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Warming and salting in the western Mediterranean during the second half of the 20th century: inconsistencies, unknowns and the effect of data processing

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SUMMARY: Many papers that have appeared since the late 1980s have reported trends for the salinity and temperature of the upper, intermediate and deep layers within the western Mediterranean. The review of these works shows that the figures reported depend on the period of time considered. In some cases, opposite results are obtained by different studies dealing with the same period of time. These results make it difficult to assess the mean trends of these variables during the second half of the 20th century and to distinguish long-term changes from decadal and multi-decadal variability. In order to determine the origin of these discrepancies, we analyse temperature and salinity profiles from MEDAR/2002 in three areas of the western Mediterranean: the Gulf of Lions, the Balearic Islands and the Alboran Sea. We use data analysis methods that have all been tested and used previously in the literature. Our results show that the scarcity of data makes trend estimations very sensitive to the data analysis methods, questioning the robustness of such estimations and showing the suitability of systematic sampling for studying long-term changes. We attempt to provide temperature and salinity trends from 1950 to 2000 for the three aforementioned regions, which show a higher degree of uncertainty than the previous studies. Long-term temperature and salinity increases for this 50-year period are within the intervals [0.02ºC, 0.19ºC] and [0.01, 0.1] for deep waters, [0.06ºC, 0.38ºC] and [0.01, 0.26] for LIW, and [0, 0.45ºC] for the upper layers. No salinity change has been observed for the upper layer.

Keywords: western Mediterranean, warming trend, salinity trend, climate change.

RESUMEN: CALENTAMIENTO Y AUMENTO DE LA SALINIDAD EN EL MEDITERRÁNEO OCCIDENTAL DURANTE LA SEGUNDA MITAD DEL SIGLO XX: INCONSISTENCIAS, INCERTIDUMBRES E INFLUENCIA DEL PROCESADO DE DATOS. – Numerosos trabajos aparecidos desde finales de la década de los 80 han mostrado tendencias para la temperatura y salinidad de las capas superficial, intermedia y profunda en el Mediterráneo Occidental. La revisión de estos trabajos muestra que las tendencias calculadas dependen del periodo de tiempo considerado. En algunos casos, trabajos que consideran el mismo periodo de tiempo muestran resultados opuestos lo que hace difícil determinar cuáles han sido los cambios de estas variables a lo largo de la segunda mitad del siglo XX, así como distinguir estos cambios a largo plazo de la variabilidad decadal y multidecadal. Con el objeto de esclarecer el origen de estas discrepancias, analizamos todos los perfiles de temperatura y salinidad disponibles en MEDAR/2002 en tres zonas del Mediterráneo Occidental: Golfo de León, Islas Baleares y Mar de Alborán. Cada serie temporal es analizada usando distintos métodos, siendo todos ellos correctos y previamente usados en la literatura existente. Nuestros resultados muestran que la escasez de datos hace la estimación de tendencias muy sensible al método de análisis de los datos, lo que cuestiona la robustez de estas estimaciones. En este trabajo se obtienen nuevas estimaciones para las tendencias de la temperatura y salinidad desde 1950 al año 2000 para las tres áreas geográficas ya mencionadas, proporcionando incertidumbres mayores que las consideradas en trabajos previos. Los incrementos medios para la temperatura y la salinidad en este periodo de 50 años estarían dentro de los intervalos [0.02ºC, 0.19ºC] y [0.01, 0.1] para las aguas profundas, [0.06ºC, 0.38ºC] y [0.01, 0.26] para el Agua Levantina Intermedia, y [0ºC, 0.45ºC] para las capas superficiales. No se observan cambios de salinidad para esta última capa.

Palabras clave: Mediterráneo occidental, tendencias, calentamiento, tendencias de salinidad, cambio climático.

INTRODUCTION

During the last decades, many works have addressed the detection of changes in the heat uptake of the upper layers of the world oceans, the thermohaline properties of water masses on a global scale and the impact of these changes on the global sea level (Gouretski and Kolterman, 2007; Levitus *et al.*, 2005; Miller and Douglas, 2004). Much of the interest is focused on long-term changes related to global warming, which are usually statistically modelled by means of linear regression. However, the analysis of oceanographic time series and trend detection is not an easy task because of the complex dynamics of the ocean-atmosphere system at a global, regional and local scale. Different time scales appear superimposed on any oceanographic time series, which makes the detection of long-term changes difficult.

Time variability and time scales in the Mediterranean Sea

In the particular case of the Mediterranean Sea, many papers published since the late 1980s have reported major changes in the upper, intermediate and deep layers in both the western and eastern Mediterranean (hereafter WMED, EMED). The processes described in the literature show the wide range of time scales mentioned above:

1) There have been changes related to processes that last several years but can be considered as isolated or specific in time, or at least that they do not have a clear recurrence. In the EMED, during the late 1970s and early 1980s the temperature of the Levantine Intermediate Water (LIW) dropped by 0.4ºC (Brankart and Pinardi, 2001) and during the late 1980s and early 1990s the area of deep water formation shifted from the Adriatic to the Aegean Sea. This event is known as the Eastern Mediterranean Transient (EMT, Roether at al., 1996; Klein *et al*., 1999; Lascaratos *et al*., 1999). Strong heat flux anomalies similar to those leading to the EMT occurred between 1974 and 1976 (Josey, 2003). However, the uncertainties in the long-term river runoff changes and the scarcity of historical hydrographic data do not allow us to establish definitively whether or not the EMT is an unprecedented phenomenon (Josey, 2003).

In the case of the WMED, Millot *et al*. (2006) have hypothesised that changes in the TS properties of waters outflowing through the Strait of Gibraltar were caused by the replacement of the Deep Water formed to the north of the Liguro-Provençal basin (Western Mediterranean Deep Water, WMDW) by deep water formed in the Tyrrhenian Sea (Tyrrhenian Deep Water, TDW). Schröder *et al.* (2006) considered that the acceleration of the deep water temperature and salinity trends after 1995 was caused by the influence of the EMT on the WMED. Pinot *et al.* (2002) reported the progressive disappearance of the Western Intermediate Water (WIW) in the Balearic Sea from 1996 to 1998 and more recently an abrupt decrease of 0.14ºC was observed in the temperature of the newly formed WMDW during the winter of 2004-2005 (Font *et al.*, 2007; López-Jurado *et al.*, 2005) followed by a strong increase in the deep water temperature and salinity in the following winter (Smith and Bryden, 2007).

2) Decadal variability. Although it cannot be considered as a periodic phenomenon in a deterministic sense with predictable amplitudes and phases, it is frequently observed that variables such as temperature, salinity, heat content and sea level exhibit anomalies of the same sign persistently for a decade or so, producing the alternation of crests and troughs in the oceanographic time series. As an example, the 1990s were extremely warm [Vargas-Yáñez *et al.*, 2002; 2005; 2008; Fuda *et al.*, 2002]. Trends or mean time derivatives computed over such short periods of time can vary by several orders of magnitude or even have a different sign to the longer-term changes.

3) Long time series show the alternation of anomalies of a different sign, or positive and negative time derivatives for periods of several decades. This is what could be considered as multi-decadal variability. As in the case of decadal variability, time derivatives calculated over these sub-periods of time can produce results some orders of magnitude higher than or with a different sign to those calculated for the long term. Metaxas *et al.* (1991) showed the evolution of the Sea Surface Temperature (SST) at some ports of the WMED and EMED. SST at Perpignan and Genoa exhibited negative and positive trends for different sub-periods of the 20th century, with relative minima at the beginning of the 20th century and in the early 1970s and maxima between 1940 and 1950. A similar behaviour has been reported for European air temperatures (Luterbacher *et al.*, 2004, Xoplaki *et al.*, 2005) and the upper 85 m of the water column in the Catalonian Shelf (Salat and Pascual, 2002; 2006).

The slowly evolving changes associated with global change are usually estimated from observational records by means of linear regression. However, the scarcity and the irregular distribution of temperature and salinity data covering the water column and the time variability described above make these changes difficult to detect. Trend figures from different places can hardly be compared and they easily change depending on the period of time considered (Millot *et al.*, 2006). Although there could exist a process producing a continuous warming of the water column with a more or less stable rate of change, the existence of decadal and multidecadal variability can yield very different results in linear trend estimations depending on the initial and end point of the time series.

Discrepancies and unknowns in temperature and salinity trends in the WMED

Deep Waters Trends

The first works dealing with trend estimations in the Mediterranean Sea were mainly focused on detecting changes in deep and intermediate waters where the natural variability is lower than in the upper layers. Bethoux *et al.* (1990) reported a positive increase of 0.12ºC and 0.03 salinity units from 1959 to 1989 for the WMDW. According to these authors these changes preserved a constant density of 1029.1 kg/m^3. Rohling and Bryden (1992) estimated positive trends for both temperature and salinity of the WMDW throughout the 20th century, and particularly in the second half. In order to compare with the values reported by Bethoux *et al.* (1990) and other authors, we consider the 1955-1989 trends which were 0.0016ºC/yr and 0.00095 yr^{-1} for temperature and salinity, respectively. Density also increased in the 1955-1989 period at a rate of 0.00037 kgm^{-3}/yr. Bethoux and Gentili (1996) estimated trends of 0.0036ºC/yr and 0.0011 yr^{-1} for the period 1959-1994 and observed a slight decrease in density, although they considered that as an initial approximation it could be considered to be constant. According to Krahmann and Schott (1998), T and S trends for the period 1960-1995 were 0.0016ºC/yr and 0.0008 yr^{-1}, with no significant trends for density, and Bethoux *et al.* (1998, 1999) reported values of 0.0035ºC/yr and 0.0011 yr^{-1} from 1959 to 1997. In these papers the density increase in the 1959-1997 period was estimated as 0.00013 kgm^{-3}/yr. Tsimplis and Baker (2000) calculated positive trends for temperature (0.0025ºC/yr), salinity (0.0011 yr^{-1}) and density (0.00034 kgm^{-3}/yr) at a 2000 m depth in the WMED in the period 1960-1997. More recently, Rixen *et al.* (2005) showed a continuous increase in temperature and salinity for the deep layer (600 m to the bottom) in the WMED from 1950 to 2000.

