



Updating temperature and salinity mean values and trends in the Western Mediterranean: The RADMED project



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ABSTRACT

The RADMED project is devoted to the implementation and maintenance of a multidisciplinary monitoring system around the Spanish Mediterranean waters. This observing system is based on periodic multidisciplinary cruises covering the coastal waters, continental shelf and slope waters and some deep stations (> 2000 m) from the Westernmost Alboran Sea to Barcelona in the Catalan Sea, including the Balearic Islands. This project was launched in 2007 unifying and extending some previous monitoring projects which had a more reduced geographical coverage. Some of the time series currently available extend from 1992, while the more recent ones were initiated in 2007. The present work updates the available time series up to 2015 (included) and shows the capability of these time series for two main purposes: the calculation of mean values for the properties of main water masses around the Spanish Mediterranean, and the study of the interannual and decadal variability of such properties. The data set provided by the RADMED project has been merged with historical data from the MEDAR/MEDATLAS data base for the calculation of temperature and salinity trends from 1900 to 2015. The analysis of these time series shows that the intermediate and deep layers of the Western Mediterranean have increased their temperature and salinity with an acceleration of the warming and salting trends from 1943. Trends for the heat absorbed by the water column for the 1943–2015 period, range between 0.2 and 0.6 W/m² depending on the used methodology. The temperature and salinity trends for the same period and for the intermediate layer are 0.002 °C/yr and 0.001 yr⁻¹ respectively. Deep layers warmed and increased their salinity at a rate of 0.004 °C/yr and 0.001 yr⁻¹.

1. Introduction

The oceans play a key role in the climate change process as it is very likely that their upper 700 m have warmed from 1971 to 2010 and it is probable that this warming process extends from 1871 to 2010 (Rhein et al., 2013). This warming corresponds to a heat absorption of 0.55 W/m² through the ocean surface and represents the 93% of the net heat absorbed by the Earth due to the present radiative imbalance (Levitus et al., 2012). In this context, the Mediterranean Sea has received an increasing attention since the early 1990s. Due to the reduced dimensions of the Mediterranean (if compared with the world oceans) the effects of climate change on the temperature and salinity of its water masses could be more easily detected. Furthermore, the Mediterranean has its own thermohaline circulation. Changes in deep water formation

and the thermohaline circulation can be studied in the Mediterranean Sea more easily than in the world oceans as deep water formation areas in the Mediterranean are more accessible than other regions of the world. Finally, water masses and circulation in the Mediterranean are affected by other anthropogenic factors different from climate change such as the damming of the main rivers draining into the Mediterranean Sea (Rohling and Bryden, 1992; Krahnmann and Schott, 1998). All these factors have led to consider the Mediterranean Sea as a natural laboratory for climate change studies (Bethoux et al., 1999).

Lacombe et al. (1985) reported a temperature and salinity increase of the deep waters in the Western Mediterranean. These results were based on the comparison of temperature and salinity data provided in previous works (Nielsen, 1912; Sverdrup et al., 1942) with those data collected along several cruises carried out from the early 1950s to the

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1970s. Later works analyzed the long term evolution of the upper, intermediate and deep layers both in the Western and Eastern Mediterranean. The upper layer corresponds to the AW and is usually considered as that extending from the surface to 150 or 200 m depth. The intermediate layer is mainly occupied by LIW and is usually considered as extending from 150 or 200 m to 600 m. Finally, the deep layer is below the intermediate layer and extends to the sea bottom. These works revealed the warming and salting of the deep waters (Béthoux et al., 1998; Leaman and Schott, 1991; Rohling and Bryden, 1992; Krahnmann and Schott, 1998; Rixen et al., 2005; Vargas-Yáñez et al., 2010a, 2010b). The existence of long term trends in the thermohaline properties of the intermediate and upper layers was not so clear. Some of these works reported changes in the salinity and temperature of the Levantine Intermediate Waters (LIW, Leaman and Schott, 1991; Rohling and Bryden, 1992; Béthoux et al., 1998; Rixen et al., 2005). On the contrary, other works found no significant trends for this water mass (Krahnmann and Schott, 1998; Painter and Tsimplis, 2003). Concerning the upper layer, occupied by Atlantic Waters (AW), several studies have used Sea Surface Temperature data from radiometers operated from satellite from the mid 1980s to show a clear warming of the Mediterranean surface waters. These results are confirmed by Skliris et al. (2012) who used in situ measurements from NOCs (National Oceanographic Center Southampton) to extend the analyses to the period 1973–2008. Nevertheless, when in situ data are used to study the upper part of the water column, some discrepancies appear. Once again, some works show no warming trends (Krahnmann and Schott, 1998; Sparnocchia et al., 1994), while others present positive trends for the AW temperature (Pascual et al., 1995; Salat and Pascual, 2006).

Other changes detected in the Mediterranean Sea are related to the abrupt shift of the deep water formation sites and rates in the Eastern Mediterranean. This event, commonly known as the Eastern Mediterranean Transient (EMT), occurred at some moment between 1987 and 1995 and led to a dramatic increase of the temperature and salinity of the new Eastern Mediterranean Deep Waters (EMDW) which replaced and uplifted the old EMDW (Roether et al., 1996, 2007). The changes observed in the Eastern Mediterranean have been transmitted to the Western Mediterranean as saltier and warmer intermediate waters would flow through the Sicily channel after the EMT (Gasparini et al., 2005). The arrival of these saltier intermediate waters and some exceptional atmospheric conditions during winters 2005 and 2006 in the Western Mediterranean would have been responsible for the appearance of a new and anomalous Western Mediterranean Deep Water (WMDW). This water mass is warmer, saltier and denser than the previous or old WMDW and has occupied the bottom layer of this basin. These events are known as the Western Mediterranean Transition (WMT, Schroeder et al., 2010, 2016; Zunino et al., 2012; López-Jurado et al., 2005).

Most of the results outlined above have been derived from the comparison of data obtained in different oceanographic cruises. In most of the cases such cruises had no common purpose nor belonged to any monitoring program. As a consequence of the lack of long term monitoring programs in the Mediterranean Sea during the last century, oceanographic data are scarce and unevenly distributed. Vargas-Yáñez et al. (2009, 2012a) have shown that this could be the cause for some of the discrepancies between different works. These authors concluded that the data scarcity and their irregular distribution could make the results very sensitive to the data analysis methodology. More recently, Llasses et al. (2015) and Jordá and Gomis (2013) have evidenced differences between the results obtained when analyzing temperature and salinity time series from different data bases and monitoring programs. Once again such discrepancies are attributed to the data scarcity, the interpolation method or even the data quality control.

During the late 1990s and the beginning of the twenty first century, several monitoring programs have been implemented in the Mediterranean Sea. Each of these programs is based on a different strategy and methodology, but all of them will contribute to a better

understanding of the changes currently affecting the Mediterranean Sea. The Hydrochanges network is based on the mooring of CTDs at key places for the monitoring of the temperature and salinity variability of the water masses within the Mediterranean Sea (Schroeder et al., 2013). Time series collected under Hydrochanges umbrella have already revealed changes in the composition of the Mediterranean outflow through the Strait of Gibraltar (Millot, 2009). The MEDARGO program maintains an array of profiling floats in the Mediterranean Sea (Poulain et al., 2007). As an example, these data have been useful in the description of the deep water formation (Smith and Bryden, 2007) or the study of the Mediterranean mesoscale circulation (Sánchez-Román et al., 2016). The Lion Mooring Line monitors in a continuous way the deep water formation in the MEDOC (MEDOC Group, 1970) area since 2007 (Houpert et al., 2016). This mooring line, equipped with instruments along the water column, is part of the Mediterranean Ocean Observing System.

The RADMED program is devoted to the implementation and maintenance of a monitoring system around the continental shelf and slope, including some deep stations (> 2000 m) around the Spanish Mediterranean (López-Jurado et al., 2015; Tel et al., 2016). This monitoring program is aimed at the study of the seasonal and long term variability of the Westernmost Mediterranean waters from a multidisciplinary point of view. Oceanographic stations are visited on a seasonal basis since 1992 in some cases and since 2007 in the case of the stations most recently included in the RADMED project. Vargas-Yáñez et al. (2010b) have shown that temperature and salinity data from the RADMED project can be merged with historical data in order to construct long time series, providing valuable information about long term changes in the Western Mediterranean. As previous analyses considered TS data up to 2008, they did not include the new stations operated since 2007. The goal of the present work is to update temperature and salinity time series by extending the previous ones to 2015 (inclusive). The new available information will allow us to obtain mean values for the properties of the Atlantic and Mediterranean waters around the Spanish Mediterranean. At the same time, linear trends will be computed in order to check the behavior of these variables along the twenty first century. The analysis of updated time series, including for the first time those stations initiated in 2007, and the use of historical data, will allow us to evaluate new long-term trends. The data set is described in Section 2, results are presented in Section 3, and finally, discussion and conclusions are in Sections 4 and 5.

2. Data and methods

A network of oceanographic stations are periodically visited in the frame of the RADMED project, funded by the Instituto Español de Oceanografía. The stations are distributed in transects perpendicular to the coast. Stations are named by a letter corresponding to each transect and a number increasing from the coast to the open sea. In the Alboran Sea, the westernmost transects are Cape Pino (P in Fig. 1), Málaga (M) and Vélez (V). For instance, the closest station to the coast in Cape Pino transect is named as P1, and the most offshore station is P4. Sacratif transect extends from Cape Sacratif in the central part of the Alborán Sea, and Cape Gata transect (CG) is on its eastern limit. Those transects extending from the eastern Spanish coast are Cape Palos (CP), Tarragona (T) and Barcelona (BNA). Two more transects are located in the Balearic islands, one of them to the south of Mallorca Island (B) and another one extending in a northeast direction from Menorca Island (MH). 37 oceanographic stations forming two triangles cover the Balearic channels: The Ibiza channel between the peninsula and Ibiza Island and the Mallorca channel between Ibiza and Mallorca. These stations are labeled as C. Finally a deep station (> 2200 m) is located to the south of Cabrera Island (EPC). All the stations are visited three-monthly, that is, once per season of the year and the samplings are multidisciplinary including temperature and conductivity profiles by means of a CTD periodically calibrated. Water samples are taken at

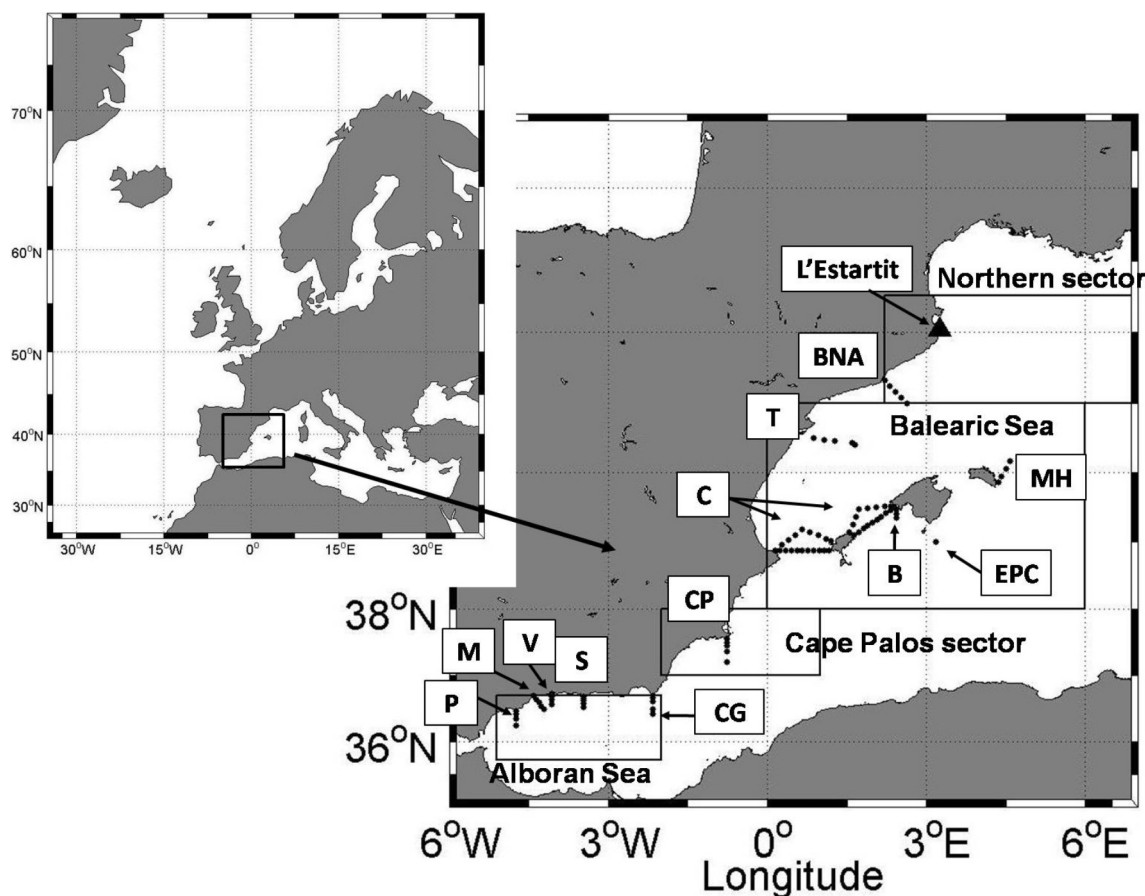


Fig. 1. Oceanographic stations from the RADMED project. Stations are distributed along transects. Each transect is labeled with a letter related to some geographical feature or location: Cape Pino P, Málaga M, Vélez V, Cape Sacratif S, Cape Gata CG, Cape Palos CP, Tarragona T, Barcelona BNA, Mallorca B, Mahón MH, Cabrera deep station EPC and two triangles in the Balearic channels C. Each station is labeled with its corresponding letter and a number increasing seaward. Stations in the Balearic channels are labeled from C1 to C37. Black triangle is L'Estartit oceanographic station operated by the Institut de Ciències del Mar in Barcelona. Four rectangles are included in this figure. Each rectangle is one area where temperature and salinity data have been obtained from the MEDAR/MEDATLAS data base. The four rectangles or geographical areas considered are: Alborán, Cape Palos, Balearic Sea and Northern sector.

Table 1

Stations included in the RADMED project. It is included the year when the sampling was initiated, the maximum depth sampled and the project under which it was initiated.

Oceanographic station	Initial project	Initial year	Maximum depth (m)
P1-P3	ECOMALAGA	1992	530
M1-M3	ECOMALAGA	1992	200
M4-M5	ECOMALAGA	2000	500
V1-V3	ECOMALAGA	1992	300
V4	ECOMALAGA	2000	490
P4	RADMED	2007	870
S1-S5	RADMED	2007	750
CG1-CG5	RADMED	2007	1130
CP1, CP3, CP4	ECOMURCIA	1996	2100
CP2	RADMED	2007	75
B1-B3	ECOBALAEARES	1994	200
C1-C10 south Mallorca Channel	CIRBAL	1996	638
C11-C21 south Ibiza Channel	CIRBAL	1996	840
C22-C29 North Ibiza Channel	CIRBAL	1996	1260
C30-C37 North Mallorca Channel	CIRBAL	1996	1230
EPC1	RADMED	2007	2315
MH1-MH4	RADMED	2007	2500
T1-T4	RADMED	2007	950
BNA1-BNA5	RADMED	2007	1670

discrete depths for oxygen, nutrients (nitrate, nitrite, silicate and phosphate) and chlorophyll determinations. In addition, water samples are taken for determination of the abundance and taxonomic composition of phytoplankton. Oblique trawls with BONGO nets are carried out for determination of zooplanktonic abundance and taxonomic composition. More details about the sampling protocols can be found in www.repositorio.ieo.es/e-ico/handle/10508/1762.

