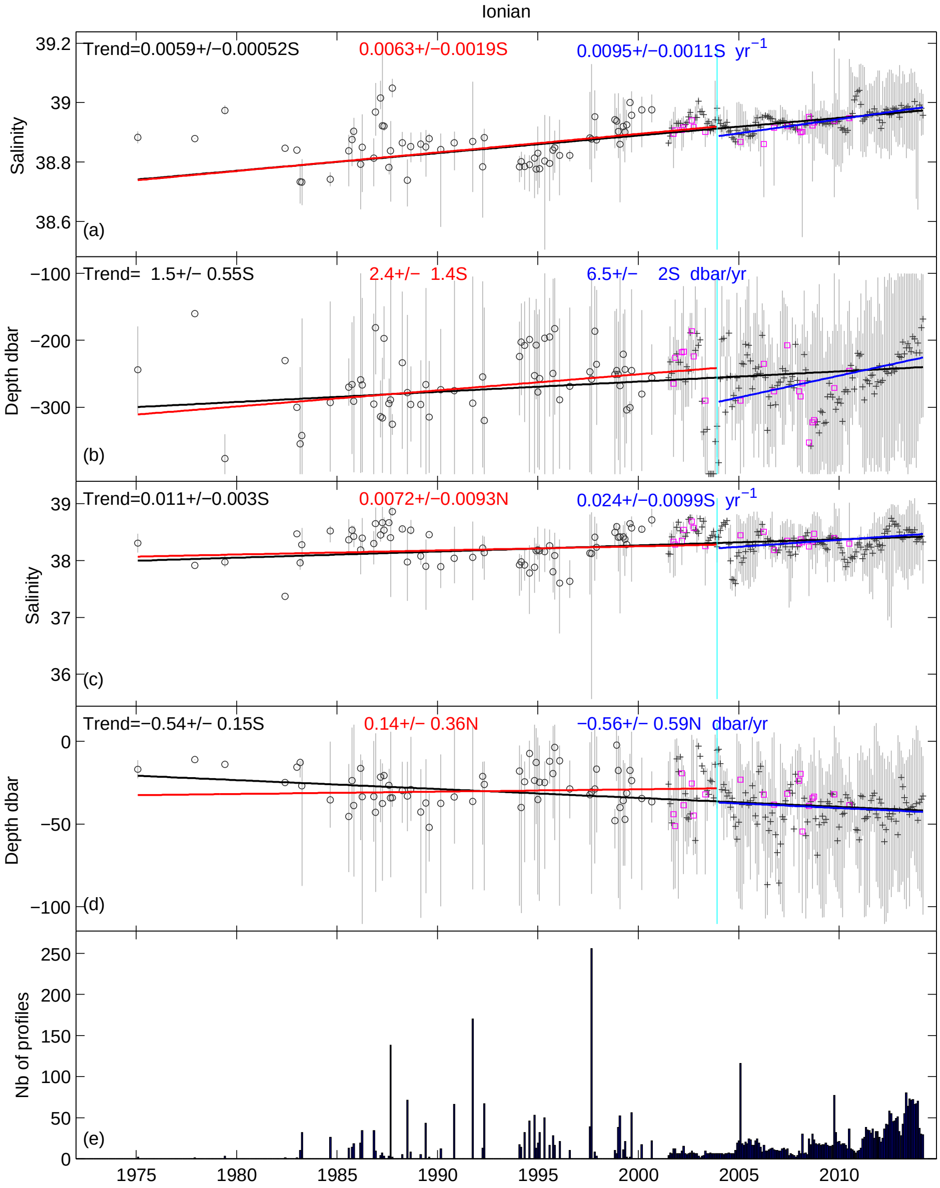

Fig. 5. The same to Fig. 2, but for the Ionian Sea.