Intermediate Waters trends

The evolution of LIW does not offer such a clear picture as that depicted for deep waters. Bethoux *et al.* (1990) did not report any TS trends for this water mass based on direct observations. Considering the different contributions of AW and LIW to the yearly formed WMDW and the total volume occupied by this water mass, these authors concluded that the observed temperature and salinity trends of WMDW from 1960 to 1989 could only be explained on the basis of both a warming of the AW and LIW and a salinity increase of LIW. Rohling and Bryden (1992) found that the salinity of LIW near the MEDOC area (the area of formation of WMDW) increased during the 20th century, and this trend (0.0025 yr^{-1}) was accelerated in the period 1955-1987. Bethoux and Gentili (1996) compared TS data at 300-400 m depth in the Ligurian Sea for the period 1960-1973 with data obtained in 1991 and 1992. They estimated a temperature and salinity increase of 0.0068ºC/yr and 0.0018 yr^{-1}. For the extended period 1959-1997 Bethoux and Gentili (1999) reported the same values, which were similar to those obtained by Sparnochia *et al.* (1994) for the period 1950-1987 in the Ligurian Sea and the Strait of Sicily. Contrary to this, Krahmann and Schott (1998) analysed T and S time series in three different areas covering the whole WMED and found no trends for these variables in the 200-500 m layer, which roughly represents the intermediate layer in the WMED. More recently, Rixen *et al.* (2005) found that the temperature of the intermediate layer in both the WMED and EMED underwent a similar evolution from 1950 to 2000. This temporal evolution of the temperature in the 150-600 m layer was described by these authors as decadal variability, but no significant trends were detected. It is also interesting to note that, in the case of salinity, the intermediate layer has a positive trend in the WMED while only decadal variability is observed in the EMED. According to these authors there was no agreement between the decadal time variability of salinity in the two basins.

TABLE 1. – Trends for the WMED from the literature. Alg. Prov. stands for Algero-Provençal. (1) Estimated from volume and heat conservation. (2) Obtained from Table 3 in Bethoux and Gentili (1999). Dashed lines indicate that the authors do not provide the corresponding information. In some papers trends are provided in the original papers at a qualitative level. Density trends are not given for some layers by some authors. Figures in bold have been calculated from the temperature and salinity trends using $\Delta\rho = \rho_0[\alpha\Delta T + \beta\Delta S]$. (*) Rixen *et al.* (2005) provide volume mean TS increases. As these increases represent an average of the changes for the upper, intermediate and deep layers, they are included in the three layers as a reference.

authors and year	area	layer depth	period	θ trend (°C yr^{-1})	S trend (yr^{-1})	σ trend (kg $m^{-3}yr^{-1}$)
Deep Layer						
Bethoux *et al.*, 1990	Alg.Prov. basin	≥ 2000 m	1959-1989	0.0039	0.00097	no trend
Leaman and Schott, 1991	NW Med.	1850-2050 m	1969-1987	0.0027	0.0019	no trend
Rohling and Bryden, 1992	Africa-42ºN/0º-10ºE	2000 m	1955-1989	0.0016	0.00095	0.00037
Bethoux and Gentili, 1996	Alg.Prov. basin	≥ 2000 m	1959-1994	0.0036	0.0011	slight decrease
						-4.3×10^{-5}
Zodiatis and Gasparini, 1996	Tyrrhenian	600-1500 m	1973-1992	0.0091	0.0024	**-0.0004**
Krahmann and Schott, 1998	39ºN-42ºN/0º-10ºE	1625-2750 m	1960-1995	0.0016	0.0008	no trend
						0.00022
Bethoux *et al.*, 1998; 1999	Alg.Prov. basin	800-2700 m	1959-1997	0.0035	0.0011	0.00013
Tsimplis and Baker, 2000	Africa-42ºN/0º-10ºE	2000 m	1960-1997	0.0025	0.0011	0.00034
Rixen *et al.*, 2005	WMED,	600-bottom	1950-2005	increase	increase	----------
	WMED+EMED	0-bottom(*)		0.0019	0.0008	0.00012
Intermediate Layer						
Bethoux *et al.*, 1990	Alg.Prov. basin		1959-1989	0.005(1)	--------	----------
Rohling and Bryden, 1992	41º-42ºN/5ºE-7.5ºE	at salinity maximum	1955-1987	--------	0.0025	----------
Bethoux and Gentili, 1996	Alg.Prov. basin	300-400 m	1960-1992	0.0068	0.0018	**-0.0001**
Sparnochia *et al.*, 1994	Ligurian Sea and Sicily Strait(2)	-----------	1950-1987	0.0091	0.0019	**-0.0005**
				0.0065	0.0016	**-0.0002**
Krahmann and Schott, 1998	39º-42ºN/0º-10ºE	275-475 m	1960-1995	no trend	no trend	**no trend**
Bethoux *et al.*, 1999	Alg.Prov. basin	---------	1959-1996	0.0068	0.0018	**-0.0001**
Rixen *et al.*, 2005	WMED,	150-600 m	1950-2000	no trend	increase	**increase**
	WMED+EMED	0-bottom(*)		0.0019	0.0008	0.00012
Upper Layer						
Bethoux *et al.*, 1990	Alg.Prov. basin	--------	1959-1989	0.02(1)	--------	----------
Krahmann and Schott, 1998	39º-42ºN/0º-10ºE	0-70 m	1960-1990	no trend	0.0042	**0.0032**
Salat and Pascual, 2002	42ºN/3.25ºE	0-85 m	1974-2001	0.02	--------	----------
Rixen *et al.*, 2005	WMED	0-150 m	1950-2000	increase	increase	----------
	WMED+EMED	0-bottom(*)		after 1980	1960-1990	0.00012
				0.0019	0.0008	
Salat and Pascual, 2006	42ºN/3.25ºE	0-85 m	1974-2005	0.032	--------	----------

Upper layer trends

Upper layers are subjected to seasonal and high frequency variability. The variance of the noise superimposed on mean climatological values or trends is very large, which makes trend detection a difficult task. Bethoux *et al.* (1990) estimated the changes in the temperature of the surface waters of the WMED and EMED from heat and volume conservation equations, but provided no direct observations. Krahmann and Schott (1998) found a positive trend for salinity in the upper layer (0-63 m) of the north-western Mediterranean from 1960 to 1990, but no significant trends were observed in the salinity of the southern Algero-Provençal basin and in the Tyrrhenian Sea. The temperature at this layer experienced no significant changes in the period 1960-1995. According to Figure 2d in Krahmann and Schott (1998), the temperature of the upper layer increased from the late 1970s to 1980, but no temperature change was observed before or after this short period of time. Rixen *et al.* (2005) showed a clear and steep increase of temperature for the upper 150 m of the water column in the WMED from 1980 to 2000 (see Fig. 1a in Rixen *et al.*, 2005). The results shown by Rixen *et al.* (2005) are coincident with those reported by Salat and Pascual (2002; 2006), which showed a positive and steep temperature trend for the upper 85 m of the water column on the Catalan shelf from 1974 to 2005.

Table 1 shows a summary of the different trends discussed above. It can be seen that different figures are obtained for the trends estimated for the same layers of the water column at different places (see column 2 in Table 1) or for different periods of time. In some cases, even different results are obtained for the same layer and the same period of time. One possibility to consider is that the scarcity of data makes trend estimation very sensitive to the data processing method or the layer definition. Only those results which are statistically significant and robust—that is, do not depend on slight variations in the data processing—should be considered as reliable. Furthermore, even if we can trust the results, we still have to consider whether they represent just the mean derivative for a short period of time and the extent to which they can be considered as a measurement of long-term changes. In order to address these questions and to discern the results dealing with long-term changes in the WMED that can be considered as robust, we analyse temperature and salinity data from MEDAR/2002 in three areas of the WMED using several data processing methods. In next section 2 we briefly present the data set and review several possibilities of trend analysis for oceanographic time series as well as different definitions of upper, intermediate and deep layers in the three areas within the WMED. In some cases these possibilities correspond to different options found in the literature, while in others they are considered in this work in order to explore their impact on trend estimation. The following section presents the main results. Temperature, salinity and density trends estimated using the different approaches described in the data set section are provided. Finally, the results are discussed, and it is attempted to determine which of them are robust or independent from the method of data analysis and to detect coincidences and contradictions in relation to previous studies.