The RADMED stations are the result of the unification and extension of previous monitoring programs: ECOMALAGA, ECOMURCIA, ECOBALEARES and CIRBAL. Table 1 summarizes the name of the previous projects and the year when sampling was initiated. Since 2007 all the stations are under the umbrella of the RADMED project. In some cases, the new oceanographic stations were initiated in 2007 when the RADMED project was launched.

The longest time series from the RADMED project are 24 years long as 2016 is not included in the present work, while the shortest ones are 9 years long. These time series are suitable for analyzing the temperature and salinity mean values in the continental shelf and slope around the Spanish Mediterranean as well as those changes operating on these properties during the last decade. For each oceanographic station and for each depth level from the surface to the sea bottom, temperature and salinity data were split into winter, spring, summer and autumn data. For each data set outliers were discarded, normality tests were carried out and mean and standard deviation values were calculated. Confidence limits at the 95% confidence levels were calculated for the mean values considering a t-student distribution.

Nevertheless, these variables exhibit both inter-annual and decadal variability making it difficult to distinguish long term changes such as

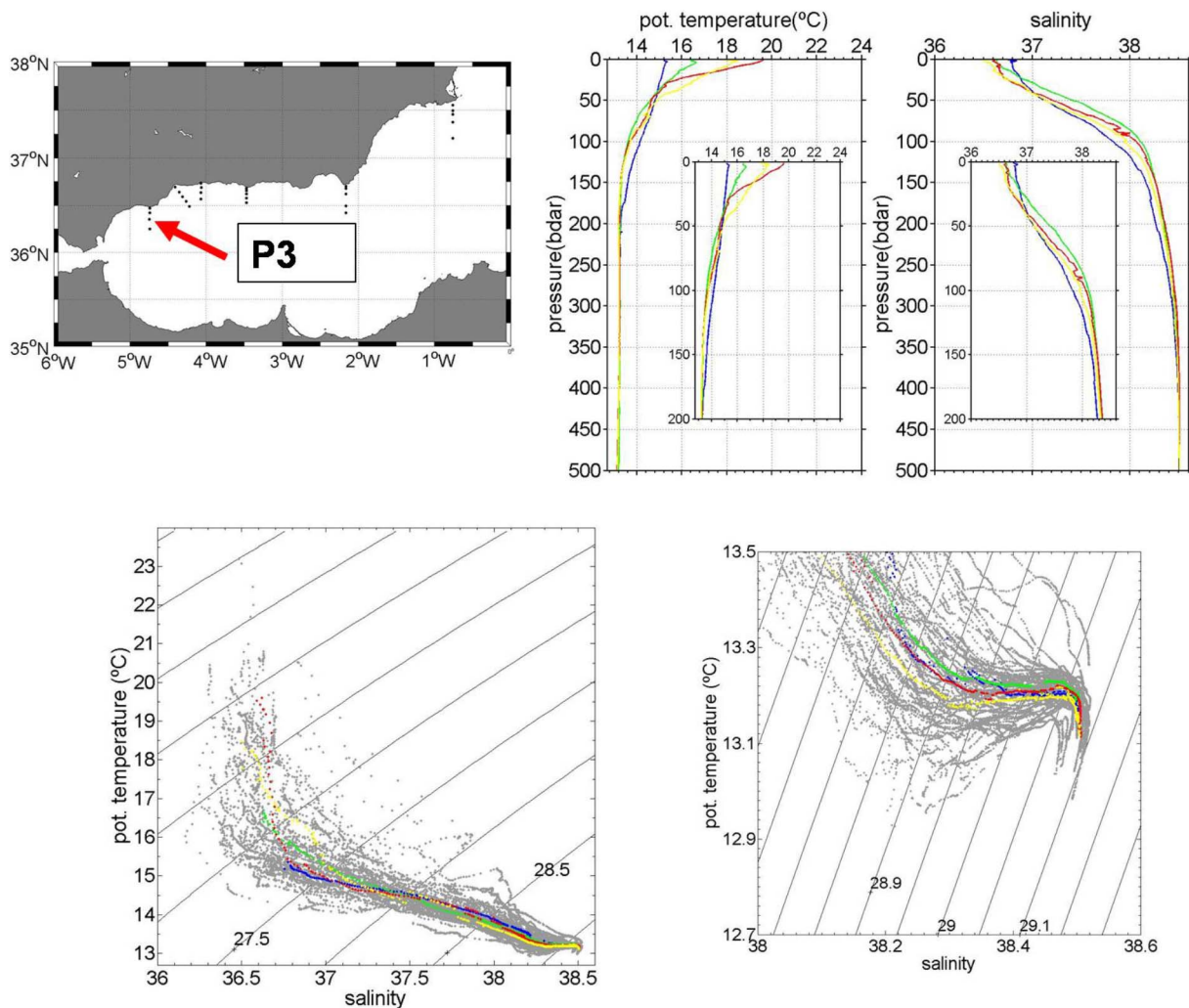


Fig. 2. Mean values for temperature and salinity in P3 station. Upper left corner shows the P3 position. The upper right figures are the average vertical temperature and salinity profiles. Blue lines are for winter, green for spring, red for summer and yellow for autumn. A zoom for the upper 200 m of the water column is included. The lower left figure shows the θS diagram for the P3 station. Grey dots correspond to all the available CTD casts from this oceanographic station. Mean θS values for winter are included in blue, green for spring, red for summer and yellow for autumn. The lower right figure is a zoom for the deepest waters in order to enhance the properties of WIW, LIW and WMDW. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

possible trends linked to climate change. In order to extend back in time our time series, four geographical areas were chosen. These regions are delimited by rectangles in Fig. 1 and are named Alborán, Cape Palos, Balearic Sea and Northern Sector (see Fig. 1). All available temperature and salinity data within each of these regions (rectangles) were obtained from the MEDAR/MEDATLAS data base (MEDAR Group, 2002). Vertical profiles were seasonally averaged obtaining four data per year and then these four data were averaged to get one temperature and salinity profile for each year and region. Finally, the RADMED profiles within the same region were annually averaged extending in time annual time series of temperature and salinity. The final results are annual temperature and salinity time series at different depth levels (from 0 to 2500 m) extending from 1900 to 2015. The homogeneity of the extended time series was checked by means of a standard normal homogeneity test (Alexanderson, 1986; Alexanderson and Moberg, 1997).

The methodology followed for the analysis of the time series is similar to that used in Vargas-Yáñez et al. (2010a, 2010b). In some years, there were not data corresponding to the four seasons of the year (winter, spring, summer and fall). In these cases two different approaches were followed. In the first one, the missing seasonal value was substituted by a climatological or long term mean value calculated from the complete series (1900–2015). This method is equivalent to consider

that the missing data has a zero anomaly or deviation from the climatological value. In the second approach the annual temperature or salinity is calculated averaging the anomalies or residuals from the available seasons. Therefore it is considered that the part of the year which is not sampled had a behavior (anomaly) similar to the one sampled. In other words, the anomalies from the seasons with data are considered as representative of those seasons with no data.

Gouretski and Koltermann (2007), Domingues et al. (2008), Levitus et al. (2009) among others, detected errors in inter-annual and decadal variability and trends in temperature time series caused by biases in the bathythermograph data. In the aforementioned works, the observed biases were corrected. In our case, as the required information for the data correction is not available, the following approach is followed. All the calculations are repeated both including and excluding bathythermograph data.

Temperature data from l'Estartit station have been analyzed. L'Estartit oceanographic station is located on the continental shelf of the Catalan Sea (Fig. 1) over a bottom depth of 80 m. This station is visited on a weekly basis by the Institut de Ciències del Mar (ICM). Four discrete temperature measurements are obtained at 0, 20, 50 and 80 m depth since 1969. These time series are included in order to obtain further information concerning the upper AW in the northern sector of our study region.

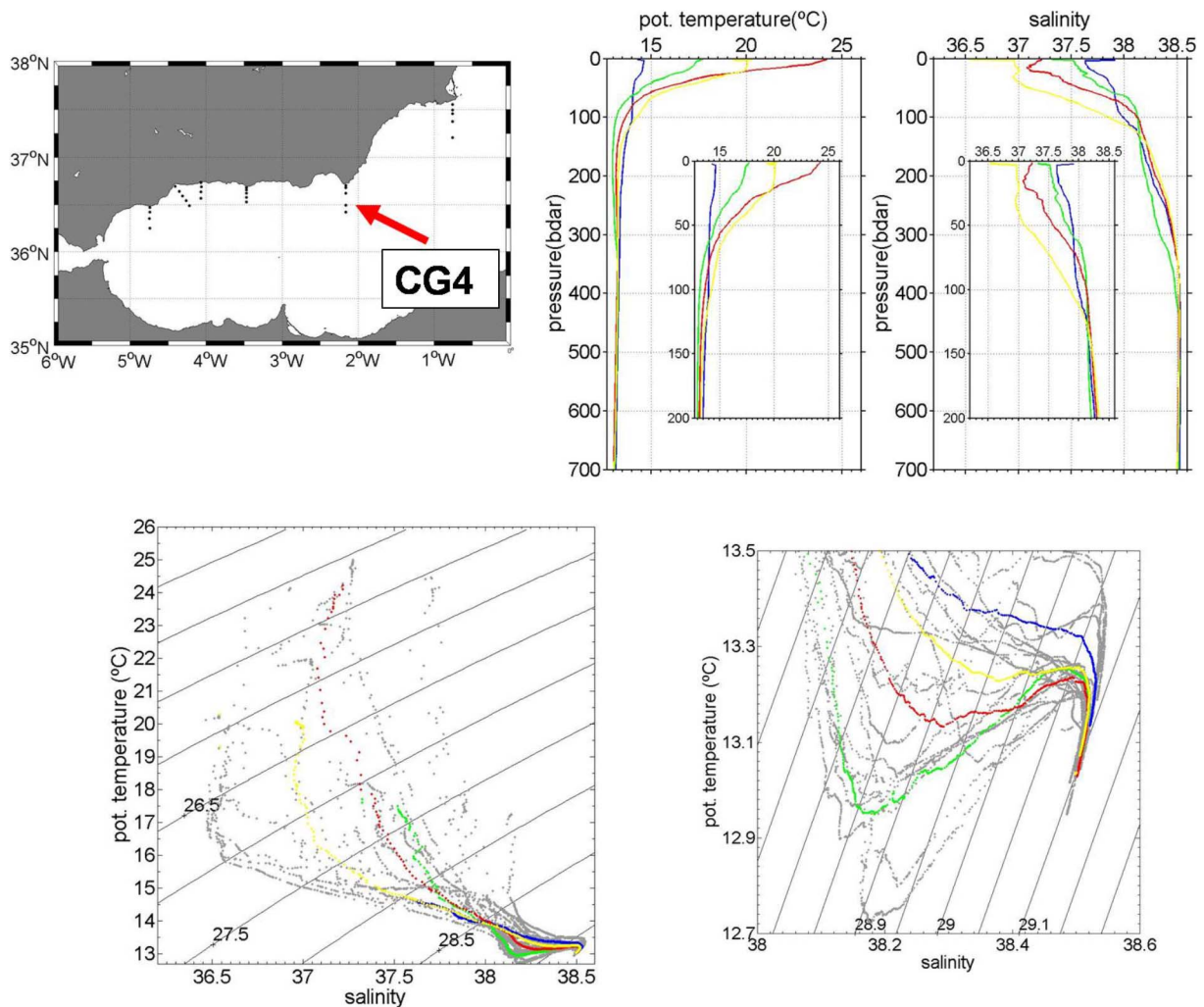


Fig. 3. The same as in Fig. 2, but for the oceanographic station CG4 in Cape Gata transect.

Finally, daily temperature measurements are taken at the sea shore (2 m depth) in Fuengirola beach (close to Cape Pino section, Fig. 1). This time series extends from 1985 to 2015 and is used as an indication of temperature variability of AW recently advected into the Mediterranean Sea through the Strait of Gibraltar.

3. Results

3.1. Mean values

Figs. 2–9 show the mean potential temperature and salinity seasonal profiles and θS diagrams for some selected stations around the peninsular waters and the Balearic Islands. Confidence intervals for the mean values, associated to the interannual variability around such mean values have not been included for the clarity of the plot. Nevertheless, a complete information about the mean values, standard deviations and the number of data used for the calculations can be found in Table SI of Supplementary material.

Vertical profiles show clearly the salinity gradient from the south to the north indicating the decreasing influence of AW arriving from the Strait of Gibraltar. Another interesting feature in these profiles is the clear seasonality of AW salinity values increasing in winter and reaching lowest values in summer. Concerning the seasonal cycle of the upper layer temperature, it is interesting that in winter, AW are warmer in the Alboran Sea (Figs. 2 and 3), decreasing the temperature northwards (see Figs. 6 and 7). The opposite situation stands for summer

when AW in the Catalan and mainly the Balearic Sea is warmer than in the southern regions. Fig. 10 summarizes these temperature and salinity values in the context of the general circulation in the Western Mediterranean. Salinity values to the south of the Balearic Islands and to the East of Menorca Island are slightly lower than in the Ibiza and Mallorca Channels.