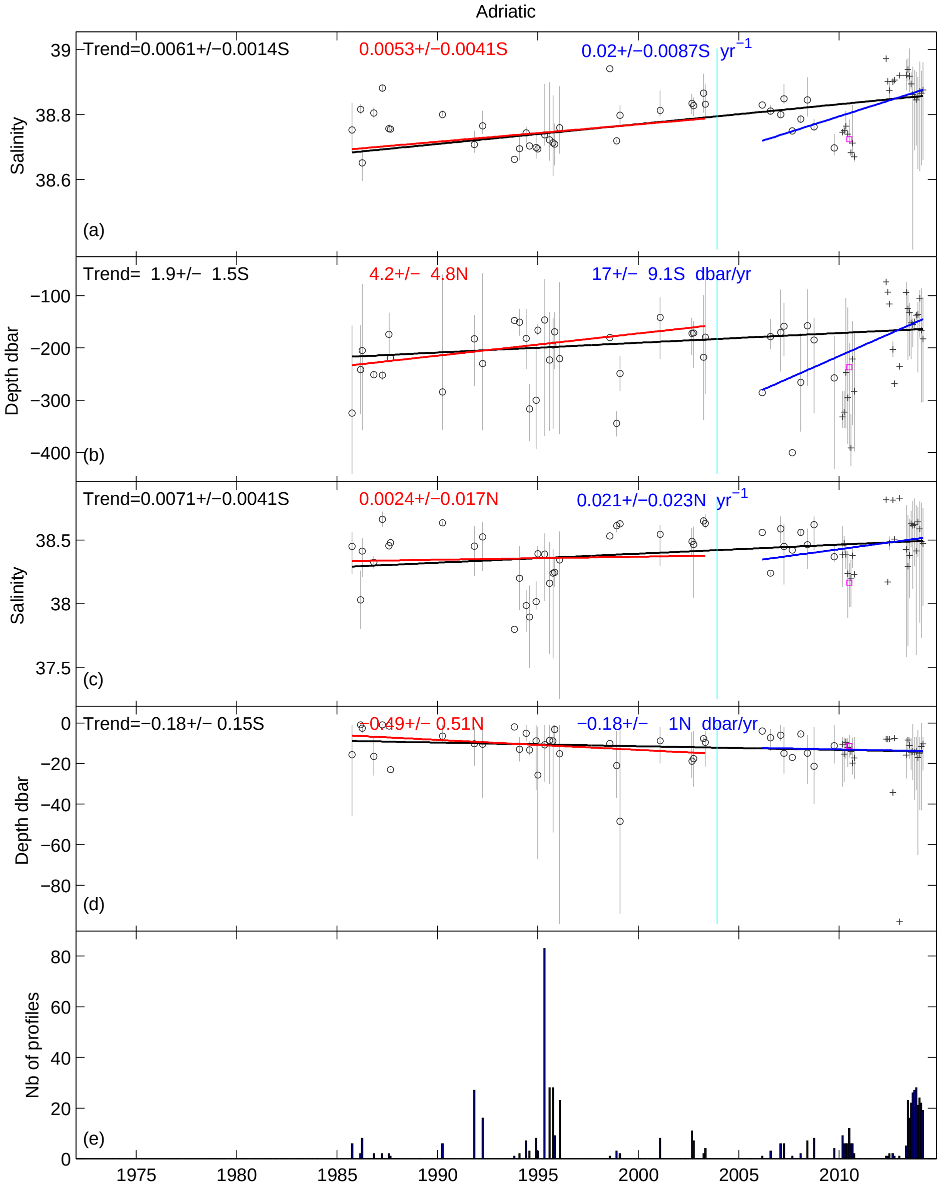

Fig. 6. The same to Fig. 2, but for the Adriatic Sea.