DATA SET

We collected all the temperature and salinity profiles from 1943 to 2000 from the MEDATLAS/2002 data base for the following boxes: 5ºW to 2.5ºW and 35.7ºN to 36.7º N (Alboran Sea), 0º to 6ºE, 38ºN to 41ºN (Balearic Sea), and an area in the Catalan Sea and south of the Gulf of Lions which hereafter will be called the Northern Sector and extends from 3.6ºE to 7ºE and 41ºN to 42.5ºN. Figure 1 shows the areas selected as well as the main features of the circulation of the upper, intermediate and deep layers. For all the TS profiles we selected 23 pressure levels from 0 to 2500 dbar. All the TS profiles within each box corresponding to the same month and year were averaged in order to construct 23 monthly time series for each box. These areas were selected at specific locations of the WMED according to their potential for highlighting different aspects of the water masses, but with the commitment to use areas large enough to get a sufficient number of TS profiles for most of the years. According to Figure 1, the Alboran sea area is

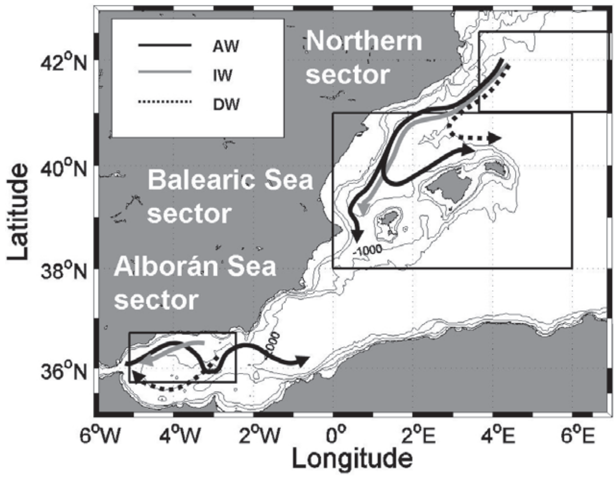

Fig. 1. – Squares are the three areas where temperature and salinity profiles have been obtained from MEDATLAS/2002 data base. The black line depicts the main paths followed by Atlantic Waters (AW). The grey line is the path followed by Intermediate Waters, which can be LIW or WIW. The black dotted line is the path followed by deep waters. We have indicated only Deep Water (DW) because according to Millot *et al.* (2006) this could be at present a mixture of WMDW and TDW.

expected to reflect possible changes in the incoming AW, while the alterations in the LIW and WMDW would reflect the modifications occurring in their source regions combined with modifications due to mixing along their pathways. On the other hand, the Northern Sector should show changes related to the yearly production of WMDW. These deep waters are also found in the NE corner of the Balearic sector, an area of added interest as it receives, on a yearly basis, the intermediate waters formed in the WMED, which are difficult to detect in other parts of the basin. The three areas selected should show changes in the LIW entering the WMED through the strait of Sicily, but these possible changes are more influenced by mixing with resident western water masses as they move from the Northern Sector to the Alboran Sea. Regarding LIW, other areas such as the Strait of Sicily and the Tyrrhenian Sea should be explored. An extension of the present work, applying the same methodology to the whole WMED, is under preparation.

In order to illustrate the irregular time distribution of the available data, the left column in Figure 2 shows the number of data averaged for each single month for obtaining the monthly time series in the Balearic Sea. This number is highly variable, being strongly dependent on depth. The right column in Figure 2 shows the mean number of profiles used to obtain the monthly values for each month of the year and different depths. There is a slight trend to-

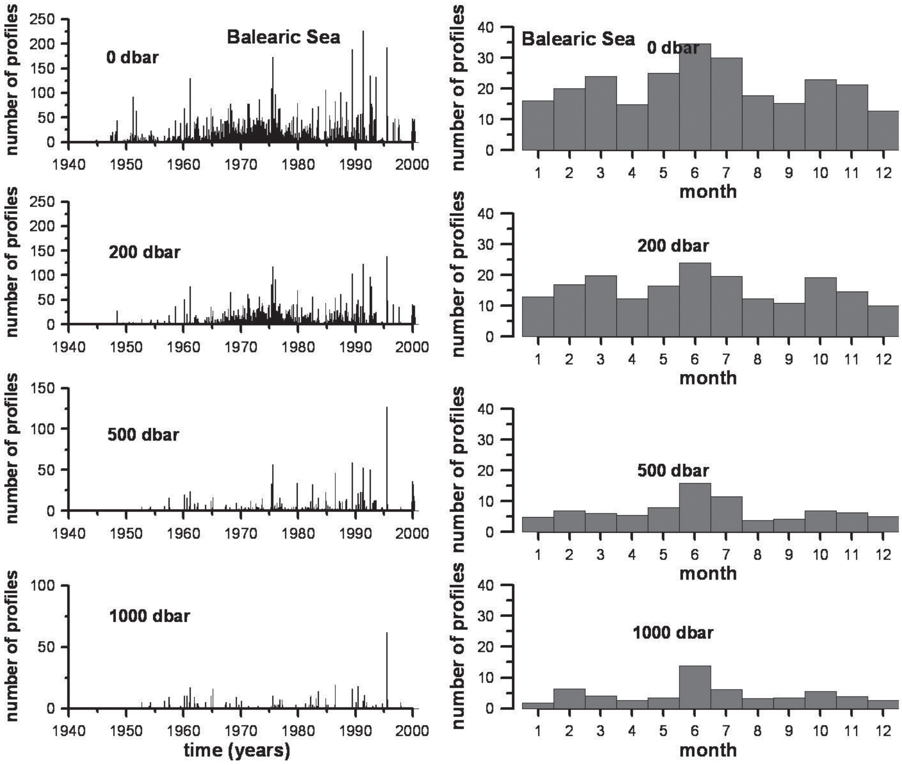

FIG. 2. – The left column shows the number of temperature data obtained for each particular month and year in the Balearic Sea. This is the number of data points averaged to obtain the monthly values which form the final time series analysed in this study. The right column is the mean number of data points used to obtain monthly data for each month of the year.

wards higher availability of TS data during the summer months and a dramatic decrease with depth. The period 1960-1990 seems to be the best sampled period, at least for the upper layers. Hereafter it is considered as the reference period for the calculation of climatologies. It is worth noting that the 1990s could be of great importance, as this period has been reported as the warmest in the WMED in the last 50 years of the 20th century (Rixen *et al.*, 2005), but it seems to be scarcely sampled.

The early works focusing on deep and intermediate layers considered that temperature and salinity at these depth levels were not influenced by the annual or seasonal cycle and the variables analysed were stationary for both the mean and the variance. All the available data corresponding to each single cruise were averaged and the time series considered were made of so many data points per year as cruises. A straigh line was fitted to the series without consideration of the month of the year when the temperature or salinity data were obtained. In other cases, temperature and salinity values averaged for different cruises several years or decades apart were compared. These comparisons or the linear trend calculations were used to check the null hypothesis, which is that all the measurements of temperature or salinity corresponding to a certain depth level came from a population normally distributed around a mean value which was stationary in time.

It is not clear to what depth the influence of the seasonal cycle is felt. For instance, WIW is formed near to or on the Gulf of Lions continental shelf in late winter and spreads to the south, reaching the Balearic Channels at a depth range of 200 to 400 m in the following spring, and is then diluted and disappears in late autumn. This water mass displaces the LIW, reducing both the temperature and salinity of intermediate waters in the Balearic Sea. Although the formation and spreading processes are subjected to a strong inter-annual variability, it is plausible that a certain seasonal cycle could exist in those depth levels and geographical areas influenced by this water mass. WMDW is formed in late winter in the Gulf of Lions and, although this is also a process with strong interannual variability and the spreading of the newly formed deep waters is not yet well known, it has been suggested that the seasonal cycle of the replenishment of the deep basin could also cause some seasonality in the Mediterranean outflow through the Strait of Gibraltar. Therefore, we argue that it could also influence the temperature and salinity of the deep layers.

Not considering the existence of the seasonal cycle, if it exists, would influence the trend detection. It would artificially increase the noise variance and reduce the probability of detecting any trend, i.e. it would reduce the power of the test. Nevertheless, it would not introduce any bias in the trend estimation, unless there is some bias in the months when the water masses are sampled. For instance, if there is a seasonal cycle with minimum values in winter and maximum ones in summer and the first cruises of the series are biased towards winter months and the last part of the series contains a larger number of summer cruises, then it would introduce some bias in the estimated trend. A possibility of eliminating the seasonality is to average the monthly values corresponding to each year and to obtain yearly time series. In this case a new question arises: years which are not properly sampled (e.g. only summer cruises are available) would produce erroneous annual means if a seasonal cycle exists. In such a case only years when all the months have been sampled, or at least all the seasons of the year have been sampled, would be appropriate for the construction of yearly time series.

Another frequently used method is to calculate a monthly climatological seasonal cycle and subtract it from the monthly time series. A monthly series of anomalies or residuals is obtained and it can be tested against the null hypothesis of stationary mean.

The different methods already discussed can be applied directly to existing observations. In this case, in most data bases the monthly or yearly time series will have gaps.

The removal of the seasonal cycle can have a large impact on the upper layers, but the removal using a monthly climatological cycle or obtaining yearly averages should produce similar results. For intermediate and deep layers we have already pointed out that a seasonal cycle, which has not been taken into account up to the moment, could exist, but the amplitude of this cycle, if it exists, should not affect trend estimations. Calculations made without removing the cycle, removing a climatological cycle and with annual averages should also produce similar results. In summary, for both the upper and deep layers all the methods described above seem to be correct and should be consistent. On the other hand, if different results are obtained changing the data processing method, one could suspect the robustness of the results.

Finally, Table 1 shows that trends are usually calculated for different definitions of upper, intermediate and deep layers. Once again we claim that slight variations in the layer definition should not affect the results dealing with long-term changes and the opposite situation would question the reliability of the results obtained.