The intermediate layer in the Western Mediterranean is occupied by Western Intermediate Water (WIW) and Levantine Intermediate Water (LIW). Lower panels in Figs. 2–9 are the θS diagrams (left lower plot) and a zoom for the deepest part of the water column (right lower plot). All the available temperature and salinity values from the RADMED project have been included (grey dots) and the average θS diagrams have been included for winter (blue), spring (green), summer (red) and autumn (yellow). López-Jurado et al. (1995) described the WIW in the Balearic Channels as a water mass with $\theta < 13^\circ\text{C}$ and $38 \leq S \leq 38.3$ and Vargas-Yáñez et al. (2012b) considered that the temperature and salinity range defining this water mass should be widened ($37.7\text{--}38.3$, $11.5\text{--}13^\circ\text{C}$). This water mass is clearly distinguishable in θS diagrams as it is the coldest water mass in the Western Mediterranean and its temperature can be lower than the bottom water temperature. If all the RADMED profiles are considered (grey dots in Figs. 2–9), the presence of this water mass can be observed in the MH transect (Fig. 8) or at EPC station (Fig. 9). The occurrence of this water mass is more frequent at station C33, in the Mallorca Channel (Fig. 5) and it can also be found to the South of Mallorca Island at B transect (not shown). Nevertheless, when the mean seasonal profiles are considered, the temperature of the

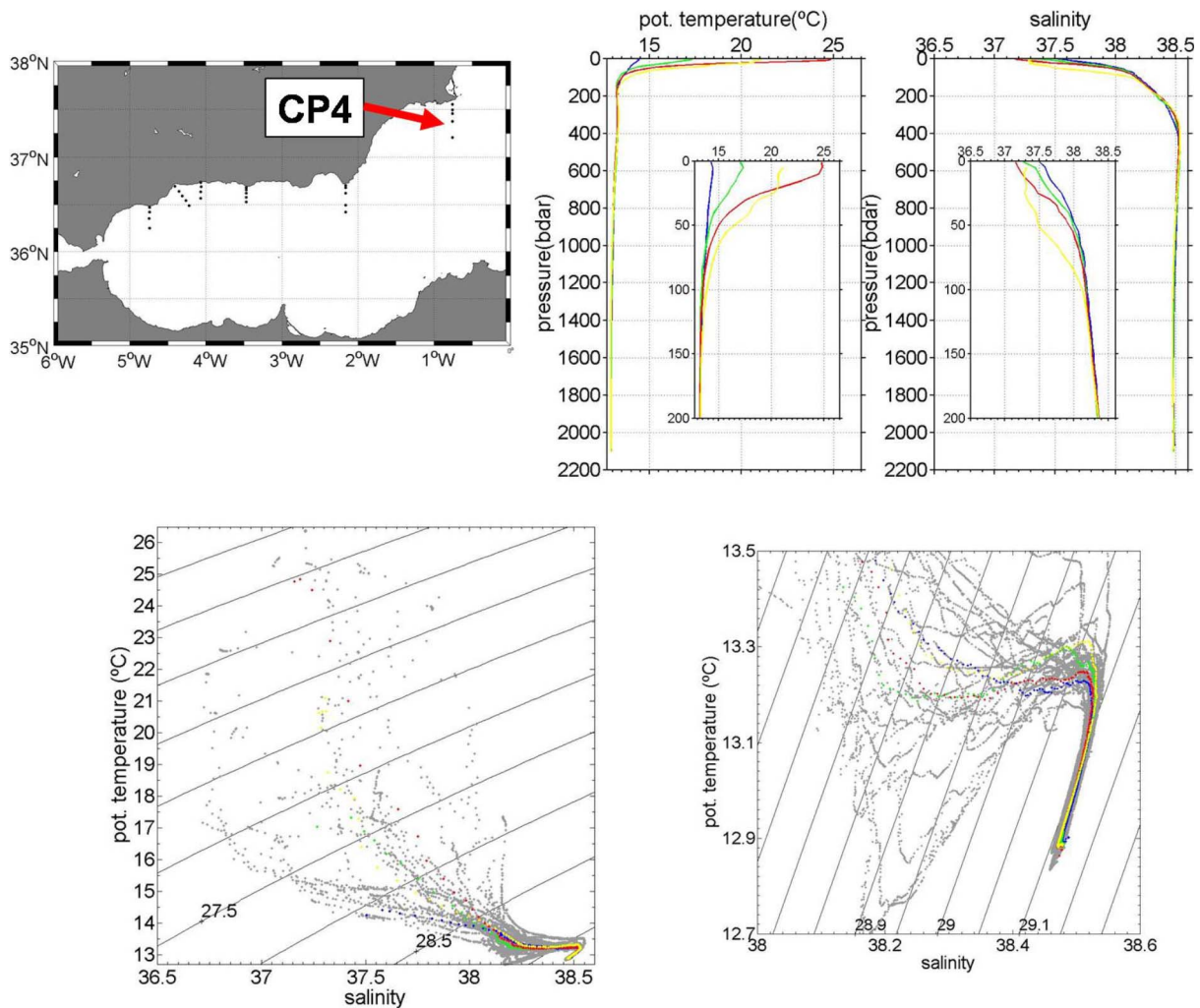


Fig. 4. The same as in Fig. 2, but for the oceanographic station CP4 in Cape Palos transect.

intermediate layer is always above 13 °C and the presence of the WIW cannot be established from the average profiles at these stations (colored ΘS diagrams in Figs. 5, 8 and 9). Fig. 11 shows the presence of WIW from the average seasonal profiles. It is also included the depth and season of the year when intermediate waters reach the WIW values according to Vargas-Yáñez et al. (2012b) criterion. According to this figure, the mean or average temperature and salinity values in the Balearic Sea show the presence of WIW at the Ibiza Channel mainly in winter and spring. On the contrary, although some years this water mass can be observed at the aforementioned Mallorca Channel (C33), Mahon transect (MH) and EPC station, the average values do not reflect its presence, suggesting that the preference pathway of this water mass would be through the Ibiza Channel. The average temperature and salinity profiles show evidence of WIW in Cape Gata, the eastern limit of the Alboran Sea, indicating that this water mass reaches this southern region in most of the years (Figs. 3 and 11). Although a clear signal of WIW is not obtained in the mean ΘS profiles for the other Alboran sea stations, Fig. 2 shows that this water mass is present in the Alboran Sea as far as P3 station during some years (grey dots). It is also worth mentioning that WIW is found in the Balearic Channels at a depth ranging between 80 and 200 m, just above the LIW waters, but also at the sea surface in some locations (Fig. 11a). This latter result indicates that these are locations of WIW formation. This result is supported by those in Vargas-Yáñez et al. (2012b) who found the winter vertical homogenization of the water column with WIW values at the continental shelf of the Ibiza Channel and Cape Palos. This process was

coincident with episodes of strong heat losses.

LIW is found below the WIW and is characterized by a relative temperature maximum and an absolute salinity maximum. This water mass is observed in all the transects (Figs. 2–9) and during all the seasons of the year. Fig. 11b summarizes the mean values of the LIW around the Spanish waters. LIW values correspond to winter season. The rest of the year is not presented as the LIW seasonal variability is very weak. LIW is observed in the average ΘS profiles in all the sections of the RADMED project coinciding with the usually accepted LIW pathway. Its presence at P3 station simply reflects the well known result that this water mass is one of the major contributors to the Mediterranean water outflow at the Strait of Gibraltar.

Deep waters extend below the LIW to the sea bottom. Mean values for the period analyzed in the RADMED project (2007–2015) range between 12.89 °C and 12.9 °C for potential temperature and 38.47–38.49 for salinity. It is interesting to note that the RADMED project was initiated after the beginning of the Western Mediterranean Transition (López-Jurado et al., 2005; Schroeder et al., 2010, 2016) and therefore the “hook shape” for the deepest part of the ΘS diagrams is clearly visible in most of the CTD casts and also in the average or mean profiles in the deepest oceanographic stations: CP4 (Fig. 4), C33 (Fig. 5), MH4 (Fig. 8) and EPC (Fig. 9).

3.2. Decadal changes from the RADMED, L'Estartit and Fuengirola stations

Linear trends were estimated for each depth level within each

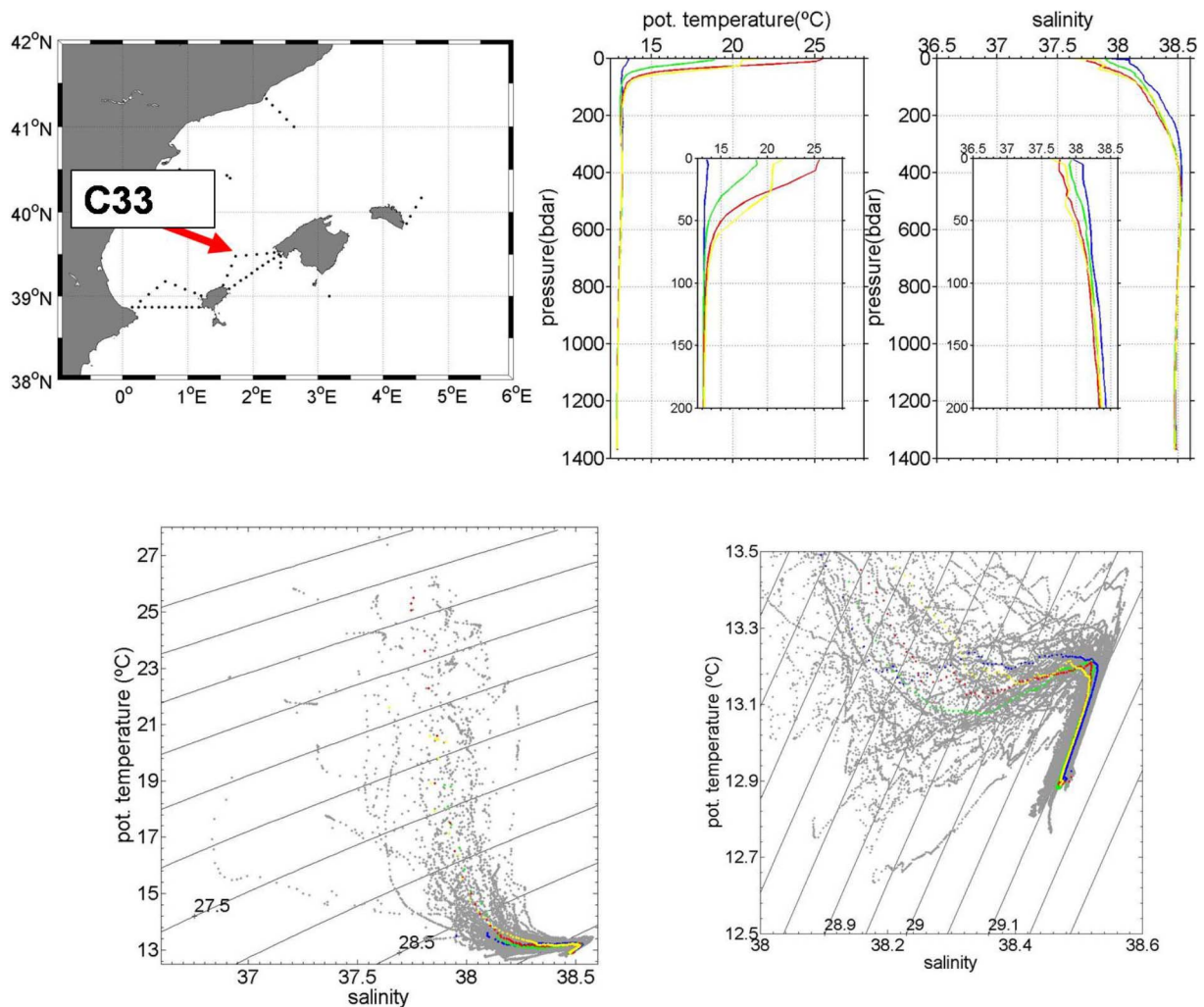


Fig. 5. The same as in Fig. 2, but for the oceanographic station C33 in the Ibiza Channel.

oceanographic station. Fig. 12 is an example of potential temperature, salinity and potential density trends as a function of depth for P3 and CG5 stations. Thin lines represent the trends plus and minus the 95% confidence interval. Fig. 13 is the same for two of the deepest stations CP4 and MH4. Confidence intervals for the upper 200 or 300 m of the water column are too large in order to conclude about the existence of any significant trend. The intermediate layer from 200 m to 600 m seems to show positive temperature and salinity trends, but the statistical significance is not clear. P3 shows significant warming and salting trends at the 95% confidence level for most of the depth levels, but not for all of them. Decadal changes are significant from 300 m depth for temperature in CG5 and from 400 m in the case of salinity. For the deepest stations such as CP4 and MH4, intermediate layers seem to have increased its temperature and salinity for the last 9 years, but these results are not statistically significant. On the contrary, deep waters below 1000 m show a clear warming and salting trend.

The only changes that are clearly observed in the surface waters are those associated to the salinity of waters to the south of Mallorca Island and the temperature at l'Estartit station. In the first case, station B3 increased its salinity from the sea surface to the sea bottom at 200 m depth. Although temperature results are not significant, they seem to have decreased (results not shown). In the case of l'Estartit station, located in the continental shelf of the Catalan Sea (over a bottom depth of 80 m), temperatures at 0, 20, 50 and 80 m depth showed clear and positive significant trends ranging from 0.18 ± 0.05 °C/decade to 0.26 ± 0.08 °C/decade (Fig. 14). Notice that these time series are the

longest ones in the present study (Fig. 14) as the monitoring of this station was initiated in 1969. The second time series according to its length is that corresponding to the sea surface temperature in Fuengirola beach. This time series shows a positive trend of 0.12 °C/decade, but this result is not statistically significant at the 95% confidence level. For comparison of the AW behavior at Fuengirola beach and at l'Estartit station, linear trends were also calculated for the common period 1985–2015 for the l'Estartit temperature time series. The results corresponding to this period of time were very similar to those obtained for the complete series from 1969 to 2015 (Fig. 14).

3.3. Long term changes from historical time series

Following the methodology in Vargas-Yáñez et al. (2010b), the Mediterranean waters surrounding the Spanish coast were divided into four areas (Fig. 1). All available temperature and salinity profiles from the MEDAR/MEDATLAS data base were obtained and merged with TS data from the RADMED stations within the same region. These time series have been extended until 2015 in the present work.

Tables 2–5 show the potential temperature and salinity trends and the absorbed heat for the upper Atlantic waters (AW, 0–200 dbar), intermediate waters (IW, 200–600 dbar) and deep waters (DW, 600 dbar-bottom). Results are presented for each of the four analyzed regions: Alboran Sea, Cape Palos region, Balearic Sea and Northern Sector. In the case of temperature and salinity, time series for each layer are constructed averaging the available data within the corresponding

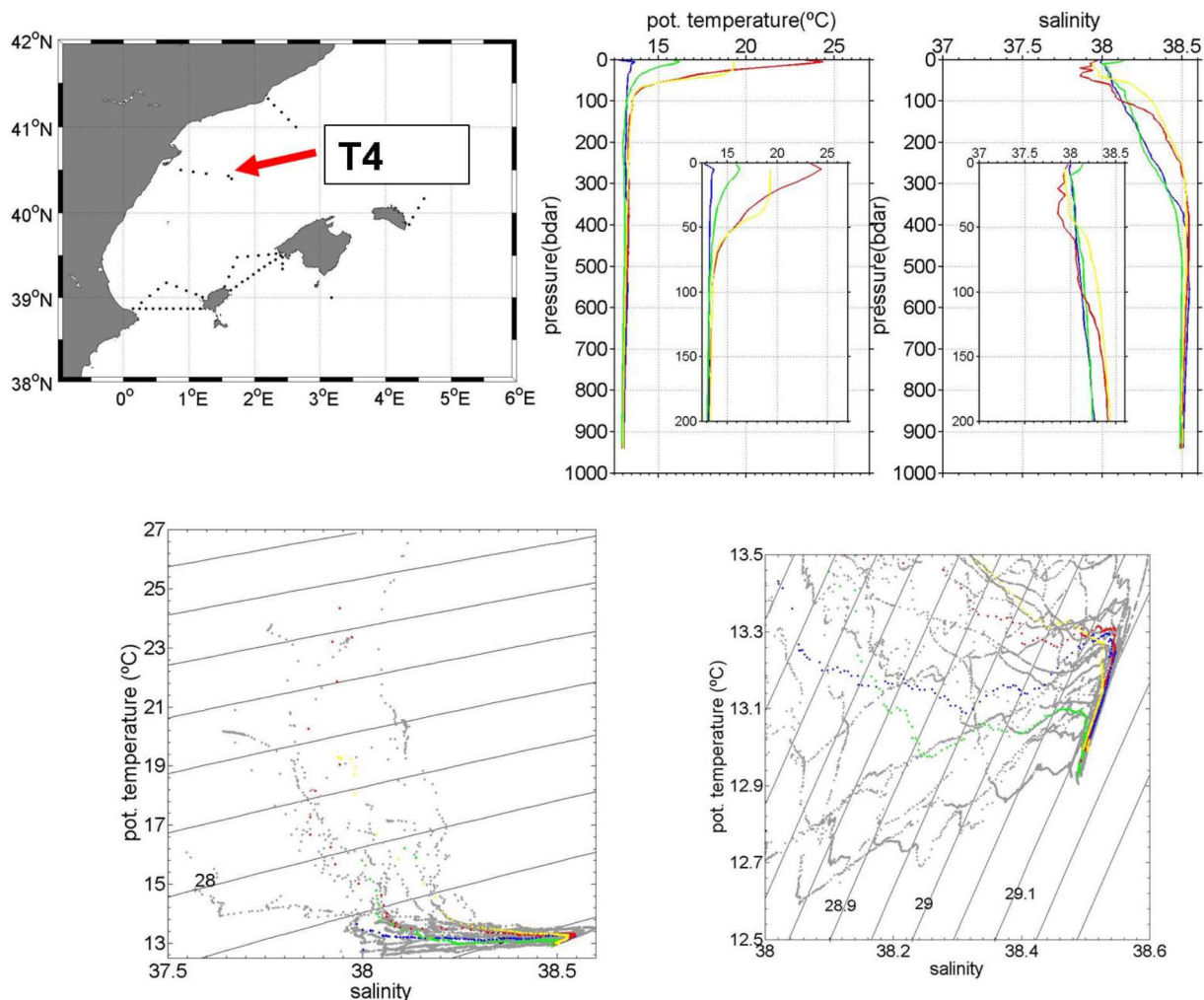


Fig. 6. The same as in Fig. 2, but for the oceanographic station T4 in Tarragona transect.

depth range. In the case of the absorbed heat, it is calculated for each area and year as the heat absorbed with respect to the 1960–1990 reference temperature profile. The absorbed heat in Joules is obtained by means of the expression:

$$Q = \int_{z_1}^{z_2} S(z)\rho(z)c_p(z)\Delta T(z)dz$$

Being $S(z)$ the surface of the box considered, ρ density, c_p specific heat capacity and ΔT the temperature difference for a particular year respect to the reference profile. The depth limits for the considered layer are expressed by z_1 and z_2 .