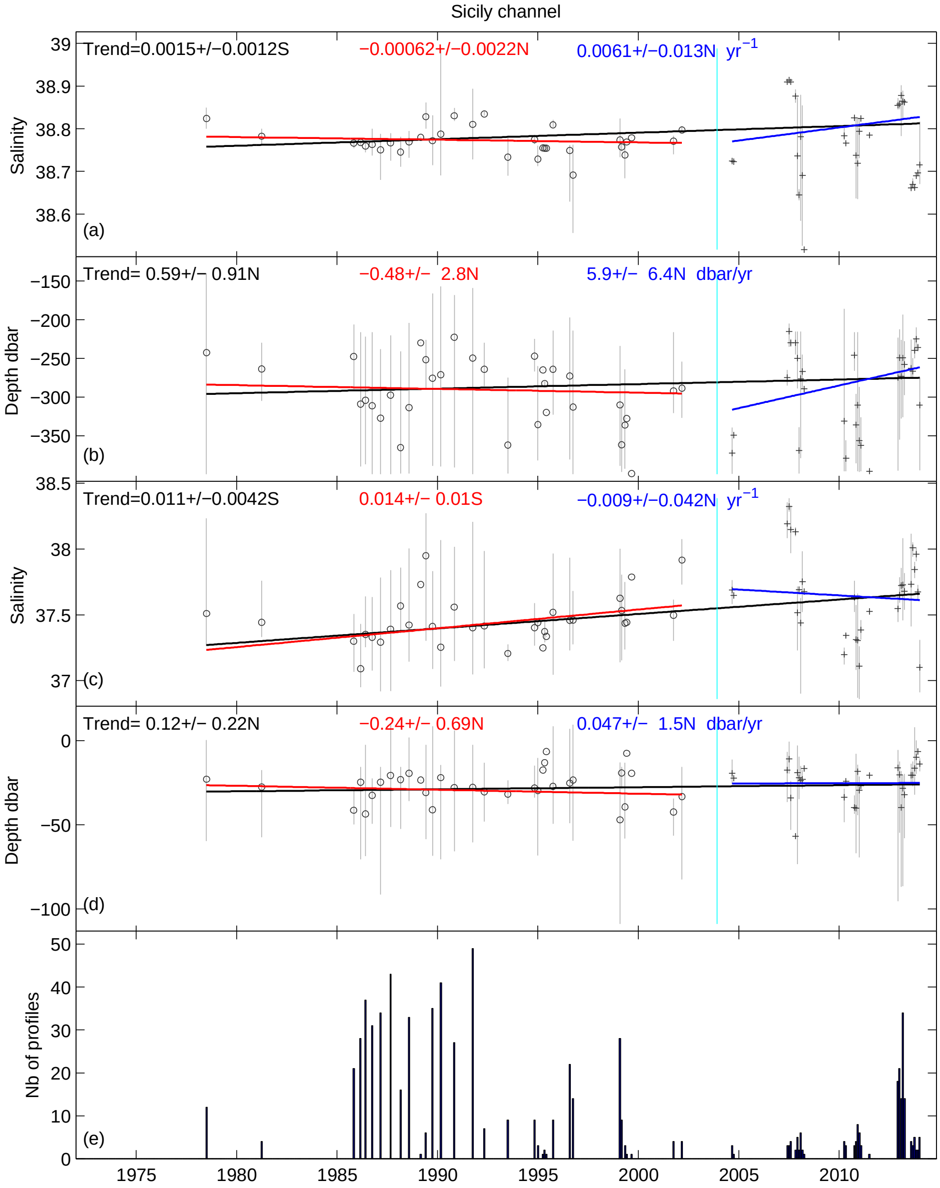

Fig. 7. The same to Fig. 2, but for the Sicily Channel.

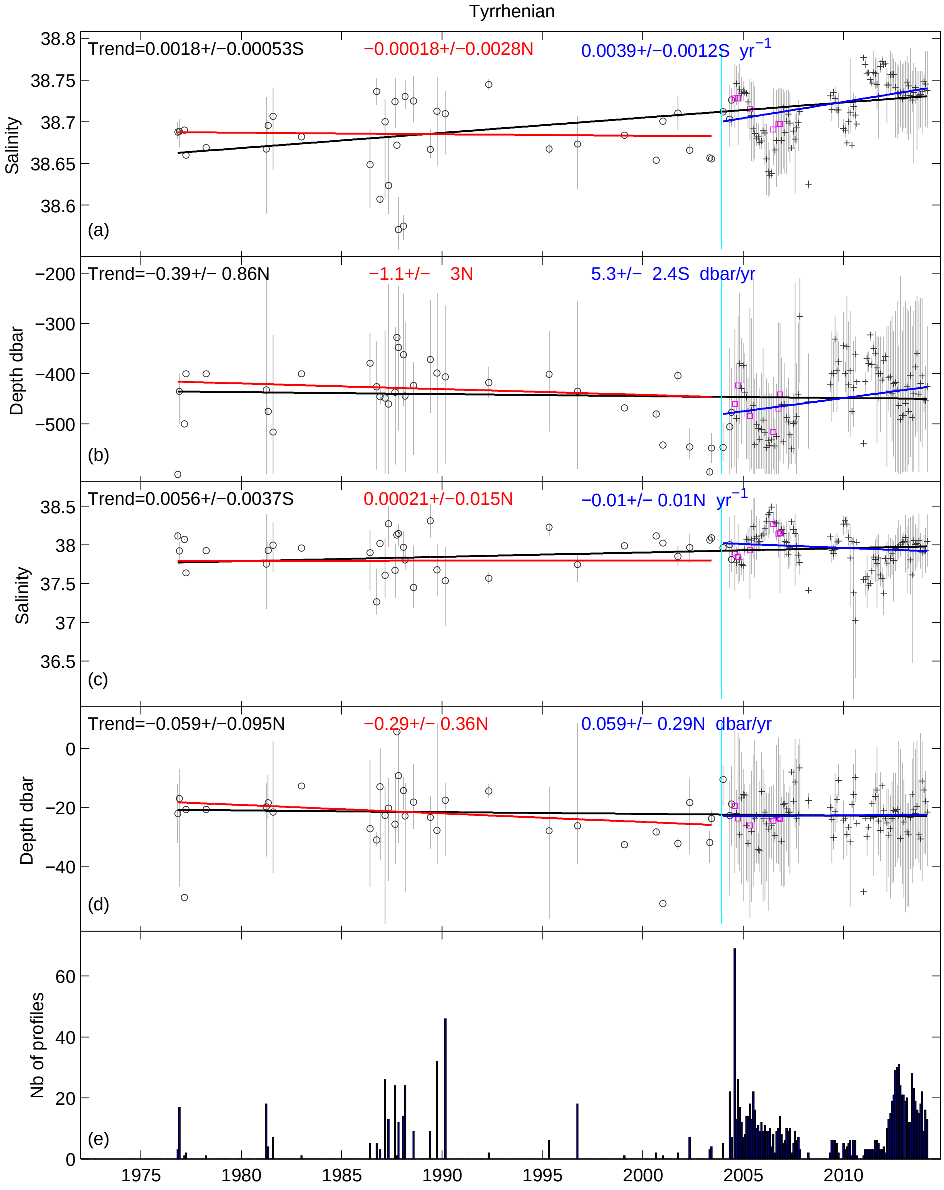

Fig. 8. The same to Fig. 2, but for the Tyrrhenian Sea.