In order to assess how robust our knowledge is about long term changes in the westernmost part of the Mediterranean Sea, we analysed the monthly time series described in this section using six different methods of data analysis for the three areas selected (Alboran Sea, Balearic Sea and Northern Sector, see Fig. 1) and for each of the 23 depth levels.

1) We averaged monthly means corresponding to the same year. In this way we constructed yearly time series. All the years were considered independently of the number of monthly means available within each year. The 1960-1990 average was subtracted from the time series and values deviating more than 3 standard deviations from the mean were discarded. These calculations will be referred to as ***case 1***.

2) We calculated the mean value and standard deviation for each month of the year. The period considered as a reference for climatology calculations was 1960-1990. Time series were converted into anomaly time series by subtracting the climatology from the monthly time series. Values exceeding 3 standard deviations were eliminated and the climatology was recalculated. These series are supposed to be stationary for the mean except for the possible existence of long term trends. Hereafter time series and calculations using these time series will be referred to as ***case 2***.

3) We calculated a mean profile using all the monthly profiles for the period 1960-1990 and subtracted it from the monthly time series.We calculated linear trends directly from these monthly time series without considering any possible seasonal cycle. Notice that if such a cycle does not exist, results from yearly averaged time series and monthly time series should agree. Hereafter this will be considered as ***case 3***. The difference from case 1 is that in that case we used yearly averaged time series, so the seasonal cycle was filtered out, and in case 3 we use monthly time series ignoring any possible seasonal cycle.

4) For ***case 4*** we constructed yearly time series considering only those years in which all the sea-

sons of the year were sampled. We first computed seasonal means, that is, a winter mean (JFM), spring mean (AMJ), summer mean (JAS) and autumn mean (OND), and then we averaged the four seasons to obtain an annual mean. The years without data for the four seasons were considered as gaps in the final time series.

5) A more restrictive ***case 5*** was considered. We constructed yearly time series using only those years in which the twelve months of the year were sampled. Nevertheless, in this case only annual averages could be calculated from 0 to 200 dbar and from 1968 to 1989. From 300 to 400 we obtained annual averages from 1973 to 1989, and no data were available for deeper layers.

6) Finally, we considered a modification of ***case 2***. For the upper 200 dbar we calculated a monthly climatological cycle, obtaining a mean value and standard deviation for each month of the year and for the period 1960-1990. From 200 dbar to the bottom the climatological mean and standard deviation were considered constant during the twelve months of the year. In this way we finally obtained monthly time series that will be referred to hereafter as ***case 6***.

Cases 1 and 6 were repeated considering also temperature and salinity time series averaged for the upper, intermediate and deep layers. Different definitions of these layers were used. For the upper one we considered three possibilities: 0-50 dbar, 0-100 dbar and 0-200 dbar. For the intermediate layer we used four different definitions: 300-400 dbar, 150-600 dbar, 200-600 dbar and 300-500 dbar. Finally, three different definitions were used for the deep layer: 600-2500 dbar, 1000-2500 dbar and 1200-2500 dbar in the Balearic Sea and the northern sector, while in the Alboran Sea the deepest level sampled was 1400 dbar. A summary of the different data analysis methods and depth levels used to construct time series is provided in Table 2.

RESULTS

Black dots in Figure 3A show the evolution of monthly potential temperature at 100 dbar in the Alboran Sea. The grey line is the time series of yearly means (case 1) and grey triangles correspond to case 4, that is, we only considered years when data for the four seasons of the year were available. The high variance present in the upper layer is obvious. Figure 3B illustrates the subtraction of the climatological seasonal cycle (case 2), and Figure 3C shows how different criteria can produce different time series. Crosses correspond to annual averages when data for all the months have been sampled and the grey line corresponds to years when at least one datum per season of the year is available.

Figures 4 and 5 illustrate the possible discrepancies between different data analysis methods for temperature and salinity. We show the time series obtained using annual averages (case 1, black dots) in both the left and right columns of Figures 4 and 5. The mean value for the period 1960-1990 has been subtracted. In the left column (Fig. A, C, E, G and I) we include the time series of anomalies after subtraction of the climatological seasonal cycle (case 2, grey line). Once each monthly value is converted into an anomaly, we averaged all the anomalies corresponding to the same year for comparison with case 1. Figures B, D, F, H and J show again the case 1 time series, as this can

Table 2. – Definition of different data analysis methods (cases) and depth levels. The complete vertical profile is made of 23 pressure levels at 0, 10, 20, 30, 50, 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1400, 1500, 1750, 2000, 2250 and 2500 dbar. In cases 1 and 6 upper, intermediate and deep layers are defined in different ways for different sub-cases (see the text in Section 2).

case	time step/time average	seasonal cycle	data restriction	pressure level
1	Annually averaged	Filtered out by the averaging	Complete yearly time series used	23 discrete pressure levels from 0 to 2500 dbar and vertically integrated upper, intermediate and deep layer
2	Monthly averaged	Monthly seasonal cycle subtracted	Complete monthly time series used	23 discrete pressure levels from 0 to 2500 dbar
3	Monthly averaged	No seasonal cycle subtracted	Complete monthly time series used	23 discrete pressure levels from 0 to 2500 dbar
4	Annually averaged	Filtered out by the averaging	Only years when data from the 4 seasons are available	23 discrete pressure levels from 0 to 2500 dbar
5	Annually averaged	Filtered out by the averaging	Only years when data from the 12 months are available	23 discrete pressure levels from 0 to 2500 dbar
6	Monthly averaged	Monthly seasonal cycle subtracted to the upper 200 dbar	Complete monthly time series used	23 discrete pressure levels from 0 to 2500 dbar and vertically integrated upper, intermediate and deep layers

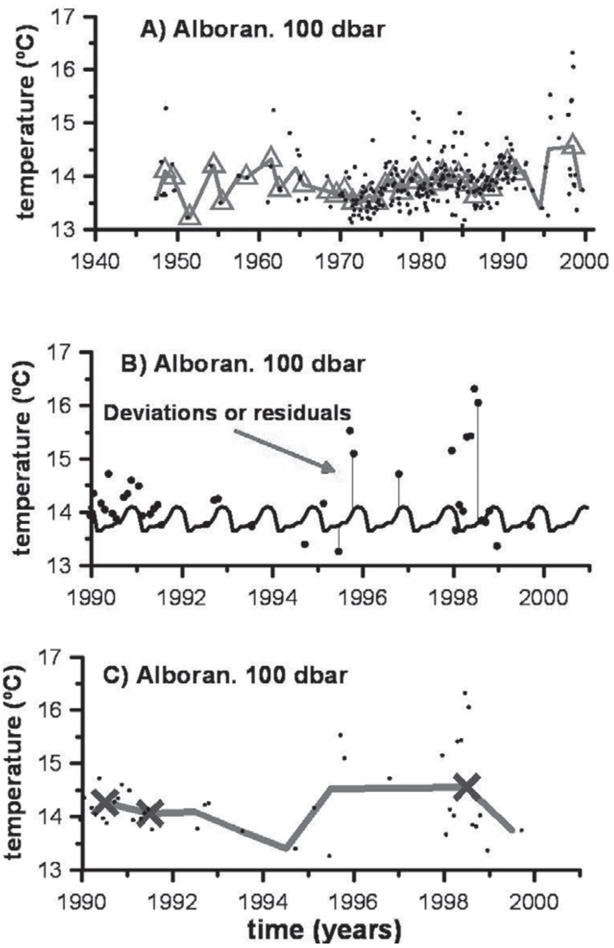

Fig. 3. – Figure 3A illustrates the large noise variance in monthly time series, especially in the upper layers (black dots). The grey line is the time series when the annual seasonal cycle has been filtered out using yearly averages, and open grey triangles show the yearly averaged time series when a restriction is imposed, in this case that valid years should contain data for at least the four seasons of the year. Figure 3B is an example of extraction of the seasonal climatological cycle. Figure 3C is a zoom of Figure 3A and shows the data point reduction when some restrictions are applied to the data validity.

be considered as the simplest one (black dots). We also include yearly mean values considering the restriction imposed in case 4 (thin line, only years when the four seasons are sampled) and case 6, in which a climatological seasonal cycle is considered for the isobaric levels above 200 dbar and a constant value is considered throughout the year from 200 dbar to the bottom (thick line).

Several questions should be considered. First of all, annual averaging of the residuals is not equivalent to annually averaging of temperature or salinity data and then subtracting a mean value for the reference period to obtain anomalies or residuals. For instance, a very large monthly anomaly can be deviated from its corresponding climatological value more than three standard deviations and discarded from the analysis. On the other hand, averaging all the temperature or salinity data within a given year can reduce the amplitude of such a large anomaly. Although it can still have an important impact on the corresponding annual value, this value could be within the accepted range of three standard deviations for the yearly time series constructed in this way. In the first case, a large anomaly does not contribute to our statistical estimations, while in the second one it does. This kind of value can have an important impact on such calculations, particularly when placed at the extremes of the time series. These concerns are important when data are scarce and time series have irregularities and gaps. Gaps or outliers in some cases, or the addition of a few data points in others, would not have any effect in time series from a systematic sampling, but they can have a large impact on series compiled from different data sources with poorly sampled periods.

A second point to note is the change in the length of the time series when some restrictions such as those in case 4 are imposed (thin lines in Figs. 4 and 5). This is something to be considered carefully when one is making trend comparisons using different data analysis methods. In this case differences can arise from both the different methodology and the different period studied.