For the absorbed heat estimation we include two different calculations. The first one considers that the missing values correspond to the climatological or long term mean. The second one considers that the available values for the layer considered are representative of the whole layer (see Section 2). The absorbed heat is also included for the complete water column. All the calculations are repeated including and excluding the bathythermograph data. Trends are estimated for the complete period of time, from 1900 to 2015 and for the period extending from 1943 to 2015. Table 6 shows the trends obtained when the four areas are considered as a single one. Time series of absorbed heat and salinity for the whole area and for the three aforementioned layers (AW, IW, DW) plus the water column are presented in Figs. 15 and 16.

For the period 1900–2015, the temperature of the AW does not show significant trends with the only exception of the Northern Sector. Nevertheless, in this case the significance of the warming trend is sensitive to the inclusion of bathythermograph data in the time series.

For the more recent period 1943–2015 the warming trends are significant in the Alboran Sea while they are not in the case of Cape Palos region and the Balearic Sea. In the Northern Sector, once again, the significance of the estimated trends is dependent on the data set used. The same lack of significant results is obtained for the whole area (Table 6). From these time series we cannot conclude the existence of robust warming trends in the AW. The AW salinity increased in the Alboran Sea and Cape Palos region for the two periods analyzed, while no significant trends were obtained in the Northern Sector. The mean values for the four areas show an increase of the AW salinity from 1900 to 2015 which is intensified during the 1943–2015 period.

With very few exceptions, the IW increased its temperature with an intensification of the warming trends for the period 1943–2015. Trends for the four areas analyzed and for the whole area, range between 0.02 °C/decade and 0.05 °C/decade. The salinity of this layer increased in all the cases despite the region or the data set used. Trends are intensified for the period 1943–2015 ranging between 0.01 decade⁻¹ and 0.02 decade⁻¹. A similar result is obtained for the deep layer with positive trends for the two periods analyzed and for all the regions and data sets. The most intense warming trends, once again, correspond to the period 1943–2015, ranging between 0.01 °C/decade and 0.05 °C/decade.

Results concerning the heat absorbed by the water column follow the same evolution to those of temperature time series. Slight differences are attributed to the different data analysis methods. In summary, the water column in the Spanish Mediterranean has absorbed heat in a significant way since 1900. This process was intensified after 1943 with

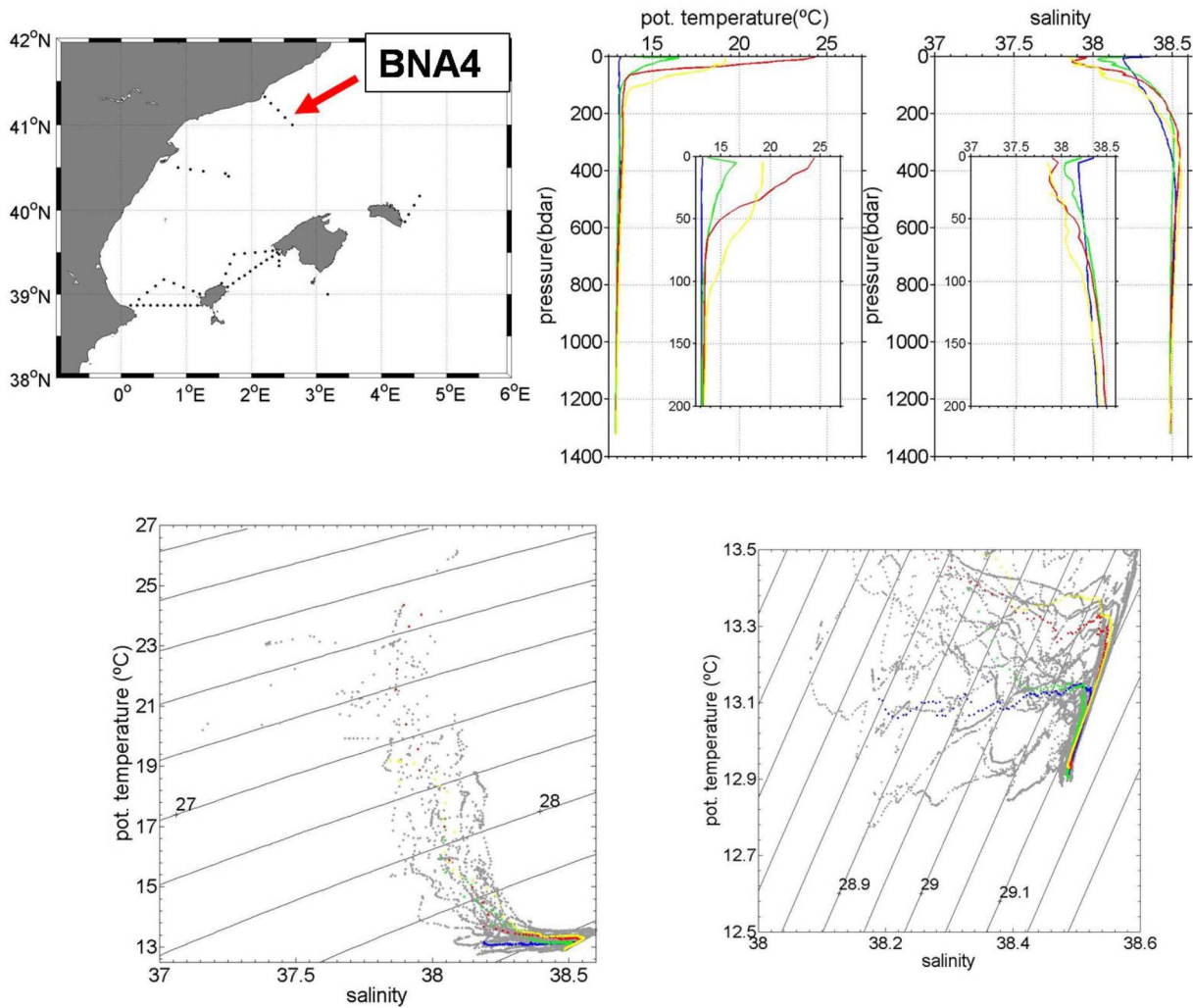


Fig. 7. The same as in Fig. 2, but for the oceanographic station BNA4 in Barcelona transect.

at a rate ranging between 0.26 W/m^2 and 0.56 W/m^2 depending on the methodology applied (see Fig. 15 and Table 6). Notice that the absorbed heat time series are in Joules and the trends should be in J/yr . Years have been converted into seconds and the trends divided by the surface of the region in order to express trends as W/m^2 .

4. Discussion

4.1. Mean temperature and salinity profiles

The θS diagrams in Figs. 2–9 show the large variability in the water masses surrounding the Spanish peninsular and insular waters. Colored profiles and θS diagrams in such figures show the mean values obtained after averaging all the available data from the beginning of the time series to 2015. Those characteristics present in the mean profiles reflect the most frequent situations corresponding to each season of the year and each region. Nevertheless we should keep in mind that any particular measurement corresponding to one single cruise can differ from the long term mean value in a certain range. Variability ranges expressed as a standard deviation or simply as a maximum minus minimum recorded values are very helpful information as they can be used in order to detect anomalous situations or extreme climatic events. For brevity, the present work only provides information concerning the long term mean values for temperature and salinity in some key points (Figs. 2–9 and 10 and 11). Table S1 in Supplementary material provides more information from such key points.

Mean values estimated in the present work cannot be considered as proper climatologies because of the present length of the available time series, nevertheless the present work aims at showing the capability of the RADMED project for providing such climatologies in the future. The accuracy of these climatologies depends both on the number of data points and the natural variability of the time series. It is worth noticing that for the estimation of climatological profiles from the MEDAR data base, a large area should be used. For instance, climatological potential temperature and salinity profiles were calculated for the Alboran Sea, Cape Palos sector and the Balearic Sea using the boxes in Fig. 1. The use of RADMED stations provides a better spatial resolution. Confidence intervals for the climatological values estimated from MEDAR data were compared with those estimated for some stations from the RADMED project at the same area. The accuracy for MEDAR climatologies was slightly better than that for the RADMED mean values for the case of the upper layer (from the surface to 200–400 m). On the contrary, confidence intervals for RADMED mean profiles were similar or even lower below this depth level (Supplementary material Figs. S1 and S2). The explanation is the data scarcity at deep levels in the MEDAR data base. This is clearer if we consider the number of data points available for each year and for different depth levels in MEDAR (Supplementary material Figs. S3, S4 and S5). When considering MEDAR data over large areas, several years lasting periods with no data can be found. Beside this, the average number of annual data decreases considerably with depth. This average number can be under four data per year below the 200 m or 500 m level depending on the geographical

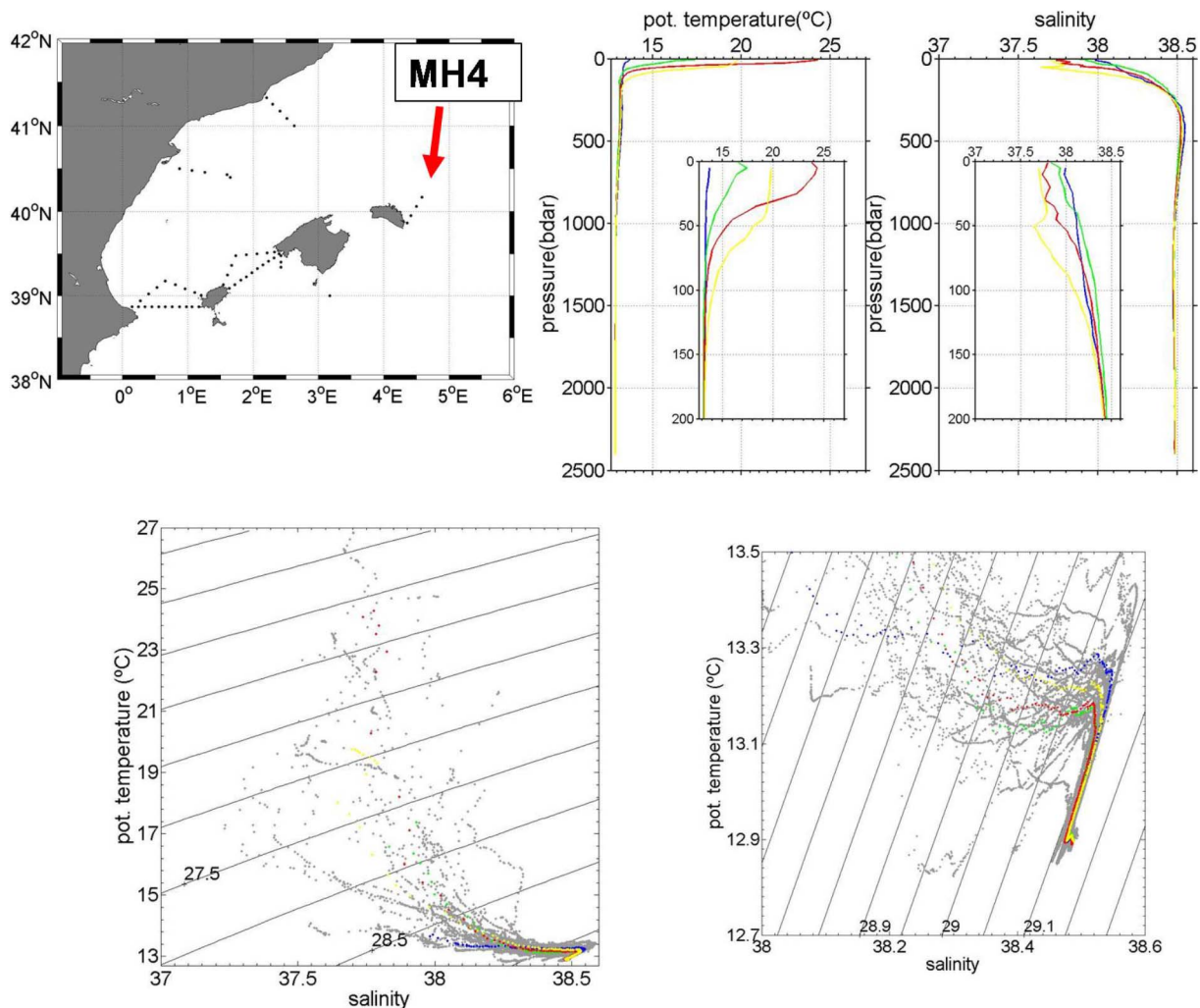


Fig. 8. The same as in Fig. 2, but for the oceanographic station MH4 in Mahón transect.

area. Therefore, in most of the cases, the RADMED sampling frequency improves the MEDAR data availability for deep levels.

4.2. Water masses and circulation

Temperature and salinity data collected from 1996 to 2015 in the Balearic Islands and from 2007 to 2015 in the Catalan Sea are analyzed. These data allowed us to speculate about the most frequent circulation of water masses within the Catalan and Balearic Seas. According to Salat and Cruzado (1981) three different water masses occupy the Catalan-Balearic Sea. The first one is named as Continental Water. These waters are found close to the coast and have low salinity values because of the influence of river discharges. The second one is named as Mediterranean Water, which occupies the area of cyclonic circulation between the peninsula and the Balearic Islands. These waters are characterized by high salinity values around 38. The branch of this cyclonic cell flowing along the continental slope of the Iberian Peninsula constitutes an extension of the northern current. The third water mass is the Atlantic Water which origin is in the Algerian current. This latter water mass would be advected to the north within eddies detached from such current (Millot, 1999). Fig. 10 shows that winter surface waters along the Catalan Slope have temperatures ranging between 13.11 °C and 13.45 °C and salinity values between 38 and 38.19. These values seem to agree with the presence of the northern current and its extension to the south along the Catalan continental slope and its bend to the North East to form the Balearic Current along the

northern Balearic continental slope (Font and Ballester, 1984; Font et al., 1988). This conclusion would be supported by the salinity values at the vertexes of the triangles formed by the oceanographic stations C (Fig. 10). These values indicate the presence of Mediterranean Water (according to Salat and Cruzado, 1981 definition) to the north of the islands. Winter salinity values at the upper 25 m at the base of the triangle between Ibiza and the peninsula are between 38.01 and 38.12. At the base of the triangle between Ibiza and Mallorca, these values are lower, ranging between 37.87 and 37.93. This result would indicate that the Ibiza Channel could be the main pathway for the Mediterranean surface waters flowing to the south. This result would coincide with those in Font et al. (1988) who reported a southward geostrophic transport of 1 Sv for the surface and intermediate waters that flow through the Ibiza Channel. Lower salinity values at the Mallorca Channel and those at the B transect to the south of Mallorca Island (37.6) would also support the frequent intrusions of Atlantic Waters through this second channel. Early works by Font and Miralles (1978) support this conclusion. These authors analyzed two hydrographic cruises corresponding to October 1976 and March 1977. The winter cruise evidenced the existence of a surface current flowing to the south through the Ibiza Channel, while Atlantic Water intrusions were observed at the Mallorca and Menorca Channels.