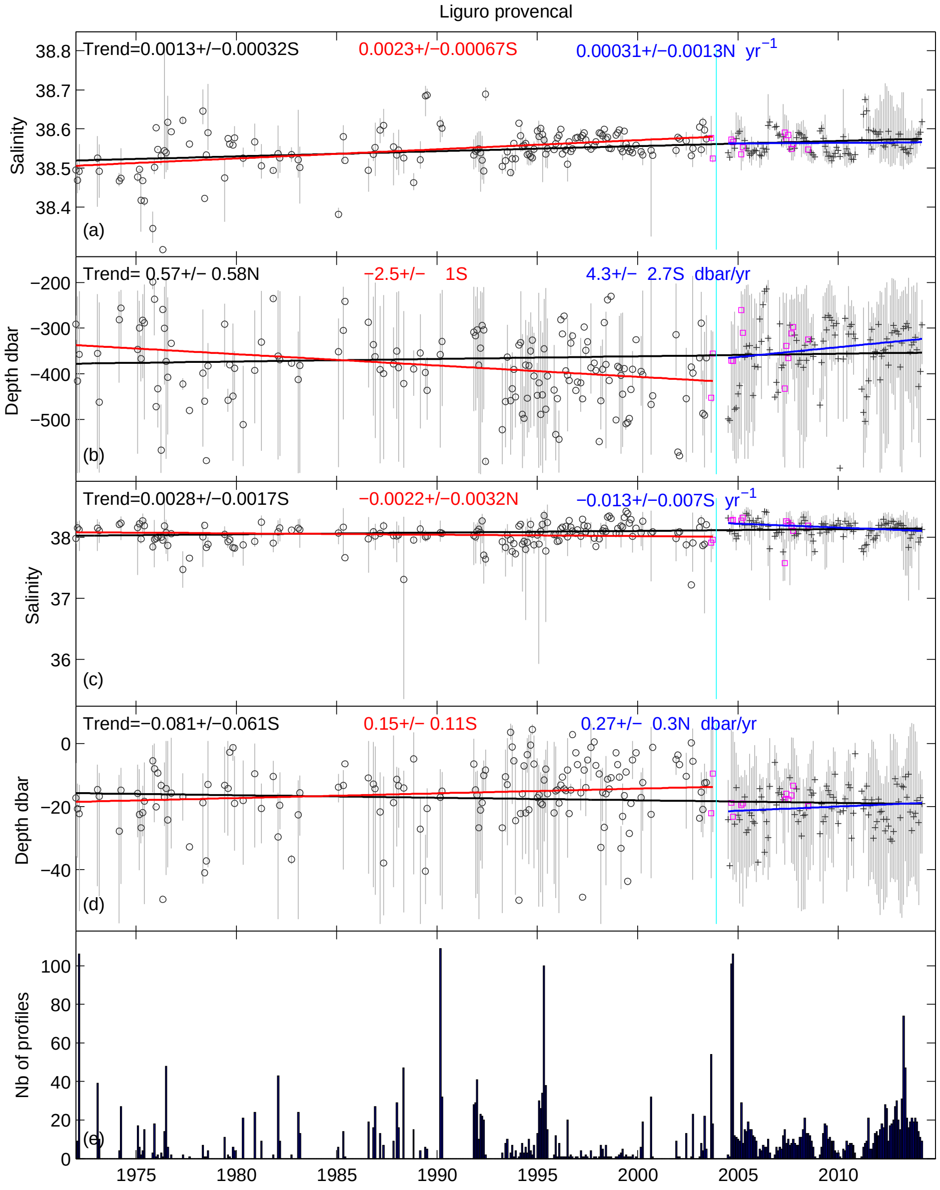

Fig. 9. The same to Fig. 2, but for the Liguro-Provençal Sea.