In Figures 4 and 5 we have marked with an arrow some "suspicious" points. These points are included in the analysis as they lie within the ranges specified by the method. However, they are present or absent in the time series depending on the methodology used. We have marked those points which, from a subjective point of view, are more likely to alter trend calculations. This question is checked objectively in the following section.

Alboran Sea trends

Figures 6 and 7 show the linear trends for potential temperature and salinity in the Alboran Sea in cases 1 to 6, with the sole exception of case 5. The years with available data during the twelve months of the year were too scarce to perform any statistical analysis. Case 4 shows that considering only years with coverage of the four seasons of the year considerably reduces the length of the series as well as the depth range that can be analysed. In all the figures, solid black lines are depth-dependent linear trends.

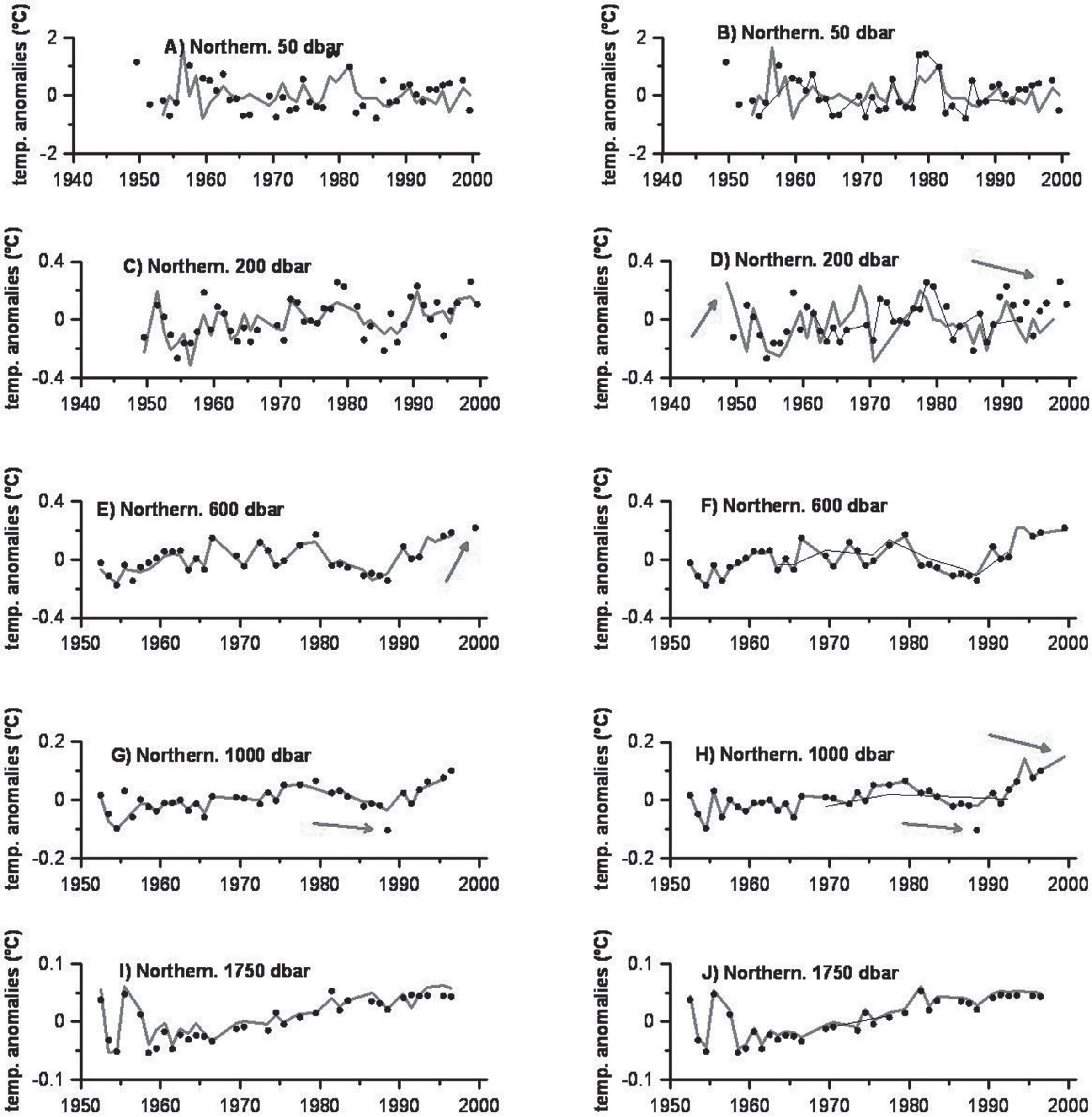

Fig. 4. – In both the left and right column we include the yearly averaged temperature after a mean value for the 1960-1990 period has been subtracted (case 1 in the text). In the left column, (Figures A, C, E, G and I), grey lines are time series of residuals or anomalies. We first get a time series of monthly anomalies by subtracting a climatological seasonal cycle (case 2) and then we obtain a yearly average of these residuals for comparison with case 1. The right column (Figures B, D, F, H and J) shows time series of residuals (grey line), which are a mixture between cases 1 and 2. A monthly climatological cycle is used for levels above 200 dbar, and a mean value for the period 1960-1990 is used from 200 dbar to the bottom (case 6). The thin black line is a series of yearly averages in which only years containing data for all the seasons of the year have been considered as valid ones. Arrows indicate data points which can induce differences in trend calculations.

Notice that important differences between different methods are observed. In case 1, significant warming trends are observed in the upper layers from 50 to 100 dbar and positive trends are detected from 200 dbar to the bottom. The warming in the upper layer is independent of the method used (Fig. 6A to E), the only difference being that in all the cases this warming corresponds to the 50-100 dbar layer, while in case 4 (Fig. 6D) it is reduced to the 50 dbar level. Figure 6D also shows different trends, but they are caused by the change in the time period analysed. When method 6 is applied to the same period of time (dash-dotted line in Fig. 6D), we obtain similar results to those corresponding to case 4. Cases 2, 3 and 6 cover the same period of time as case 1, but there are important differences. The magnitude of the trends is lower than in case 1, and they are significant only at the 600-800 dbar layer and at the

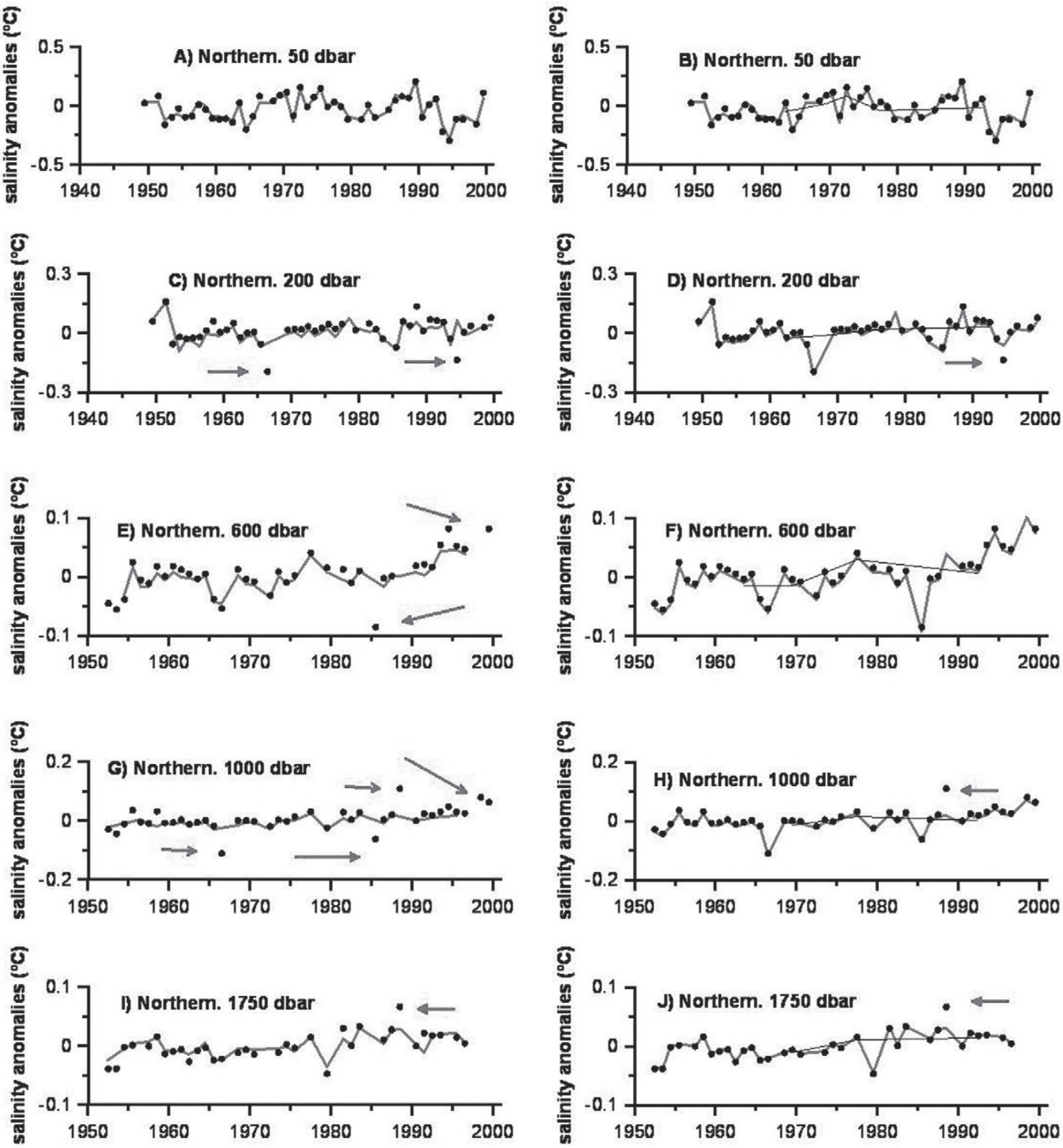

FIG. 5. – The same as in Figure 4, for the salinity in the northern sector.

bottom layer (1400 dbar), not being significant for the rest of the water column.