Nevertheless, not all the information concerning the circulation through the Balearic channels fully supports the picture depicted above. Pinot et al. (1995), Pinot and Ganachaud (1999) analyzed cruises carried out in May 1991 and June 1993 respectively. These authors

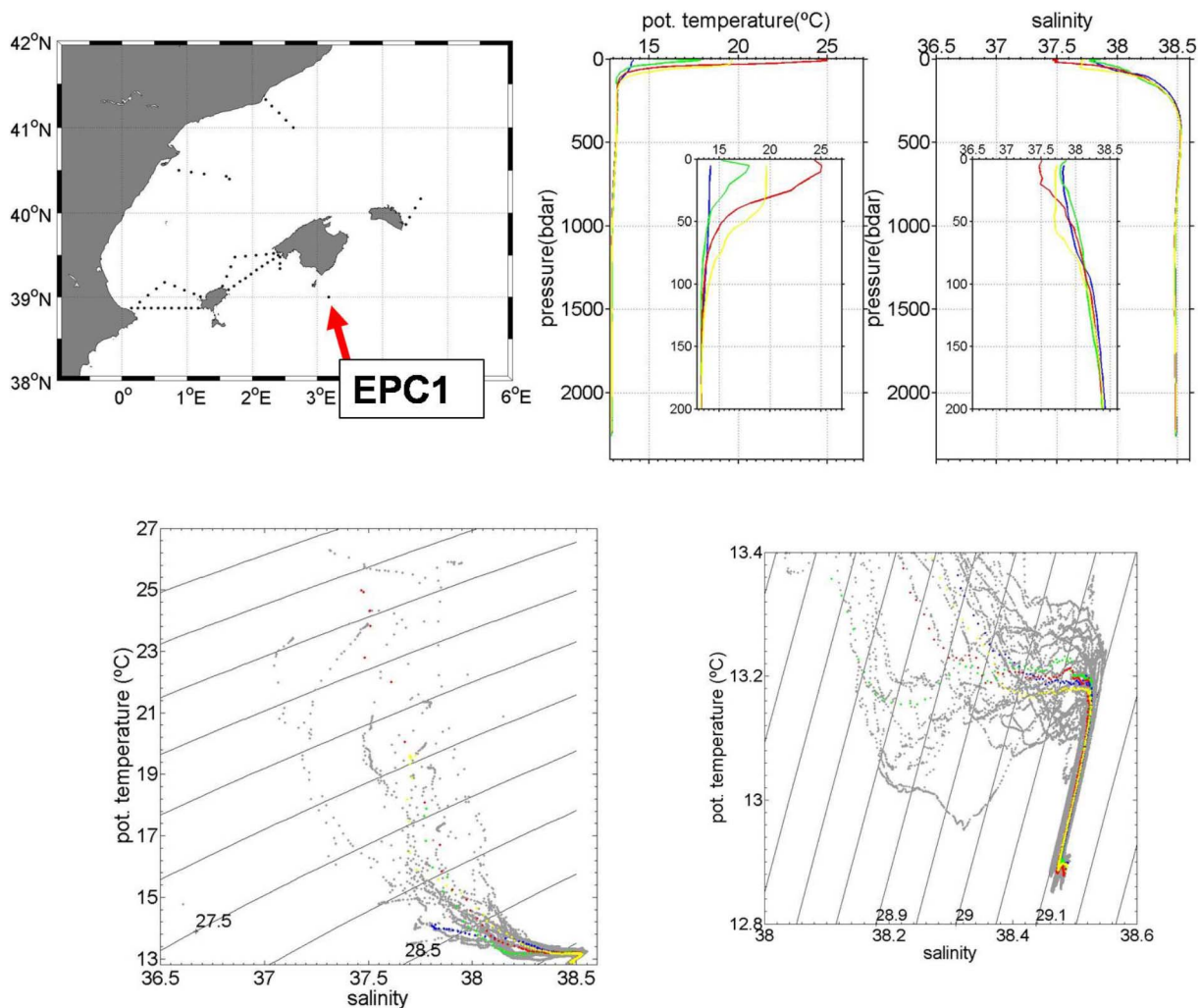


Fig. 9. The same as in Fig. 2, but for the oceanographic station EPC to the south of Cabrera Island.

described the extension of the northern current along the Catalan slope with a transport around 1 Sv. These works show that most of the transport is deflected to the NE forming the Balearic current with an important contribution of Atlantic Waters flowing through the Mallorca Channel and also through the Ibiza Channel. These authors hypothesize that large volumes of WIW arriving at the channels in spring could form anticyclonic gyres. According to Balbín et al. (2014) these eddies would block the southward circulation of both upper and intermediate waters.

Results in Pinot et al. (1995) and Pinot and Ganachaud (1999) are not necessarily in contradiction with those works that had considered the Ibiza channel as the main path of modified Atlantic Water and intermediate waters towards the south, neither they are in contradiction with the results presented in this work. Results in Pinot et al. (1995), Pinot and Ganachaud (1999) are based on spring cruises. According to these authors the blocking of the circulation through the channels would be caused by large volumes of WIW which source would be to the north in the Catalan or the Ligurian Sea, arriving to the Balearic Sea in spring. On the contrary, results in early works by Font and Miralles (1978) would be based on data from winter cruises. On the other hand, the results shown in the present work are based on long term mean values obtained from observations along more than a decade. These mean values suggest that the Ibiza channel seems to be the preferential path for both surface modified Atlantic waters and WIW flowing southward, while the Mallorca and Menorca channels would be more favorable places for northward AW intrusions. Lower salinity values to the East of Menorca Island also indicate the frequent presence of AW

which, according to Millot (1999), would have its origin in eddies detached from the Algerian current. According to present data, these intrusions would be more frequent and progress further to the north during summer months. Nevertheless, it should be kept in mind that these conclusions concern the mean values and only represent the most likely situation. Any particular year can differ substantially from the general pattern proposed in this work.

It is also worth mentioning the presence of temperature and salinity values within the WIW range both in winter and spring at a depth range from the sea surface to 200 m (Fig. 11a). López-Jurado et al. (1995) studied the circulation of WIW in the Balearic Channels and concluded that low salinity WIW ($S \sim 37.7$) with a local origin could be found in the channels during winter, while higher salinity WIW ($38.1 \leq S \leq 38.3$) which origin could be further to the north would arrive to the channels in spring. Fig. 11a shows that WIW temperature and salinity values can be observed in winter at the sea surface in Barcelona (BNA) and Tarragona (T) sections and in the peninsular continental shelf of the Ibiza channel. These results would support that WIW is formed not only at the northern sector of the Liguro-Provençal basin, but also in the continental shelf of the Balearic Channels. Vargas-Yáñez et al. (2012b) have shown that WIW can be formed even further to the south in locations such as Cape Palos (CP) during very severe winters. Nevertheless, the mean values presented in Figs. 2–9 and 11a indicate that this is not the most frequent situation. The analysis of the RADMED data allows us to distinguish a clear signal of the WIW in the mean values obtained at the eastern limit of the Alboran Sea (CG

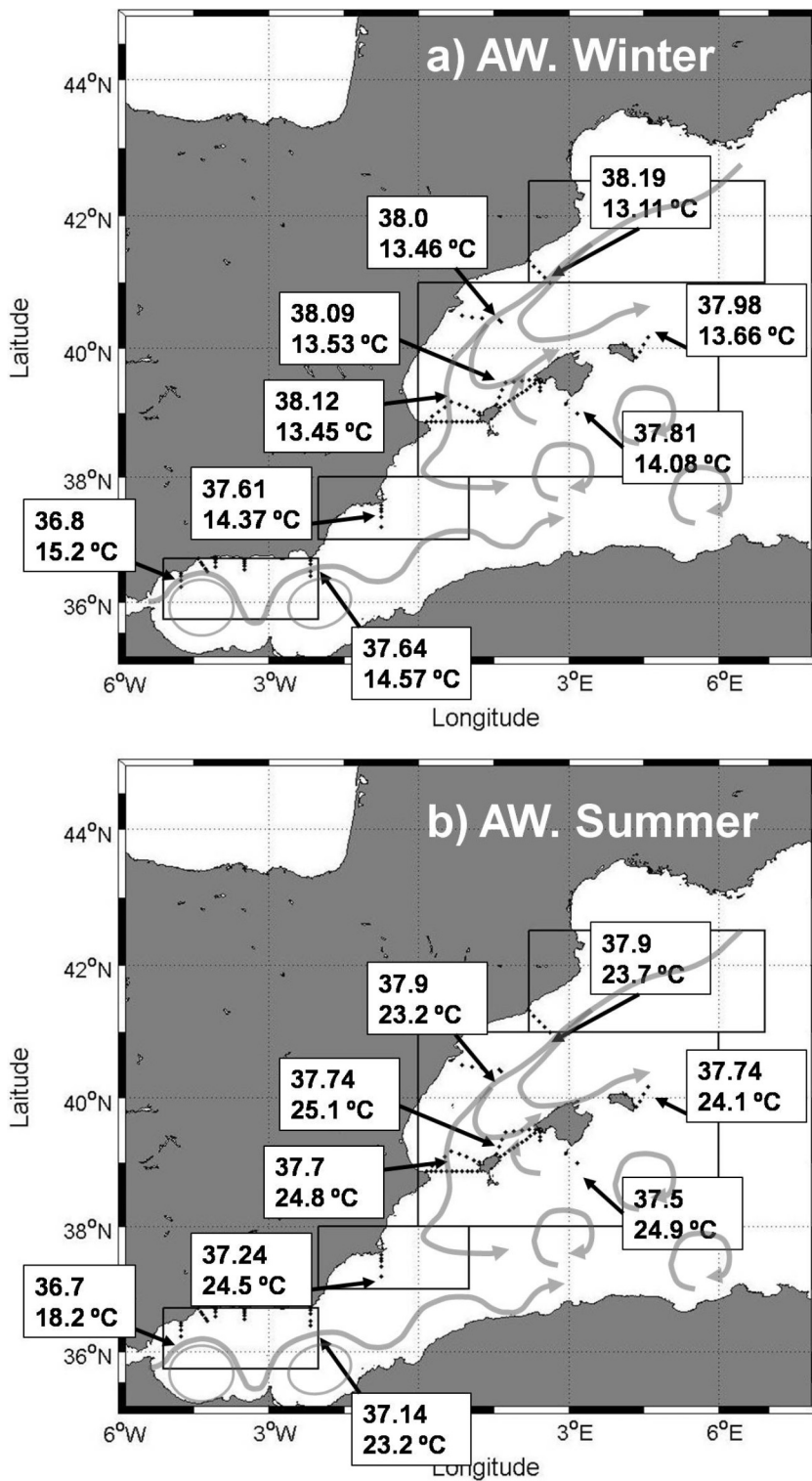


Fig. 10. (A) Sea surface temperature and salinity mean values from the RADMED summer cruises in some selected stations. (B) The same for winter.

section, Fig. 11a). Furthermore, according to Fig. 2, large volumes of WIW can reach as far to the southwest as Cape Pino section (P) during some particular years. Nevertheless, when average temperature and salinity profiles are obtained, the temperature for the layer above LIW is higher than 13 °C, suggesting that an important presence of WIW is not the most likely situation in this section.

Below the WIW, all the stations show the presence of a relative maximum of temperature and an absolute maximum for salinity which characterize the LIW. This feature is observed along the Catalan slope and to the north and south of the Balearic Islands. This result would

suggest that the northern current is extended to the south transporting intermediate waters, both WIW and LIW, coinciding with previous works mentioned above. The presence of LIW along the continental slope in the Alboran Sea would also coincide with the commonly accepted pathway for this water mass. In fact, Parrilla et al. (1986) used the core method to identify the presence of LIW in the Alboran Sea ($S > 38.47$). These authors found that the LIW occupies the 200–600 m layer in the Alboran Sea from the Spanish to the Moroccan coast. Nevertheless, the thickness of the high salinity layer associated to the LIW maximum was higher at the northern part of the Alboran Sea,

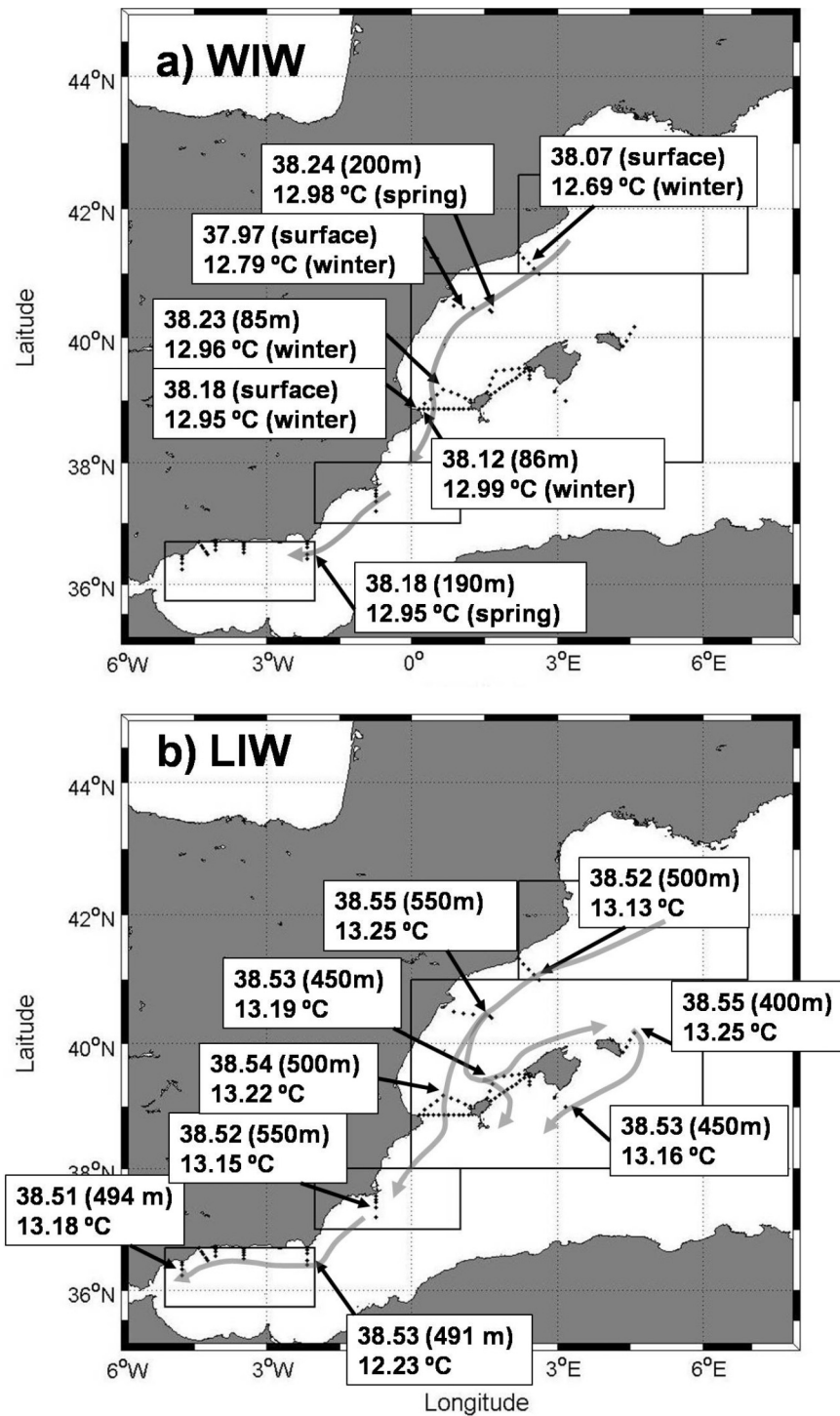


Fig. 11. (A) WIW values detected in the RADMED averaged profiles. WIW values are considered as $\theta < 13^\circ\text{C}$ $37.7 \leq S \leq 38.3$. It is included the depth and the season when the WIW is present in the mean profiles. (B) Potential temperature and salinity for the salinity maximum associated to LIW in winter mean profiles.

decreasing to the south. As this water mass progresses from East to West, Parrilla et al. (1986) concluded that the stronger presence of LIW at the northern sector of the Alboran Sea was caused by the effect of the Coriolis force.