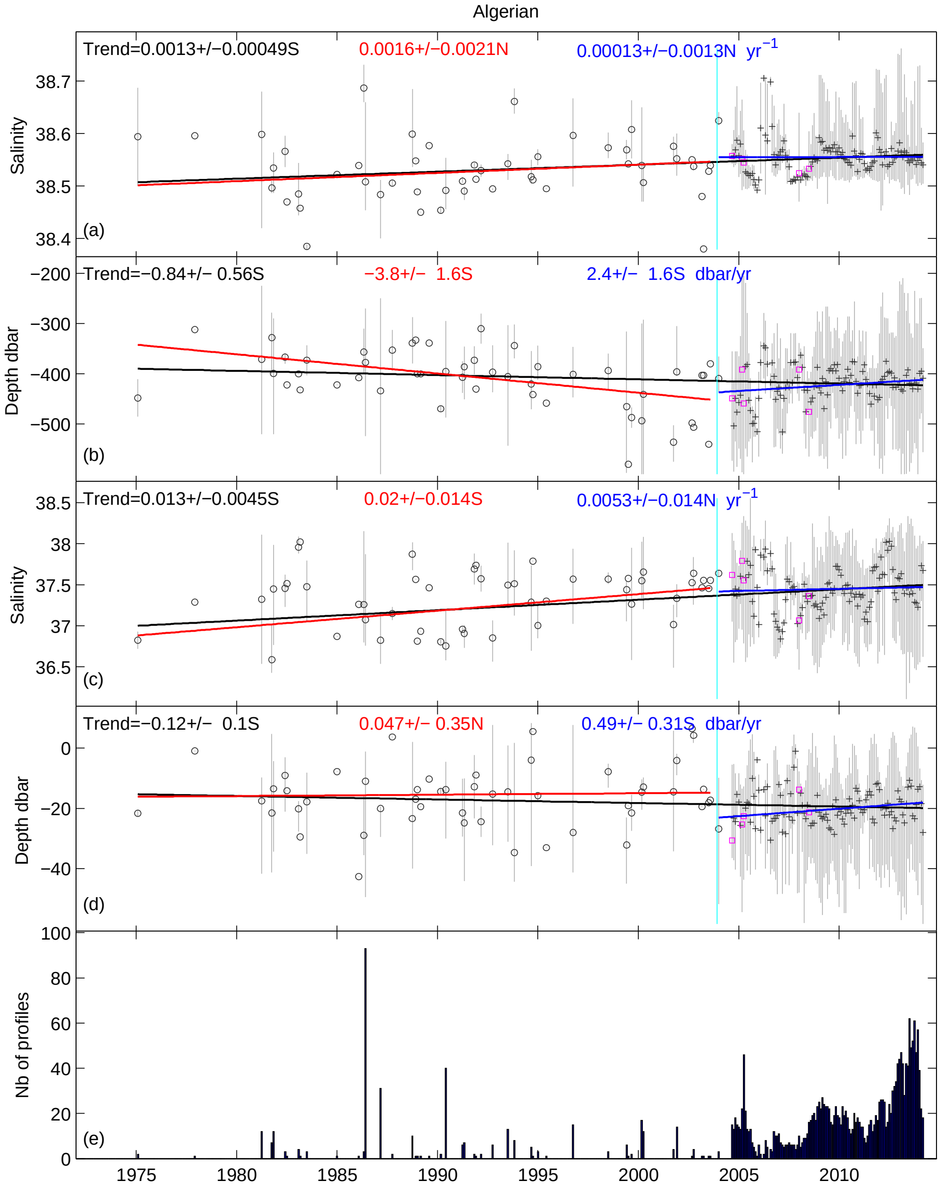

Fig. 10. The same to Fig. 2, but for the Algerian Sea.

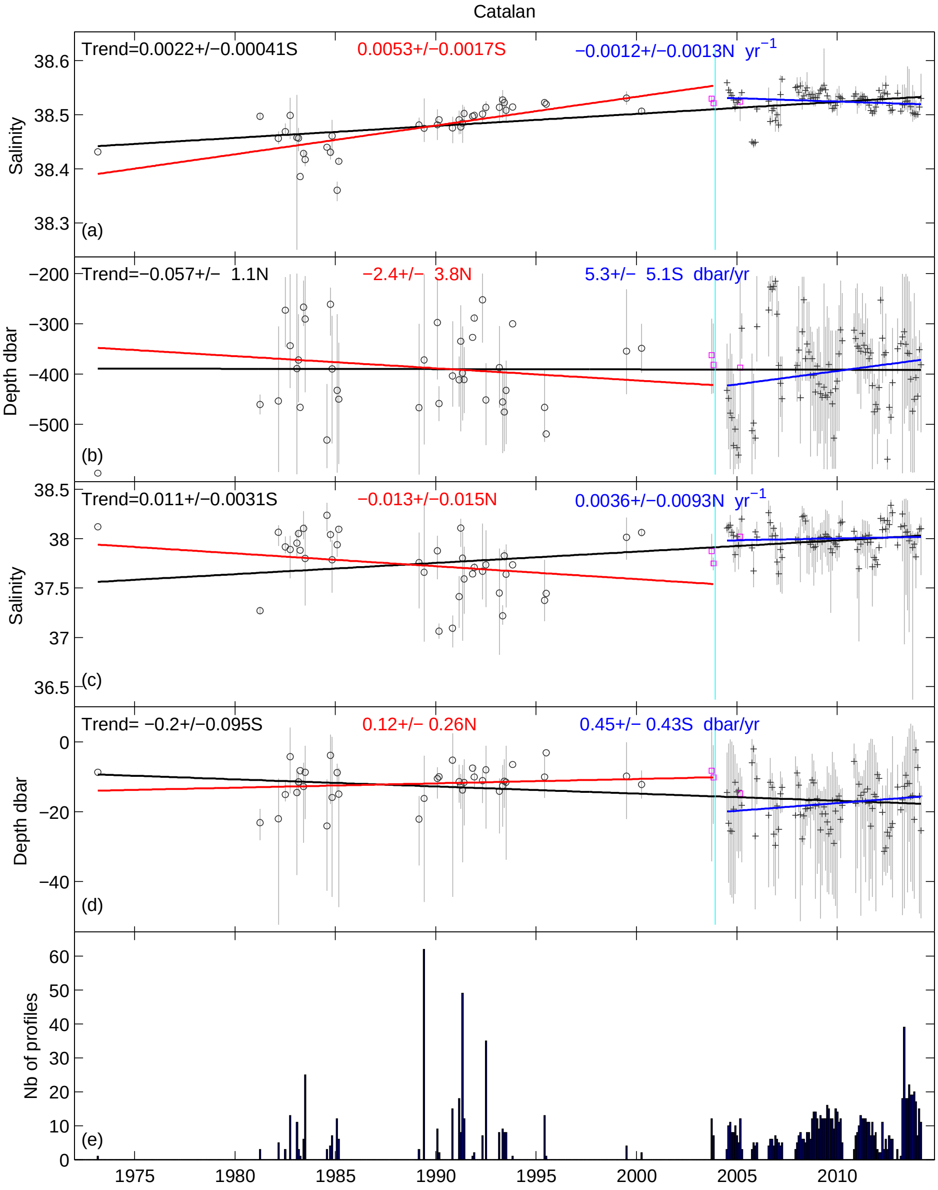

Fig. 11. The same to Fig. 2, but for the Catalan Sea.