Trend estimations for salinity seem to be more robust. It can be established that a positive trend exists from 200 dbar to the bottom. The only difference is for case 2, with lower values, and the lack of significance for the 1200 dbar level. Notice that cases 1, 3 and 6 (Fig. 7 A, C and E) show higher salinity trends for the intermediate layer, particularly at the pressure levels occupied by the LIW (200-600 dbar).

Balearic Sea trends

Temperature and salinity trends in the Balearic Sea area are shown in Figures 8 and 9. As in the Alboran Sea area, the restriction imposed in case 4, accepting only the years in which the four seasons of the year have been sampled, introduces important differences, but they are mainly caused by the change in the available time period. This is confirmed by the similar results obtained when case 6 is applied to the same period (Fig. 8D). A common feature in all the

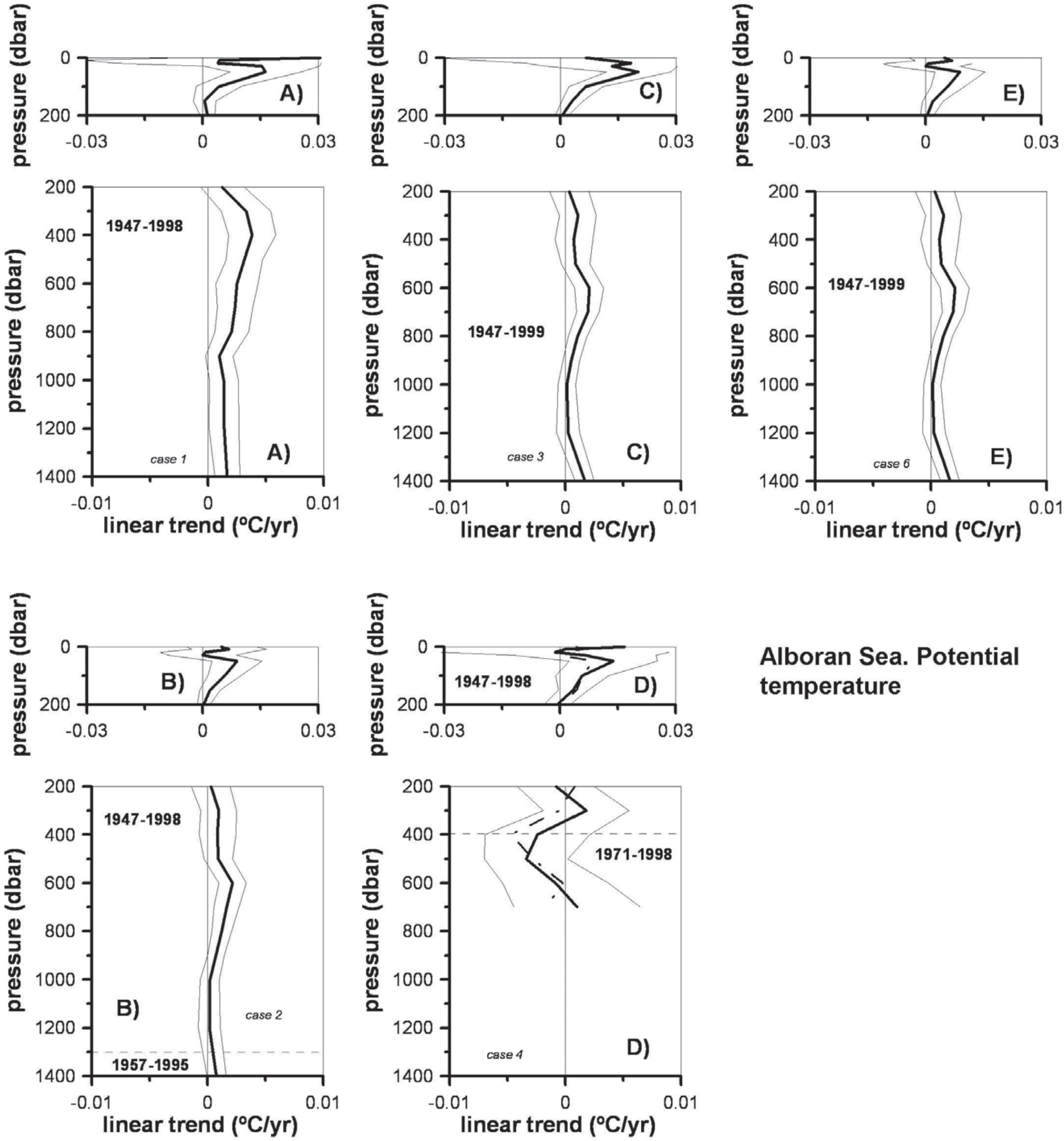

FIG. 6. – Potential temperature trends for the Alboran Sea as a function of pressure using different analysis methods. A for case 1 (see the text), B for case 2, C for case 3, D for case 4 and E for case 6. In all the figures the thick black line is the linear trend and the thin lines the 95% confidence intervals. In Figure 6D we have included case 6 (dash-dotted line) applied to the same period of time covered by case 4. Depending on the case, time series for different pressure levels have different extensions. The period analysed for the trend estimation is inserted in the plots. A dashed line indicates when there is an abrupt change in the length of the time series.

cases is the large confidence intervals in the upper 200 dbar and the lack of significance at this pressure range. Temperature trends are positive from 200 dbar to the bottom in all cases, but there are changes in the isobaric levels where these trends are significant. In cases 1, 3 and 6, warming trends are significant from 700 dbar to the bottom, while in case 2, statistical significance is found below 1000 dbar.

For salinity, results are more consistent. In case 1 there is a salinity increase from the surface to the bottom. In the upper layer it is significant from 50 to 200 dbar. For cases 2, 3 and 6, the pressure range

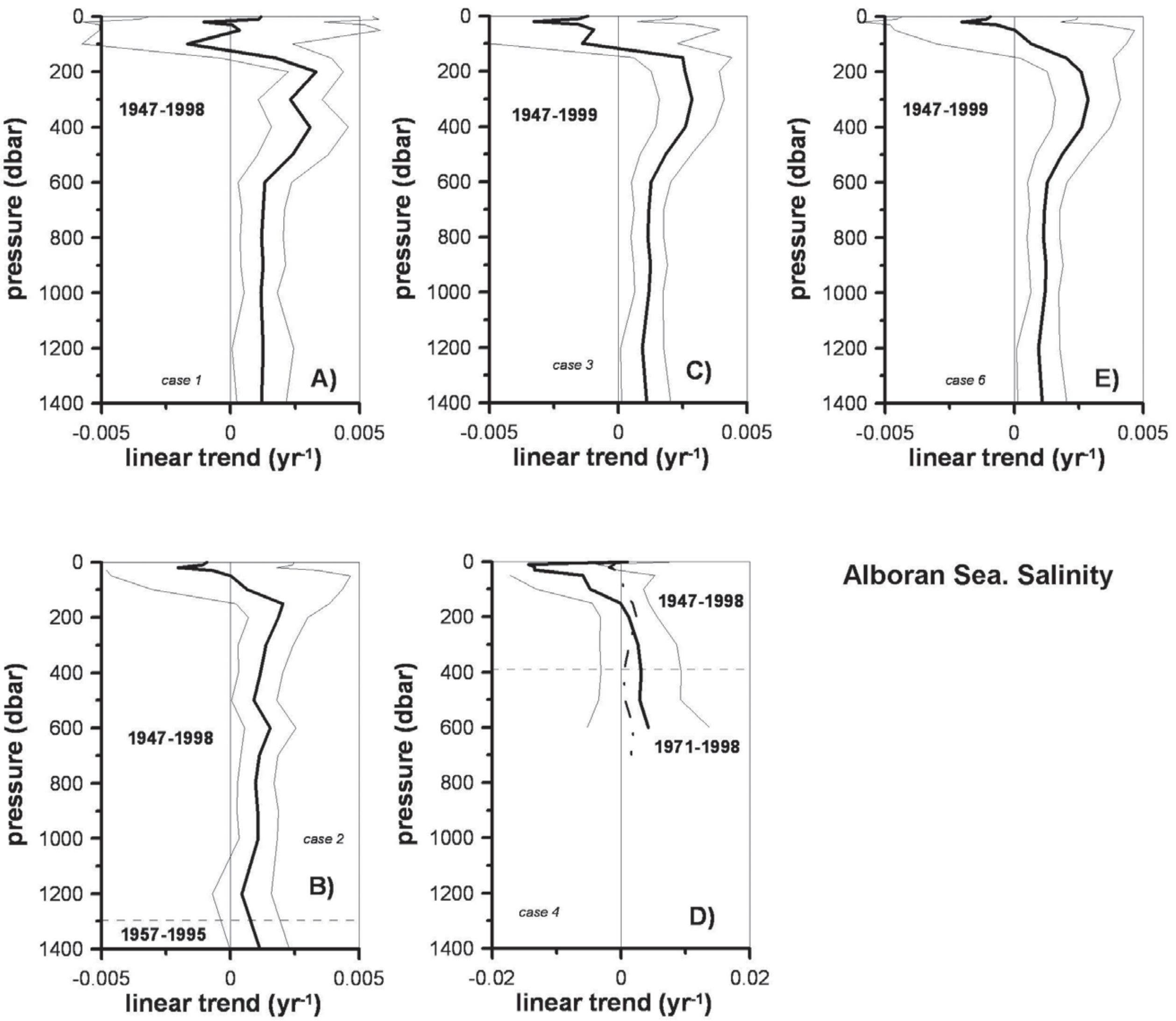

FIG. 7. – As in Figure 6, but for salinity trends in the Alboran Sea.

within the upper layer where the trends are significant is considerably reduced to a thin layer around 100 dbar. From 200 dbar to 1100 dbar the salinity trend is significant or marginally significant ($p<0.1$) in all the cases and then is positive and significant from 1200 dbar to the bottom.