The layer from 800 m to the sea bottom is occupied by WMDW formed by winter deep convection in the Gulf of Lions. Mean values for potential temperature and salinity from 1000 m to 2400 m are very homogeneous in the deep stations occupied in the RADMED project. In this depth range and for the four seasons of the year, the potential temperature mean values ranged between 12.89 °C and 12.97 °C, while salinity values were between 38.47 and 38.49. The lowest mean values estimated in the RADMED project (12.89 °C, 38.47) are much higher

than those values reported during the last century. Lacombe et al. (1985) reported WMDW potential temperature and salinity values increasing from 12.66 °C, 38.38 in 1909 to 12.72 °C, 38.42 in 1975. Bethoux and Gentili (1996) showed time series of potential temperature and salinity monotonically increasing up to 1990. Maximum values reached in these series were lower than 12.8 °C and 38.46. The differences between present calculations and previous works could be caused by the increasing long term trends already detected in the Mediterranean Sea deep layers (Vargas-Yáñez et al., 2010a, 2010b; Borghini et al., 2014). Beside these trends, the recent Western Mediterranean Transition has been responsible for the formation of very warm and salty deep waters, denser than previous WMDW. This new water mass

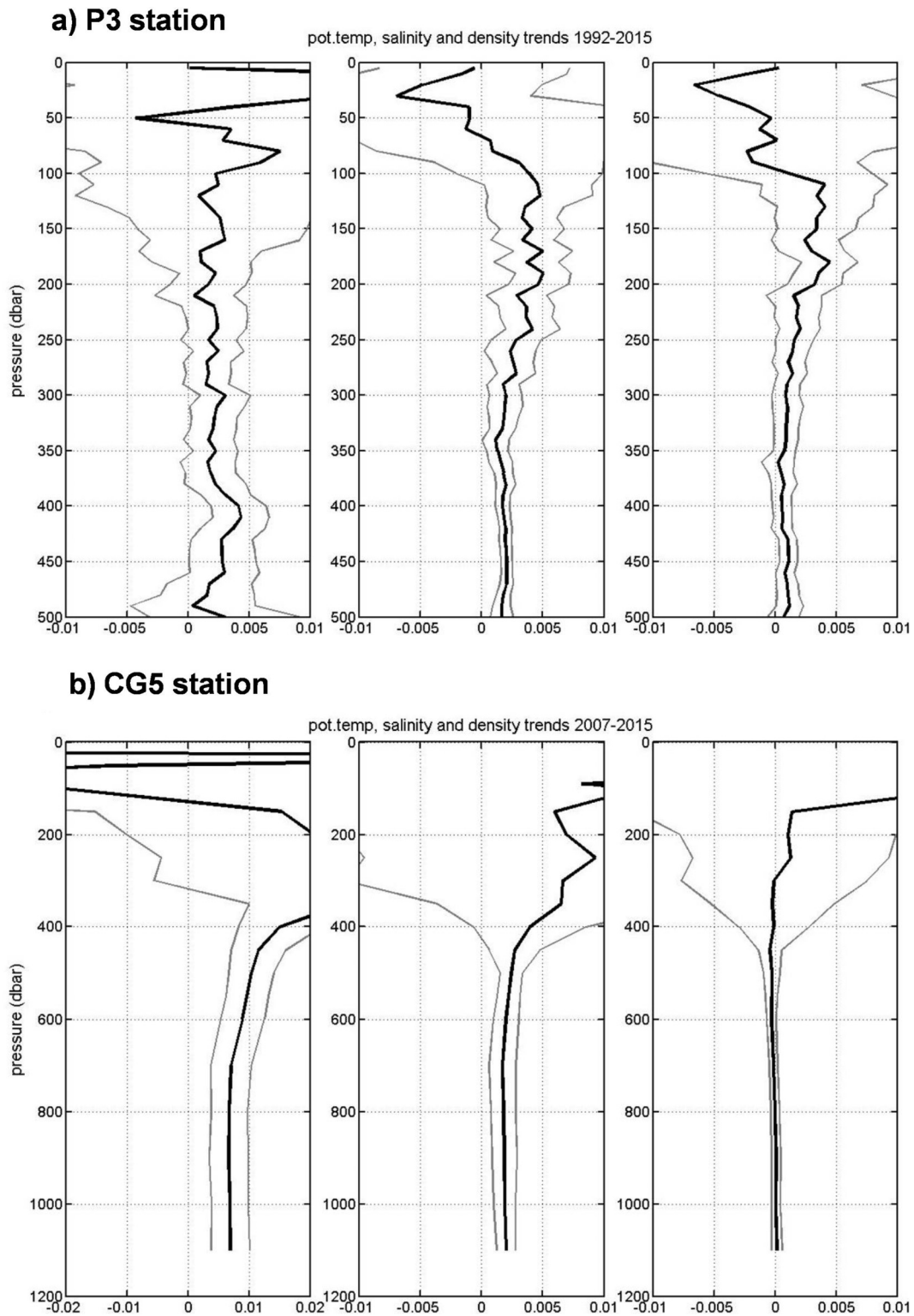


Fig. 12. Linear trends for potential temperature (left), salinity (centre) and potential density (right) as a function of depth. Linear trends are calculated from the RADMED time series. (A) for P3 station and (B) for CG5 station.

has occupied the bottom layer uplifting old WMDW. The signature of this new water mass on temperature and salinity time series is an important increase of both variables. Its signal on θ S diagrams is a “hook shape” at the deepest levels. Below the classical mixing line between the LIW salinity and temperature maxima and the WMDW minima, the presence of this new WMDW produces an increase of both potential temperature and salinity below the previous minima. This behavior has

been extensively described in López-Jurado et al. (2005), Schroeder et al. (2016, 2010), Smith and Bryden (2007). This feature can be clearly observed in the deepest stations of the RADMED project MH4 (Fig. 8) and EPC1 (Fig. 9) and is also suggested in shallower stations such as C33 (Fig. 5) and CP4 (Fig. 4). It is also worth mentioning that the new bottom water is not only observed during some years (grey dots in Figs. 4, 5, 8, and 9), but also in the mean profiles. This latter situation

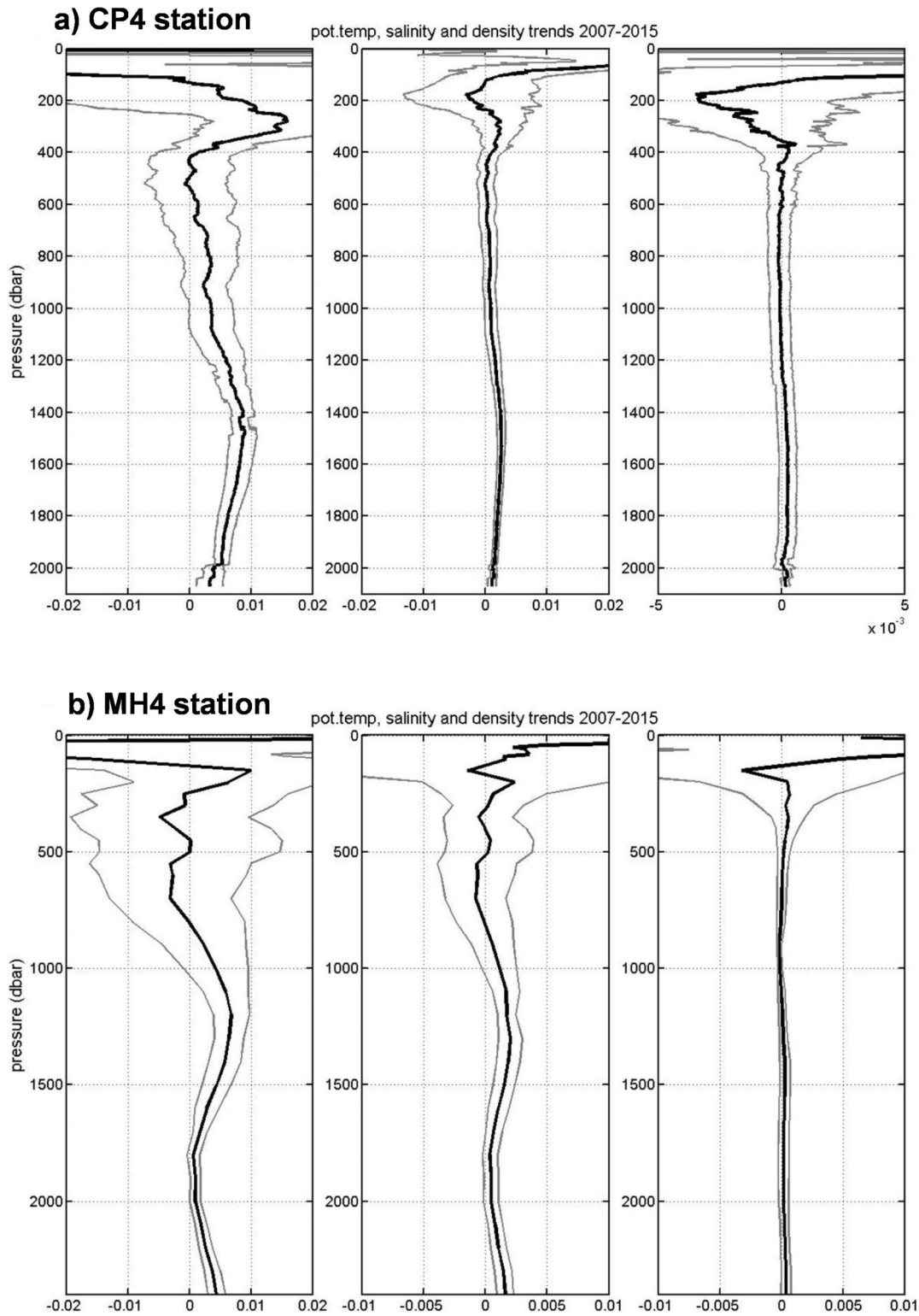


Fig. 13. The same as in Fig. 12, but for CP4 station (A) and MH4 station (B).

would suggest the persistence of this water mass since the beginning of the RADMED project in 2007.

Finally, it is worth mentioning that the circulation in the Balearic channels and in the Alboran Sea is subject to interannual and decadal variability and the results outlined above could be sensitive to the period of time analyzed. As the RADMED time series get longer, the present results will become more robust or will allow us to study such inter-annual and decadal variability in the circulation patterns already

described.

4.3. Long term changes

Concerning the long term changes operating in the Mediterranean since the beginning of the twentieth century, the update and extension of time series by means of the RADMED data seem to confirm some previous results and clarify others (see Tables 2–6 and Figs. 15 and 16).

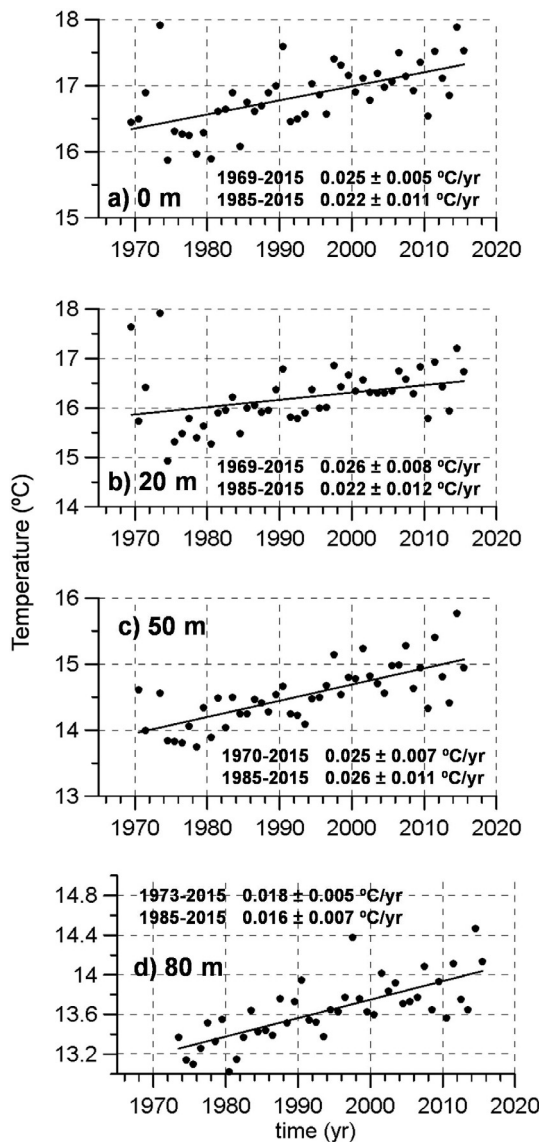


Fig. 14. Temperature times series at 0, 20, 50 and 80 m depth from l'Estartit station. Linear trends and 95% confidence intervals are included.

Table 2

Linear trends in the Alboran Sea for temperature (°C/decade), salinity (decade⁻¹) and heat absorbed (W/m²), for the AW (0–200 dbar), Intermediate layer (200–600 dbar), deep layer (600 dbar-bottom) and for the water column (surface-sea bottom). All the trends are calculated for two periods: 1900–2015 and 1943–2015. The estimation of the heat absorbed is made following two different methods named in the text as zero anomalies and representative anomalies. Numbers in bold are significant at the 95% confidence level. All the calculations are repeated including bathythermograph data and excluding them.