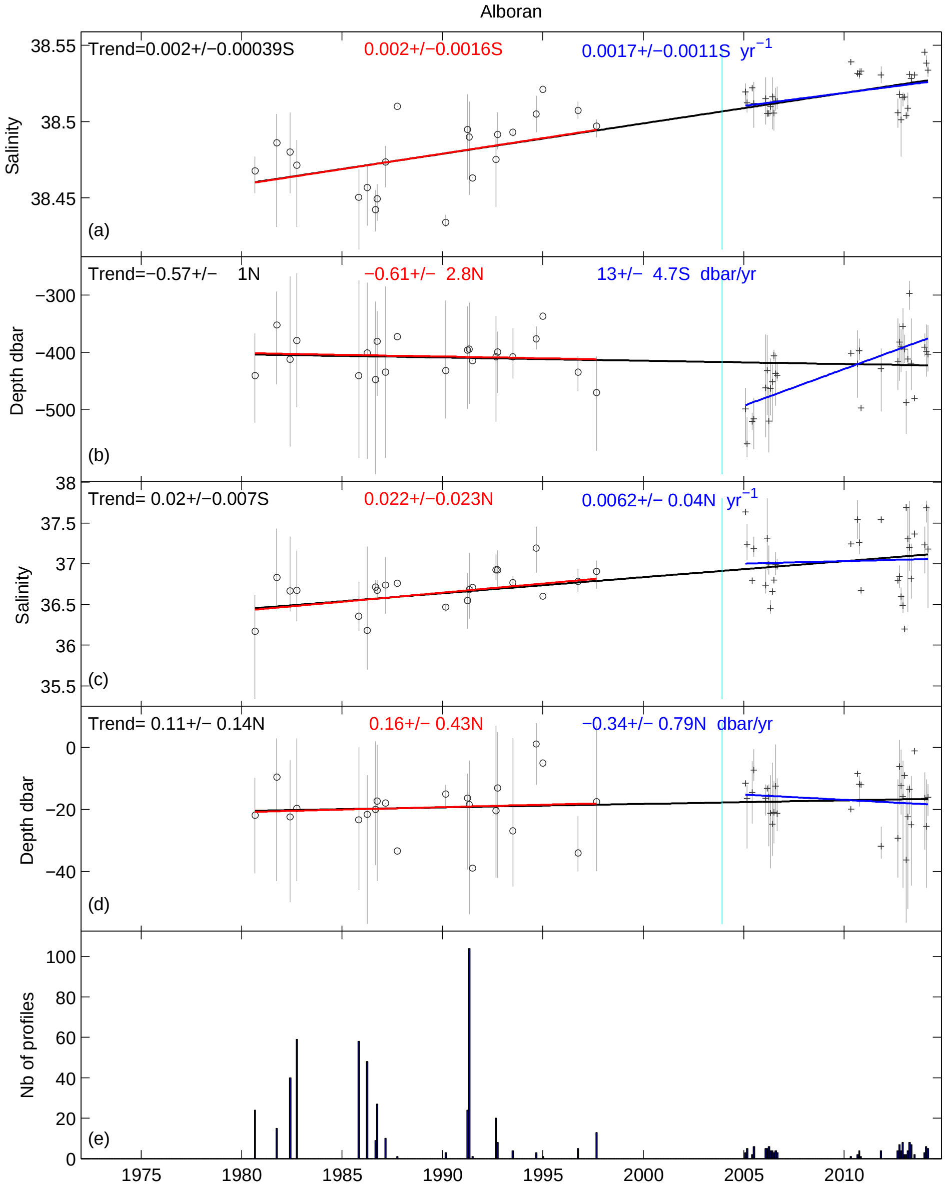

Fig. 12. The same to Fig. 2, but for the Alboran Sea.