Northern sector trends

Temperature and salinity trends in the northern sector are presented in Figures 10 and 11. For case 1 temperature trends are positive from the surface to 200 dbar, while in cases 2, 3 and 6 they are negative in the upper 100 dbar and positive from 100 to 200 dbar. However, trends in the uppermost 100 dbar are not significant in any of the cases, while they are positive and significant from 100 to 200 dbar in all of the cases. From 200 dbar to the bottom, temperature increased significantly. The only differences are found in the bottom layer (2500 dbar) in case 2. Another difference is the larger confidence intervals calculated in case 1, but this does not affect the magnitude of the trends and the conclusions that can be extracted from them, as they all are significant at the standard level of 95% of confidence.

Salinity trends are negative at the upper 50 dbar and positive from this level to the bottom. Different data processing methods affect the pressure level where these trends become significant. In case 1, the salinity trends are significant below 500 dbar, while in cases 2, 3 and 6 they are significant below 300 dbar.

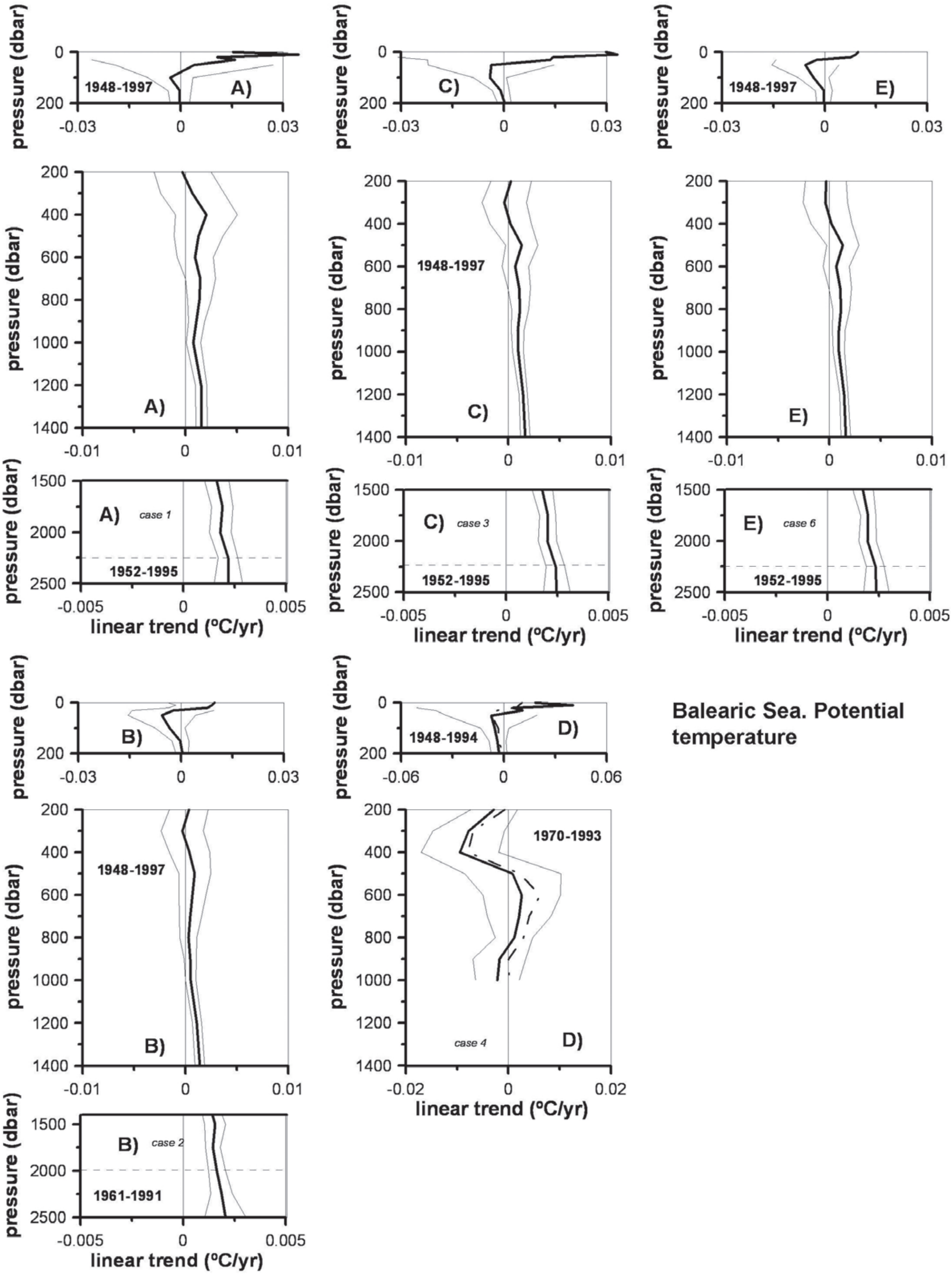

FIG. 8. – As in Figure 6, but for the Balearic Sea.

Dependence on layer definition

The above sections have shown that in some cases, depending on the data processing method, there can be differences in the sign of the trends or in their statistical significance. Instead of considering individual pressure levels, it is a frequent practice to consider the depth-averaged temperature for

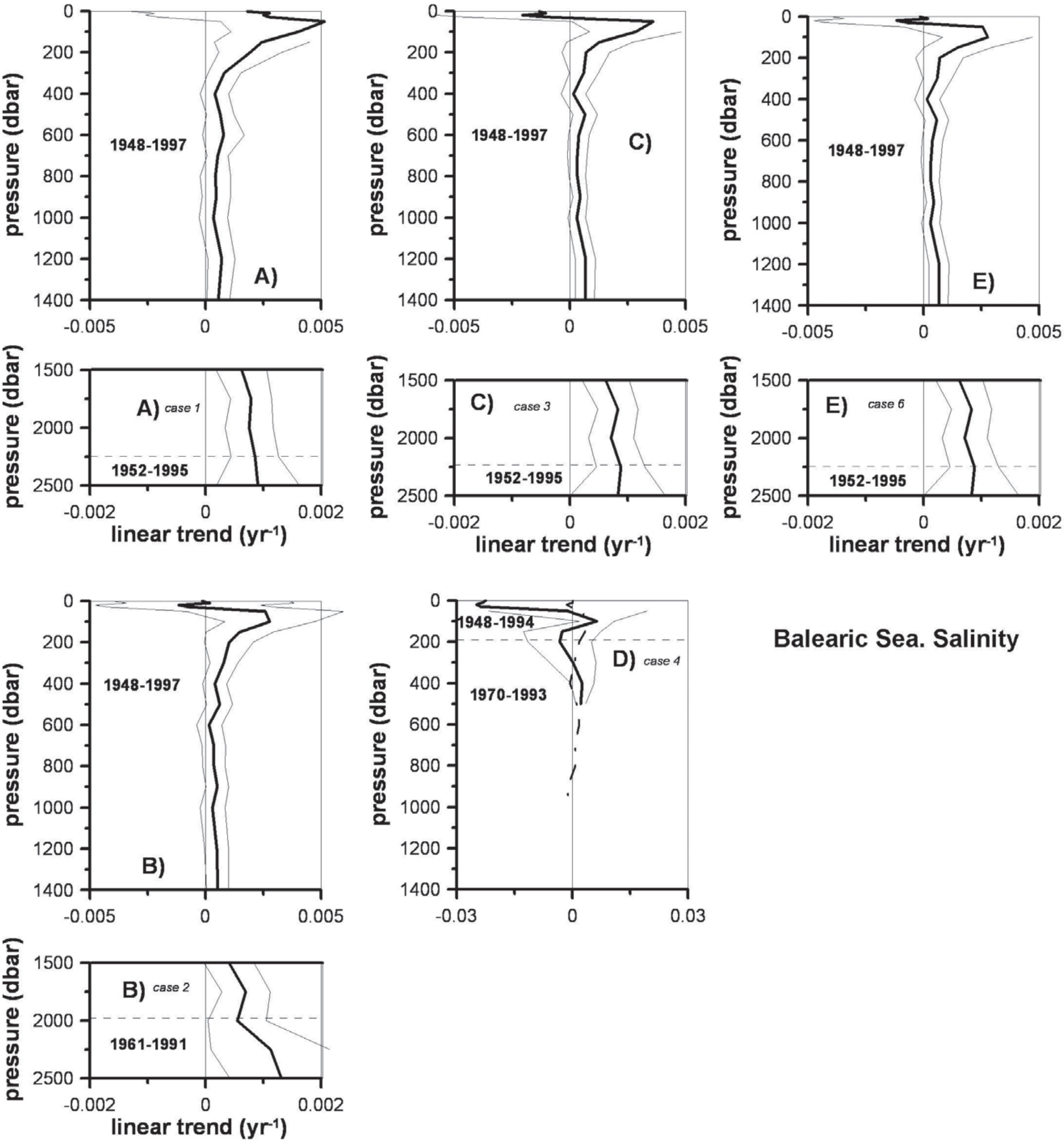

FIG. 9. – As in Figure 6, but for salinity trends in the Balearic Sea.

a certain pressure or depth range. We have shown that trends and confidence intervals change continuously and depend on the method used. Therefore, this depth dependence could also influence results depending on the layer definition.