Alboran Sea								
With BT	θ		S		Q _{abs.}		Q _{abs.}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. Anom.	1943–2015
AW	-0.027	-0.1	0.034	0.1	-0.024	-0.07	-0.024	-0.10
IW	0.012	0.03	0.007	0.02	0.047	0.12	0.041	0.13
DW	0.013	0.01	0.005	0.01	0.053	0.10	0.027	0.19
0-bottom					0.09	0.21	0.07	0.29
Without BT	θ		S		Q _{abs.}		Q _{abs.}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	-0.0007	-0.08	0.035	0.1	-0.014	-0.07	-0.022	-0.10
IW	0.014	0.04	0.007	0.02	0.045	0.03	0.053	0.15
DW	0.012	0.03	0.005	0.01	0.023	0.08	0.049	0.18
0-bottom					0.067	0.20	0.106	0.28

In the case of the upper layer occupied by AW, Vargas-Yáñez et al. (2010b) had shown a warming of this layer until 2008. The RADMED data extension until 2015 is not able to produce significant results. The sampling interval (four times per year) does not allow us to filter out short time scale variability and the final seasonal and annual time series contain a very large variance associated to time scales different from the long term changes. Beside this, the large natural variability of the upper layers makes the long trend estimations very sensitive to the addition of a few new years. The Fuengirola beach time series is made of daily temperature measurements. Annual series filter out most of the short time scale variability. The linear trend for this time series is 0.12 ± 0.13 °C/decade. The confidence interval is calculated at the 95% confidence level. If the 90% level is considered the result is 0.12 ± 0.10 °C/decade. Following the IPCC terminology, it is very likely that the AW in the Fuengirola beach increased its temperature. However, this trend is not significant in the 95% level that is followed in the rest of this work and in previous ones (Vargas-Yáñez et al., 2009, 2010a, 2010b). If the temperature time series in l'Estartit station are considered (Fig. 14), the temperature at 0, 20, 50 and 80 m increased at a rate ranging between 0.18 ± 0.05 °C/decade and 0.26 ± 0.08 °C/decade, being these results significant at the 95% level (extremely likely). There are several possibilities for this difference in the confidence levels obtained for these two results. First, the AW in Fuengirola arrives directly from the Strait of Gibraltar without being modified by atmospheric conditions and mixing within the Mediterranean Sea. On the contrary, AW in l'Estartit is the result of intense modifications after completing a cyclonic circuit in the Western Mediterranean. Therefore it could be speculated that the warming of Mediterranean waters is the result of processes occurring within the Mediterranean, while these changes would not affect or would not be so intense in the nearby Atlantic Ocean. This hypothesis is not supported by the increase of the heat content in the Atlantic reported by Levitus et al. (2012). This work shows a large increase of the heat content in the North Atlantic from 1955–1959 to 2006–2010 in the same latitude range corresponding to the Mediterranean Sea. A second possibility is that the Fuengirola beach and l'Estartit time series cover a different period of time. Nevertheless, when linear trends were calculated using l'Estartit time series for the same period of time corresponding to Fuengirola time series, the results did not change substantially (Fig. 14). A third possibility is that this is simply a statistical result caused by the different length and variance of these time series. In the case of Fuengirola beach, the length of the temperature time series is 31 years and the standard deviation depends on the month of the year varying between 0.56 °C for winter months to

Table 3

The same as in Table 1, but for Cape Palos region.

Cape Palos region								
With BT	θ		S		Q_{abs}		Q_{abs}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	0.006	0.02	0.01	0.03	0.013	0.04	0.018	0.02
IW	0.004	0.03	0.005	0.02	0.010	0.07	0.009	0.10
DW	0.012	0.04	0.005	0.01	0.081	0.28	0.147	0.49
0-bottom					0.091	0.46	0.168	0.69
Without BT	θ		S		Q_{abs}		Q_{abs}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	0.01	0.04	0.01	0.03	0.013	0.09	0.016	0.10
IW	0.008	0.03	0.005	0.02	0.030	0.12	0.031	0.11
DW	0.016	0.05	0.005	0.01	0.064	0.22	0.131	0.47
0-bottom					0.097	0.49	0.174	0.73

Table 4

The same as in Table 1, but for the Balearic Sea region.

Balearic Sea								
With BT	θ		S		Q_{abs}		Q_{abs}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	–0.0004	–0.03	0.011	0.03	–0.019	–0.06	–0.017	–0.07
IW	0.0007	0.02	0.004	0.01	0.0080	0.05	0.013	0.06
DW	0.02	0.04	0.006	0.01	0.0753	0.18	0.170	0.40
0-bottom					0.0791	0.21	0.170	0.41
Without BT	θ		S		Q_{abs}		Q_{abs}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	–0.003	–0.02	0.011	0.03	0.019	0.005	0.026	0.015
IW	0.008	0.02	0.004	0.01	0.029	0.08	0.035	0.08
DW	0.013	0.04	0.006	0.01	0.077	0.17	0.177	0.41
0-bottom					0.124	0.32	0.225	0.47

Table 5

The same as in Table 1, but for the northern sector.

Northern sector								
With BT	θ		S		Q_{abs}		Q_{abs}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	0.01	0.03	–0.001	–0.003	0.030	0.043	0.033	0.045
IW	0.006	0.03	0.003	0.01	0.043	0.135	0.047	0.150
DW	0.01	0.03	0.004	0.01	0.061	0.216	0.194	0.564
0-bottom					0.105	0.380	0.211	0.759
Without BT	θ		S		Q_{abs}		Q_{abs}	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	0.02	0.07	–0.001	–0.003	0.046	0.157	0.044	0.235
IW	0.008	0.03	0.003	0.01	0.035	0.118	0.037	0.123
DW	0.011	0.03	0.004	0.01	0.060	0.204	0.129	0.457
0-bottom					0.134	0.531	0.169	0.721

1.8 °C in September. L'Estartit time series are 47 years long and the standard deviations range between 0.45 °C and 1 °C. The larger the variability superimposed on linear trends, the longer the time series should be in order to detect such trends in a significant way. Therefore we consider that this is the explanation for the lower significance of

warming trends in Fuengirola beach temperature time series.

Updated time series from 1900 to 2015 show that the intermediate layer has increased its salinity in all the regions analyzed (Alboran Sea, Cape Palos, Balearic Sea and northern sector, Tables 2–5) and for the whole area (Fig. 16, Table 6). The salting trends have intensified after

Table 6
The same as in Table 1, but for the whole area.

The whole area								
With BT	θ		S		$Q_{abs.}$		$Q_{abs.}$	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	0.01	−0.02	0.01	0.03	−0.010	−0.033	−0.009	−0.038
IW	0.006	0.02	0.005	0.01	0.017	0.066	0.022	0.070
DW	0.017	0.04	0.006	0.01	0.060	0.153	0.180	0.430
0-bottom					0.077	0.206	0.176	0.454

Without BT								
	θ		S		$Q_{abs.}$		$Q_{abs.}$	
	1900–2015	1943–2015	1900–2015	1943–2015	Zero anom.	1943–2015	Repr. anom.	1943–2015
AW	0.008	0.03	0.01	0.03	0.019	0.028	0.015	0.049
IW	0.009	0.02	0.005	0.01	0.029	0.080	0.036	0.094
DW	0.015	0.04	0.006	0.01	0.059	0.140	0.182	0.424
0-bottom					0.106	0.256	0.246	0.558

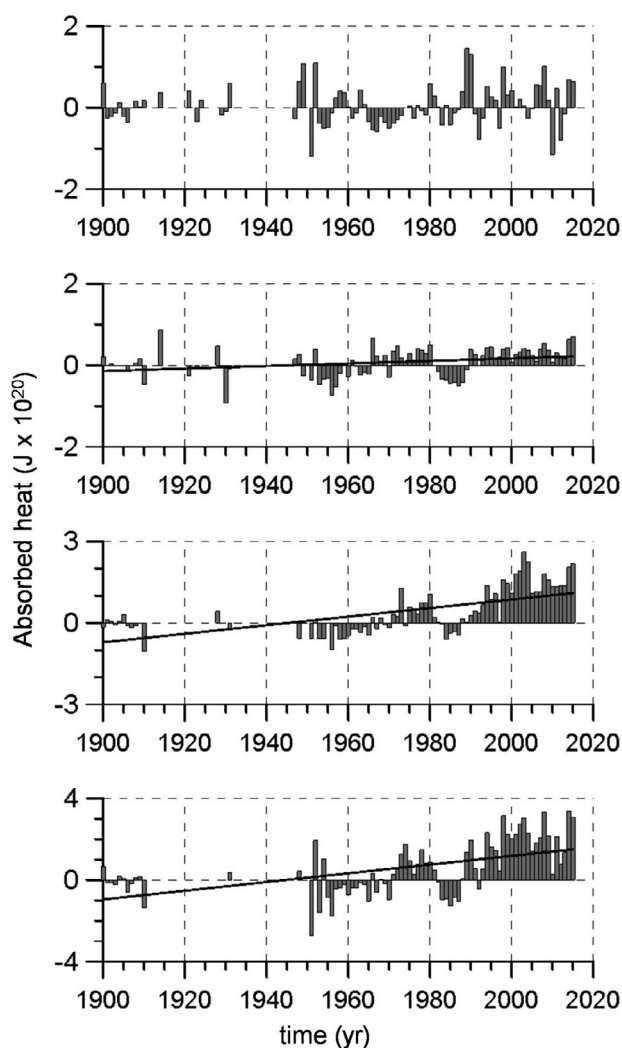


Fig. 15. Heat absorbed by the upper layer (0–200 m), intermediate layer (200–600 m), deep layer (600 m–bottom) and water column (surface–bottom). The heat absorbed is calculated with respect to the climatological temperature profile averaged for the period 1960–1990. Heat content data are averaged for the four regions analyzed (Alboran Sea, Cape Palos, Balearic Sea and northern sector).

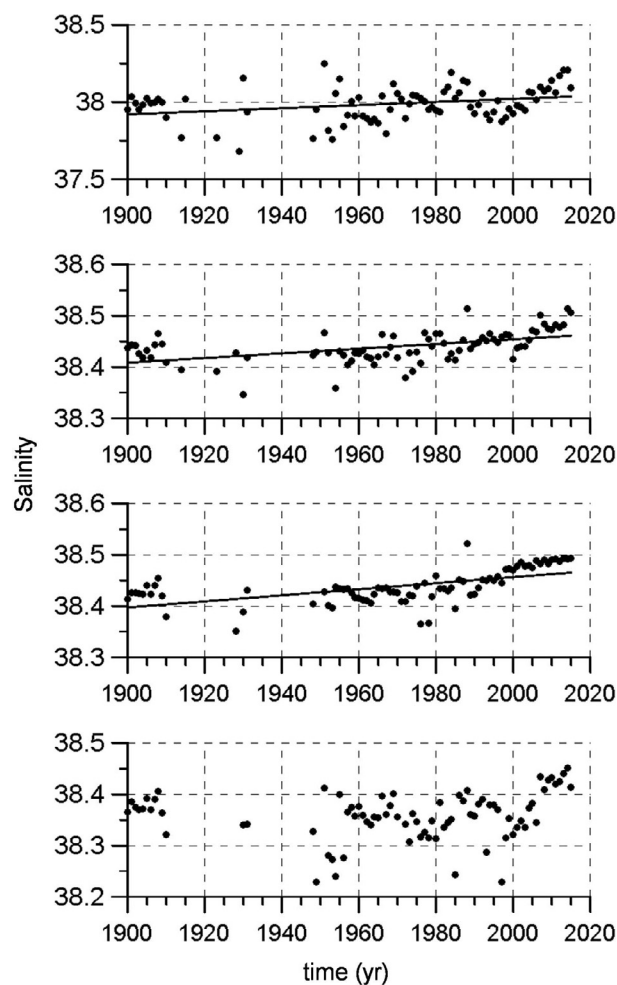


Fig. 16. Salinity time series for the upper, intermediate and deep layer and the water column. Salinity data are averaged for the four regions analyzed (Alboran Sea, Cape Palos, Balearic Sea and northern sector).

1943 with values between 0.01 and 0.02 decade^{−1}. The temperature of the intermediate layer has also increased (Fig. 15, Table 6). As in the case of salinity, these warming trends have intensified after 1943 with values between 0.02 and 0.04 °C/decade. The extension of present time series with the inclusion of the new data (2007–2015) seems to confirm previous results in Vargas-Yáñez et al. (2010a, 2010b) indicating that

the last decade had a similar behavior to the previous ones.

Finally, the deep waters of all the areas analyzed have increased its temperature and salinity. The temperature and salinity trends for the whole area and from 1900 to 2015 were 0.02 °C/decade and 0.006 decade⁻¹. Once again there was an acceleration of the warming and salting rates since the mid twentieth century (0.04 °C/decade and 0.01 decade⁻¹). These warming trends are higher than those previously reported in Vargas-Yáñez et al. (2010b). The increase in the temperature trends could be linked to the new bottom water masses appeared in the WMED after 2005. These results are very robust as they do not depend on the period of time analyzed or the methodology.

The positive trends for the l'Estartit station and those in Fuengirola beach (with a lower degree of confidence) and the salinity and temperature increase of the intermediate layer make us hypothesize that the deep water warming and salting is the result of the positive temperature and salinity trends in the water masses contributing to deep water formation: AW and LIW. Furthermore, this would be the result of an increase in net evaporation and heat absorption through the sea surface. These trends would be enhanced during the last years of the series by the influence of the Western Mediterranean Transition. This is a phenomenon which should be monitored in order to determine whether it will change the structure of the Western Mediterranean water masses or the “old” situation will be restored. Updated time series show that the heat content of the water column in the area of study has increased at a rate between 0.2 and 0.6 W/m² since 1943. This result is consistent with that in Levitus et al. (2012) who estimated the heat absorption of 0.27 W/m² for the upper 2000 m of the world ocean.

5. Conclusions

The RADMED time series have shown to be a valuable tool for assessing the mean or average hydrographic conditions along the continental shelf and slope in the Spanish Mediterranean as well as long term changes or trends. Temperature and salinity mean values in winter are coherent with the extension of the northern current along the Catalan continental slope carrying severely modified AW and WIW and LIW below. The three water masses would partially flow to the south, mainly through the Ibiza channel while another fraction of these water masses would be deflected to the North East flowing to the north of the Balearic Islands forming the Balearic current. The Mallorca channel, the Menorca channel and the eastern side of Menorca Island would be more favorable places for AW northward intrusions. This picture would correspond to the average or more frequent situation, but some particular years could present important alterations such as the Ibiza channel blocking by WIW eddies. The summer temperature and salinity mean values indicate that the AW would progress further to the north decreasing the surface water salinity. The highest temperatures from all the sections analyzed correspond to summer surface waters in the Balearic Islands.

WIW is mainly formed during winter in the Gulf of Lions and the Ligurian Sea arriving to the Balearic channels in spring. Nevertheless, the RADMED project has revealed that the Balearic channels could also be a frequent site of intermediate water formation and exceptionally this process could be displaced further to the south reaching areas as Cape Palos. As already stated, the WIW progresses to the south mainly through the Ibiza channel and is diluted by mixing with waters above and below on its pathway. Nevertheless, it can be considered that this water mass is clearly identifiable as a temperature and salinity minimum above the LIW in Cape Gata (within the Alboran Sea) during most of the years. Although it would not be so frequent, some years this water mass can maintain its characteristics with temperatures below 13 °C in Cape Pino section, close to the Gibraltar Strait.

The inclusion of new deep stations in the RADMED project since 2007 and the maintenance of some deep stations from previous projects (ECOMURCIA and CIRBAL) have allowed us to detect and monitor the effects of the Western Mediterranean Transition in the Western

Mediterranean. Deep stations have revealed that the new bottom waters, warmer and saltier than previous WMDW have been present in this area of the Western Mediterranean during this period of time.

It is extremely likely that intermediate and deep layers have increased their temperature and salinity during the last century and the beginning of the present one, being these trends accelerated during the second half of the twentieth century. Considering the large variance of the upper layer, the RADMED time series are not long enough neither they have the appropriate frequency for the detection of long term trends. Nevertheless, based on Fuengirola beach and l'Estartit time series, we speculate that the upper layer has also increased its temperature during the last 30 or 40 years. The increase in the water column heat content seems to be in agreement with those figures obtained for the rest of the world ocean.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.poccean.2017.09.004>.