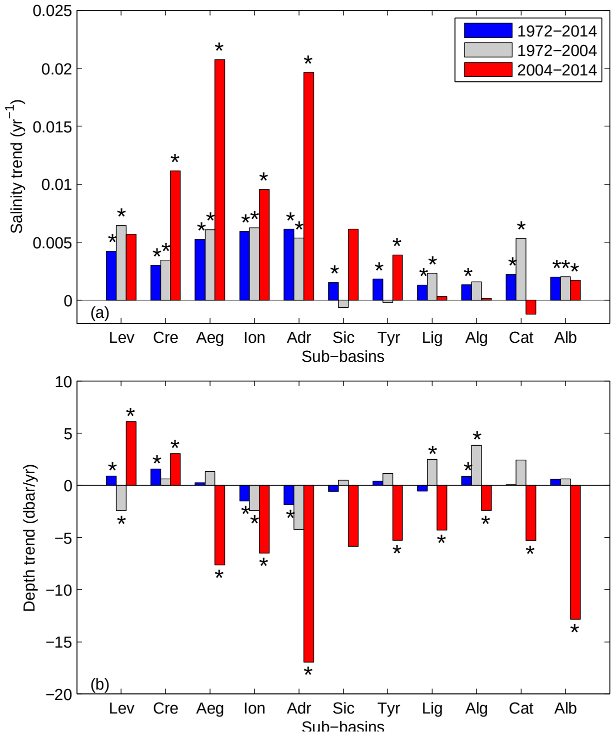

Fig. 13. The salinity (a) and depth (b) trends of LIW core in each sub-basin, with blue (gray/red) bars for the period of 1972-2014 (1972-2004/2004-2014), and the stars denoting the significant trends under 95% significant interval. The first 3 letters of the sub-basin names are used.

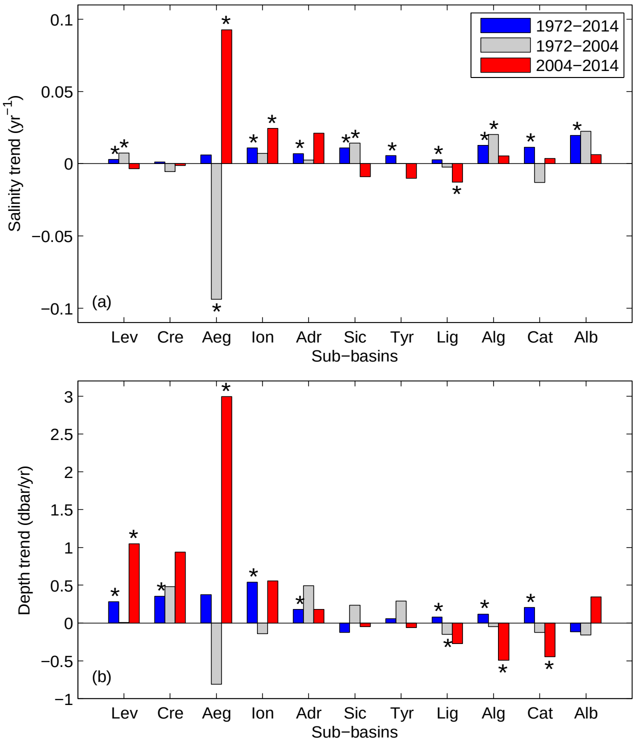

Fig. 14. The same to Fig. 13, but for SAW core.

Table 1. The depth ranges for AW and LIW in each sub-basin, where the first 3 letters of the sub-basins names are used.

Areas	Depth ranges (dbar)		Sub-basins
	AW	LIW	
Western Part	0-50	200-600	Alb, Alg, Cat, Lig, Tyr
Central Part	0-100	100-400	Sic, Ion, Adr
Eastern Part	0-100	100-300	Aeg, Cre, Lev

Table 2. The results of the regressions to fit the seasonal cycles for the LIW cores. Amp. is the amplitude, R^2 is the determination coefficient and sig. is the significance of regression with N for No and Y for Yes. The first 3 letters of the sub-basin names are used.

	Salinity of LIW			Depth of LIW		
Sub-basins	Amp.	R^2	Sig.	Amp. (dbar)	R^2	Sig.
Lev	0.017	0.012	N	19.931	0.096	Y
Cre	0.001	0.000	N	14.094	0.076	Y
Aeg	0.049	0.083	Y	34.235	0.204	Y
Ion	0.004	0.003	N	4.255	0.004	N
Adr	0.049	0.199	Y	44.087	0.187	Y
Sic	0.014	0.021	N	16.643	0.063	N
Tyr	0.005	0.010	N	8.188	0.009	N
Lig	0.019	0.081	Y	19.724	0.034	Y
Alg	0.012	0.037	N	5.957	0.010	N
Cat	0.016	0.095	Y	23.303	0.044	N
Alb	0.008	0.054	N	30.839	0.145	Y

Table 3. The same to Table 2, but for the AW core.

	Salinity of AW			Depth of AW		
Sub-basins	Amp.	R^2	Sig.	Amp. (dbar)	R^2	Sig.
Lev	0.088	0.127	Y	14.421	0.241	Y
Cre	0.059	0.052	Y	18.666	0.352	Y
Aeg	0.461	0.063	Y	14.284	0.162	Y
Ion	0.137	0.142	Y	11.220	0.241	Y
Adr	0.071	0.049	N	2.123	0.012	N
Sic	0.173	0.174	Y	13.619	0.482	Y
Tyr	0.124	0.107	Y	11.057	0.606	Y
Lig	0.111	0.168	Y	7.262	0.295	Y
Alg	0.164	0.157	Y	9.528	0.548	Y
Cat	0.169	0.234	Y	5.523	0.272	Y
Alb	0.441	0.373	Y	8.017	0.358	Y

Table 4. Summary of salinity trends of LIW core in the three periods (1972-2014/1972-2004/2004-2014), with the difference between the periods of 2004-2014 and 1972-2004 and the stars denoting the significant trends under 95% significant interval. The first 3 letters of the sub-basin names are used.