References

- Alexanderson, H., 1986. A homogeneity test applied to precipitation data. *J. Climatol.* 6, 661–675.
- Alexanderson, H., Moberg, A., 1997. Homogenization of Swedish temperature data. Part 1: homogeneity test for linear trends. *Int. J. Climatol.* 17, 25–34.
- Balbín, R., López-Jurado, J.L., Flexas, M.M., Reglero, P., Vélez-Velchí, P., González-Pola, C., Rodríguez, J.M., García, A., Alemany, F., 2014. Interannual variability of the early summer circulation around the Balearic Islands: driving factors and potential effects on the marine ecosystem. *J. Mar. Syst.* 138, 78–81. <http://dx.doi.org/10.1016/j.jmarsys.2013.07.004>.
- Bethoux, J.P., Gentili, B., Morin, P., Nicolas, E., Pierre, C., Ruiz-Pino, D., 1999. The Mediterranean Sea: a miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic. *Prog. Oceanogr.* 44, 131–146.
- Béthoux, J.P., Gentili, B., Tailleux, D., 1998. Warming and freshwater budget change in the Mediterranean since 1940s, their possible relation to the greenhouse effect. *Geophys. Res. Lett.* 25 (7), 1023–1026.
- Bethoux, J.P., Gentili, B., 1996. The Mediterranean Sea, coastal and deep-sea signatures of climatic and environmental changes. *J. Mar. Syst.* 7, 383–394.
- Borghini, M., Bryden, H., Schroeder, K., Sparnocchia, S., Vetrano, A., 2014. The Mediterranean is becoming saltier. *Ocean Sci.* 10, 693–700. <http://dx.doi.org/10.5194/os-10-693-2014>.
- Domingues, C.M., Church, J.A., White, N.J., Glecker, P.J., Wijffels, S.E., Barker, P.M., Dunn, J., 2008. Improved estimates of upper-ocean warming and multidecadal sea level rise. *Nature* 453, 1090–1093. <http://dx.doi.org/10.1038/nature07080>.
- Font, J., Miralles, L., 1978. *Res. Exp. Cient. B/O Cornide* 7, 155–162.
- Font, J., Ballester, A., 1984. Seasonal velocity variations in the continental side of the Catalan Gyre. *Rapp. Comm. Int. Mer Médit.* 29 (3), 105–106.
- Font, J., Salat, J., Tintoré, J., 1988. Permanent features of the circulation in the Catalan Sea. *Oceanol. Acta* 9, 51–57.
- Gasparini, G.P., Ortona, A., Budillon, G., Astraldi, M., Sansone, E., 2005. The effect of the Eastern Mediterranean Transient on the hydrographic characteristics in the Strait of Sicily and in the Tyrrhenian. *Deep-Sea Res. I* 52, 915–935.
- Gouretski, V., Koltermann, K.P., 2007. How much is the ocean really warming? *Geophys. Res. Lett.* 34, L01610. <http://dx.doi.org/10.1029/2006GL027834>.
- Houpert, L., Durrieu de Madron, X., Testor, P., Bosse, A., D'Ortenzio, F., Bouin, M.N., Dausse, D., Le Goff, H., Kunesch, K., Labaste, M., Coppola, L., Mortier, L., Raimbault, P., 2016. Observations of open-ocean deep convection in the northwestern

- Mediterranean Sea: seasonal and interannual variability of mixing and deep water masses for the 2007–2013 period. *J. Geophys. Res., Oceans* 121. <http://dx.doi.org/10.1002/2016JC011857>.
- Jordá, G., Gomis, D., 2013. Reliability of the steric and mass components of the Mediterranean Sea level es estimated from hydrographic gridded products. *Geophys. Res. Lett.* 40, 3655–3660. <http://dx.doi.org/10.1002/grl.50718>.
- Krahmann, G., Schott, F., 1998. Longterm increases in Western Mediterranean salinities and temperatures: anthropogenic and climatic sources. *Geophys. Res. Lett.* 25 (22), 4209–4212.
- Lacombe, H., Tchernia, P., Gamberoni, L., 1985. Variable bottom water in the Western Mediterranean Basin. *Prog. Oceanogr.* 14, 319–338.
- Leaman, K.D., Schott, F., 1991. Hydrographic structure of the convection regime in the Gulf of Lions: winter 1987. *J. Phys. Oceanogr.* 21, 575–598.
- Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., García, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S., Zweng, M.M., 2012. World ocean heat content and thermocline sea level change (0–2000 m), 1955–2010. *Geophys. Res. Lett.* 39, L10603. <http://dx.doi.org/10.1029/2012GL051106>.
- Levitus, S., Antonov, J.I., Boyer, T.P., Locarnini, R.A., García, H.E., Mishonov, A.V., 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.* 36, L07608. <http://dx.doi.org/10.1029/2008GL037155>.
- Llases, J., Jordá, G., Gomis, D., 2015. Skills of different hydrographic networks in capturing changes in the Mediterranean Sea at climate scales. *Climate Res.* 63, 1–18.
- López-Jurado, J.L., Balbín, R., Amengual, B., Aparicio-González, A., Fernández de Puelles, M.L., García-Martínez, M.C., Gaza, M., Jansá, J., Morillas-Kieffer, A., Moya, F., Santiago, R., Serra, M., Vargas-Yáñez, M., Vicente, L., 2015. The RADMED monitoring program: towards an ecosystem approach. *Ocean Sci. Discuss.* 12, 645–671. <http://dx.doi.org/10.5194/osd-12-6452015>.
- López-Jurado, J.L., González-Pola, C., Vélez-Belchí, P., 2005. Observation of an abrupt disruption of the long-term warming trend at the Balearic Sea, western Mediterranean Sea, in summer 2005. *Geophys. Res. Lett.* 32. <http://dx.doi.org/10.1029/2005GL024430>.
- López-Jurado, J.L., García-Lafuente, J., Cano, N., 1995. Hydrographic conditions of the Ibiza Channel during November 1990, March 1991 and July 1992. *Oceanol. Acta* 18 (2), 235–243.
- MEDAR Group, 2002. MEDATLAS/2002 Database Mediterranean and Black Sea Database of Temperature Salinity and Bio-Chemical Parameters. Climatological Atlas.
- MEDOC Group, 1970. Observation of the formation of Deep Water in the Mediterranean Sea, 1969. *Nature* 227 (5262), 1037–1040.
- Millot, C., 2009. Another description of the Mediterranean Sea outflow. *Prog. Oceanogr.* 82 (2), 101–124. <http://dx.doi.org/10.1016/j.pocean.2009.04.016>.
- Millot, C., 1999. Circulation in the Western Mediterranean Sea. *J. Mar. Syst.* 20, 423–442.
- Nielsen, J.N., 1912. Hydrography of the Mediterranean and Adjacent Waters. Report on the Danish Oceanographical Expeditions 1908–1910 to the Mediterranean and Adjacent Seas, vol. I, pp. 72–191.
- Painter, S.C., Tsimplis, M.N., 2003. Temperature and salinity trends in the upper waters of the Mediterranean Sea as determined from MEDATLAS data set. *Cont. Shelf Res.* 23, 1507–1522.
- Parrilla, G., Kinder, T.H., Preller, R., 1986. Deep and intermediate Mediterranean water in the Western Alboran Sea. *Deep-Sea Res.* 33 (1), 55–88.
- Pascual, J., Salat, J., Palau, M., 1995. Evolución de la temperatura del mar entre 1973 y 1994, cerca de la costa catalana, en *Int. Coll. Okeanos*, 23–28, Montpellier.
- Pinot, J.M., Ganachaud, A., 1999. The role of Winter intermediate waters in spring-summer circulation of the Balearic Sea I. Hydrography and inverse modeling. *J. Geophys. Res.* 104 (C12), 29843–29864.
- Pinot, J.M., Tintoré, J., Gomis, D., 1995. Multivariate analysis of the surface circulation in the Balearic Sea. *Prog. Oceanogr.* 36, 343–376.
- Poulain, P.M., Barbanti, R., Font, J., Cruzado, A., Millot, C., Gertman, I., Griffa, A., Molcard, A., Rupolo, V., Le Bras, S., Petit de la Villeon, L., 2007. MedArgo: a drifting profiler program in the Mediterranean Sea. *Ocean Sci.* 3, 379–395.
- Rhein, M., Rintoul, S.R., Aoki, S., Campos, E., Chambers, D., Feely, R.A., Gulev, S., Johnson, G.C., Josey, S.A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L.D., Wang, F., 2013. Observations: ocean. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Rixen, M., Bakers, J.M., Levitus, S., Antonov, J., Boyer, T., Maillard, C., Fichaut, M., Balopoulos, E., Iona, S., Dooley, H., García, M.J., Manca, B., Giorgetti, A., Mazella, G., Mikhailov, N., Pinardi, N., Zavatarelli, M., 2005. The Western Mediterranean Deep Water: a proxy for climate change. *Geophys. Res. Lett.* 32, L12608. <http://dx.doi.org/10.1029/2005GL022702>.
- Roether, W., Klein, B., Manca, B.B., Theoharis, A., Kioroglou, S., 2007. Transient Eastern Mediterranean deep waters in response to massive dense-water output of the Aegean Sea in the 1990s.
- Roether, W., Manca, B.B., Klein, B., Bregant, D., Georgopoulos, D., Beitzel, V., Kovacevic, V., Luchetta, A., 1996. Recent changes in the Eastern Mediterranean Deep Waters. *Science* 271, 333–335.
- Rohling, E.J., Bryden, H.L., 1992. Man-induced salinity and temperature increase in Western Mediterranean Deep Water. *J. Geophys. Res.* 97 (C7), 11191–11198.
- Salat, J., Pascual, J., 2006. Principales tendencias climatológicas en el Mediterráneo Noroccidental a partir de más de 30 años de observaciones oceanográficas en la costa catalana. En *Clima, Sociedad y Medio Ambiente*. In: Cuadrat Prats, J.M., Sánchez, M. A., Vicente Serrano, S.M., Lanjeri, S., De Luis Arrillaga, N., González-Hidalgo, J.C. (Eds.), *Publicaciones de la Asociación Española de Climatología (AEC), Serie A, No. 5*, pp. 284–290.
- Salat, J., Cruzado, A., 1981. Masses d'eau dans la Méditerranée Occidentale: Mer Catalan et eaux adjacentes. *Rapp. Comm. Int. Médit.* 27 (6), 201–209.
- Sánchez-Román, A., Ruiz, S., Pascual, A., Mourre, B., Guinehut, S., 2016. On the mesoscale monitoring capability of Argo floats in the Mediterranean Sea. *Ocean Sci. Discuss.* <http://dx.doi.org/10.5194/os-2016-77>.
- Schroeder, K., Chiggiato, J., Bryden, H.L., Borghini, M., Ismail, S.B., 2016. Abrupt climate shift in the Western Mediterranean Sea. *Sci. Rep.* 6, 23009. <http://dx.doi.org/10.1038/srep23009>.
- Schroeder, K., Millot, C., Bengara, L., Ben, Ismail S., Bensi, M., Borghini, M., Budillon, G., Cardin, V., Coppola, L., Curtil, C., Drago, A., El Moumni, B., Font, J., Fuda, J.L., García-Lafuente, J., Gasparini, G.P., Kontoyiannis, H., Lefevre, D., Puig, P., Raimbault, P., Rougier, G., Salat, J., Sammari, C., Sánchez Garrido, J.C., Sanchez-Roman, A., Sparnocchia, S., Tamburini, C., Taupier-Letage, I., Theoharis, A., Vargas-Yáñez, M., Vetrano, A., 2013. Long-term monitoring programme of the hydrological variability in the Mediterranean Sea: a first overview of the HYDROCHANGES network. *Ocean Sci.* 9, 301–324. <http://dx.doi.org/10.5194/os-9-301-2013>.
- Schroeder, K., Josey, S.A., Hermann, M., Grignon, L., Gasparini, G.P., Bryden, H.L., 2010. Abrupt warming and salting of the Western Mediterranean Deep Water after 2005: atmospheric forcing and lateral advection. *J. Geophys. Res.* 115, C08029. <http://dx.doi.org/10.1029/2009JC005749>.
- Skliris, N., Sofianos, S.S., Gkanasos, A., Mantziadou, A., Versatis, V., Axaopoulos, P., Lascaratos, A., 2012. Decadal scale variability of sea surface temperature in the Mediterranean Sea in relation to atmospheric variability. *Ocean Dyn.* <http://dx.doi.org/10.1007/s10236-011-0493-5>.
- Smith, R.O., Bryden, H.L., 2007. Observations of new western Mediterranean deep water formation using ARGO floats 2004–2006. *Ocean Sci. Discuss.* 4, 733–783.
- Sparnocchia, S., Manzella, G.M.R., La Violette, P.E., 1994. The interannual and seasonal variability of the MAW and LIW core properties in the Western Mediterranean Sea. In: La Violette, P.E. (Ed.), *En Seasonal and Interannual Variability of the Western Mediterranean. Coastal and Estuarine Studies American Geophysical Union, Washington*.
- Sverdrup, H.U., Johnson, M.W., Fleming, R.H., 1942. *The Oceans, Their Physics, Chemistry, and General Biology*. Prentice Hall, New York, pp. 1087.
- Tel, E., Balbín, R., Cabanas, J.M., García, M.J., García-Martínez, M.C., González-Pola, C., Lavín, A., López-Jurado, J.L., Rodríguez, C., Ruiz-Villareal, M., Sánchez-Leal, R.F., Vargas-Yáñez, M., Vélez-Belchí, P., 2016. IEOOS: The Spanish Institute of Oceanography Observing System. *Ocean Sci. Discuss.* 12, 345–353. <http://dx.doi.org/10.5194/os-12-345-2016>.
- Vargas-Yáñez, M., Mallard, E., Rixen, M., Zunino, P., García-Martínez, M.C., Moya, F., 2012a. The effect of interpolation methods in temperature and salinity trends in the Western Mediterranean. *Medit. Mar. Sci.* 13 (1), 118–125.
- Vargas-Yáñez, M., Zunino, P., Schroeder, K., López-Jurado, J.L., Plaza, F., Serra, M., Castro, C., García-Martínez, M.C., Moya, F., Salat, J., 2012b. Extreme Western Intermediate Water formation in Winter 2010. *J. Mar. Syst.* <http://dx.doi.org/10.1016/j.jmarsys.2012.05.010>.
- Vargas-Yáñez, M., Zunino, P., Benali, A., Delpy, M., Pastre, F., Moya, F., García-Martínez, M.C., Tel, E., 2010a. How much is the Western Mediterranean really warming and salting? *J. Geophys. Res.* 115, C04001. <http://dx.doi.org/10.1029/2009JC005816>.
- Vargas-Yáñez, M., Moya, F., García-Martínez, M.C., Tel, E., Zunino, P., Plaza, F., Salat, J., Pascual, J., López-Jurado, J.L., Serra, M., 2010b. Climate change in the Western Mediterranean Sea 1900–2008. *J. Mar. Syst.* 82, 171–176.
- Vargas-Yáñez, M., Moya, F., Tel, E., García-Martínez, M.C., Guerber, E., Bourgeon, M., 2009. Warming and salting in the Western Mediterranean during the second half of the 20th century: inconsistencies, unknowns and the effect of data processing. *Sci. Mar.* 73 (1). <http://dx.doi.org/10.3989/scimar.2009.73n1007>.
- Zunino, P., Schroeder, K., Vargas-Yáñez, M., Gasparini, G.P., Coppola, L., García-Martínez, M.C., Moya, F., 2012. Effects of the Western Mediterranean Transition on the resident water masses: pure warming, pure freshening and pure heaving. *J. Mar. Syst.* 96–97, 15–23. <http://dx.doi.org/10.1016/j.jmarsys.2012.01.011>.