Sub-basins	1972-2014	1972-2004	2004-2014	Difference
Lev	0.004±0.001*	0.006±0.003*	0.006±0.006	-0.001
Cre	0.003±0.001*	0.003±0.003*	0.011±0.003*	0.008
Aeg	0.005±0.002*	0.006±0.003*	0.021±0.010*	0.015
Ion	0.006±0.001*	0.006±0.002*	0.010±0.001*	0.003
Adr	0.006±0.001*	0.005±0.004*	0.020±0.009*	0.014
Sic	0.002±0.001*	-0.001±0.002	0.006±0.013	0.007
Tyr	0.002±0.001*	-0.000±0.003	0.004±0.001*	0.004
Lig	0.001±0.000*	0.002±0.001*	0.000±0.001	-0.002
Alg	0.001±0.000*	0.002±0.002	0.000±0.001	-0.001
Cat	0.002±0.000*	0.005±0.002*	-0.001±0.001	-0.007
Alb	0.002±0.000*	0.002±0.002*	0.002±0.001*	-0.000

Table 5. The same to Table 4, but for the depth of LIW core.

Sub-basins	1972-2014	1972-2004	2004-2014	Difference
Lev	0.885±0.529*	-2.437±1.259*	6.088±2.082*	8.526
Cre	1.561±0.647*	0.611±1.551	3.024±2.448*	2.413
Aeg	0.232±1.136	1.314±2.069	-7.637±5.122*	-8.951
Ion	-1.523±0.548*	-2.405±1.419*	-6.509±1.972*	-4.104
Adr	-1.864±1.506*	-4.248±4.757	-16.955±9.101*	-12.707
Sic	-0.590±0.907	0.484±2.808	-5.869±6.444	-6.352
Tyr	0.388±0.861	1.130±2.976	-5.265±2.423*	-6.395
Lig	-0.569±0.580	2.476±1.027*	-4.306±2.663*	-6.782
Alg	0.843±0.556*	3.828±1.633*	-2.437±1.646*	-6.266
Cat	0.057±1.131	2.416±3.793	-5.320±5.082*	-7.737
Alb	0.567±1.044	0.611±2.810	-12.848±4.722*	-13.459

Table 6. The same to Table 4, but for the salinity of AW core.

Sub-basins	1972-2014	1972-2004	2004-2014	Difference
Lev	0.003±0.002*	0.007±0.004*	-0.003±0.010	-0.011
Cre	0.001±0.003	-0.005±0.008	-0.001±0.012	0.004
Aeg	0.006±0.034	-0.094±0.061*	0.093±0.058*	0.187
Ion	0.011±0.003*	0.007±0.009	0.024±0.010*	0.017
Adr	0.007±0.004*	0.002±0.017	0.021±0.023	0.019
Sic	0.011±0.004*	0.014±0.010*	-0.009±0.042	-0.023
Tyr	0.006±0.004*	0.000±0.015	-0.010±0.010	-0.010
Lig	0.003±0.002*	-0.002±0.003	-0.013±0.007*	-0.010
Alg	0.013±0.004*	0.020±0.014*	0.005±0.014	-0.015

Cat	0.011±0.003*	-0.013±0.015	0.004±0.009	0.017
Alb	0.020±0.007*	0.022±0.023	0.006±0.040	-0.016

Table 7. The same to Table 4, but for the depth of AW core.

Sub-basins	1972-2014	1972-2004	2004-2014	Difference
Lev	0.280±0.181*	0.007±0.456	1.048±0.826*	1.040
Cre	0.354±0.331*	0.480±0.683	0.938±1.368	0.459
Aeg	0.376±0.524	-0.808±0.890	2.995±2.608*	3.803
Ion	0.537±0.150*	-0.141±0.364	0.558±0.595	0.699
Adr	0.181±0.150*	0.493±0.512	0.180±1.009	-0.314
Sic	-0.122±0.219	0.237±0.689	-0.047±1.510	-0.284
Tyr	0.059±0.095	0.289±0.358	-0.059±0.288	-0.348
Lig	0.081±0.061*	-0.149±0.110*	-0.272±0.300	-0.122
Alg	0.117±0.105*	-0.047±0.345	-0.492±0.306*	-0.446
Cat	0.205±0.095*	-0.125±0.263	-0.446±0.430*	-0.321
Alb	-0.114±0.135	-0.158±0.425	0.345±0.785	0.502

Table 8. The salinity trends of LIW cores reported by Painter and Tsimplis (2003, hereafter PT2003), Rohling and Bryden (1992, hereafter RB1992) and Sparnocchia et al. (1994, hereafter S1994). Note that the sub-basin names on different rows correspond to different geographical regions, which are also different from the sub-basin definitions used in this report.

	PT2003	RB1992	S1994
	From 1960 to 1990		From 1950 to 1987
Balearic	0.00084	0.002461	
Eastern Ionian	-0.00195	0.004549	
Western Levantine	0.00289	0.002074	
Levantine Basin	-0.0007		
Sicilian Basin	0.0011		
Sicily Strait			0.0016
Ligurian Sea			0.0021
Balearic Sea			0.0011
Sardinia Channel			0.0011
Gulf of Lions			-0.00053
Alboran Sea			-0.00079