Table 3 shows trends and 95% confidence intervals for different definitions of the upper, intermediate and deep layers. At this point it is important to note that estimating trends of depth-averaged temperatures is not equivalent to averaging trends calculated over the same pressure range. Although calculations for trend estimations are linear, calculations involved in the estimation of confidence intervals are not. More importantly, we first construct monthly time series of depth-averaged temperature and salinity time series, obtaining three time series

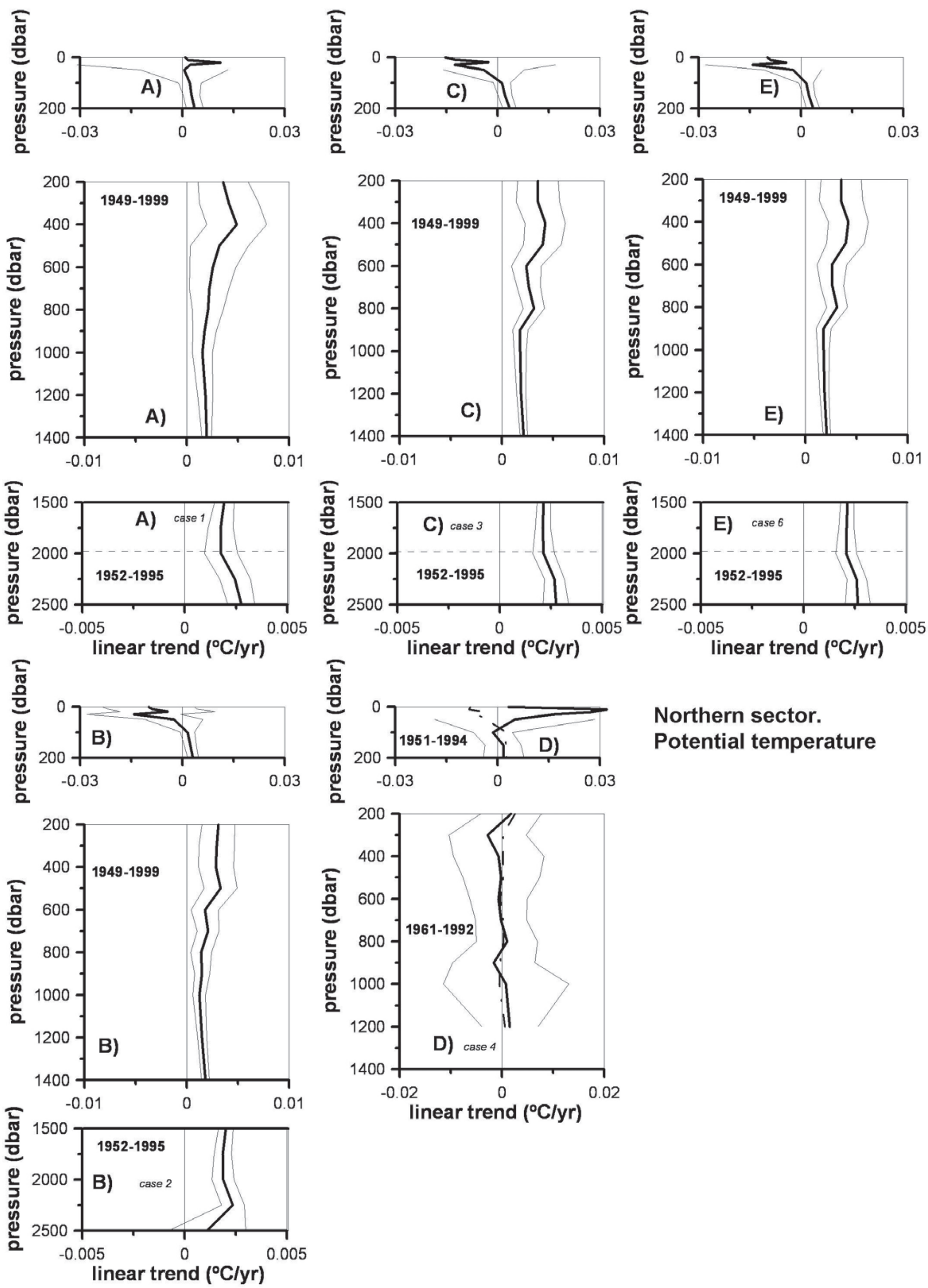

FIG. 10. – As in Figure 6, but for the Northern Sector.

for the upper, intermediate and deep layers, respectively. The depth-averaging process produces a variance reduction which can affect trend calculations, leading to extreme or abnormally high values and the rejection of outliers. In the cases presented in table 3 we have constructed time series for the upper, intermediate and deep layers from yearly-averaged potential temperature and salinity

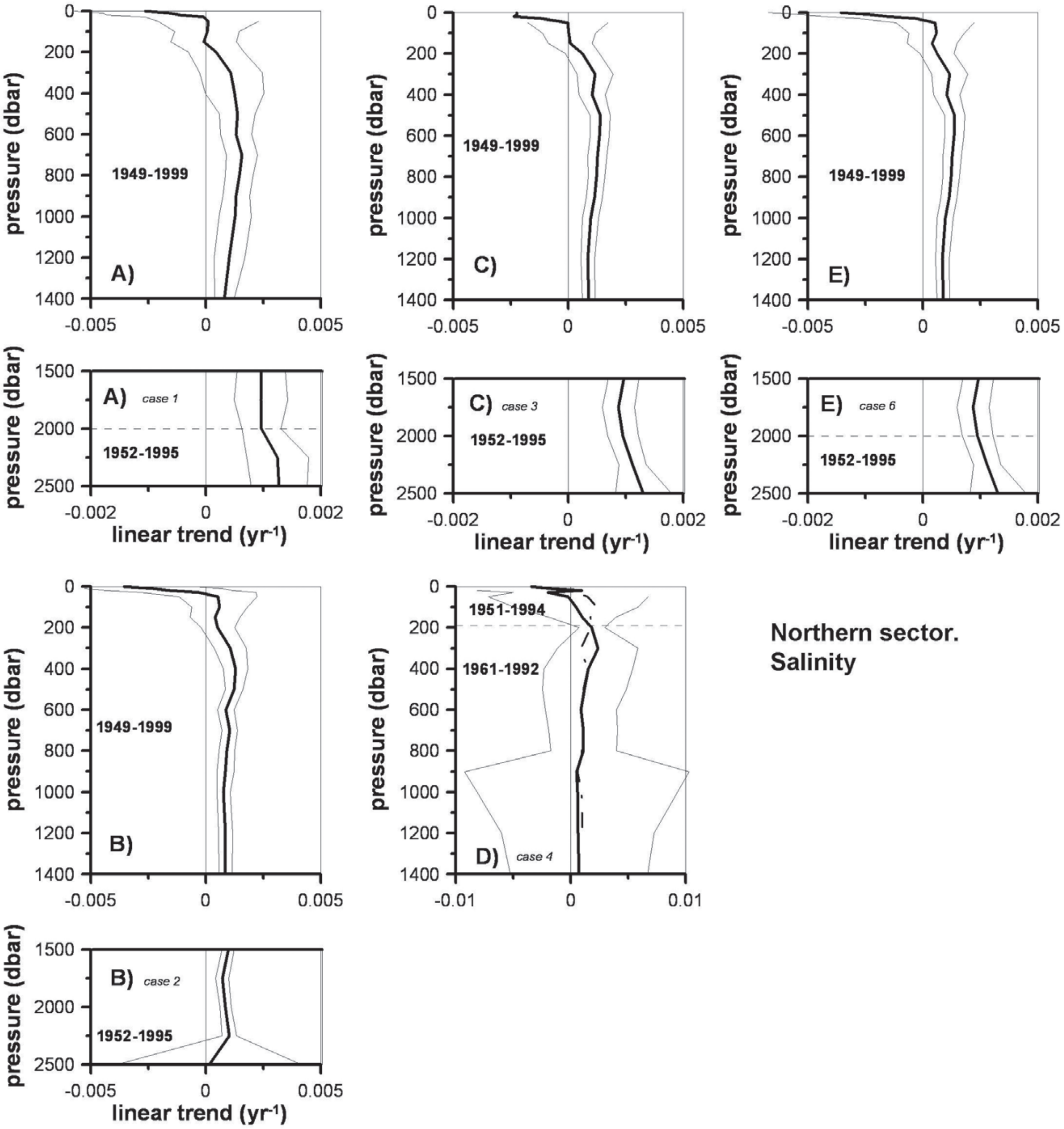

FIG. 11. – Salinity trends for the Northern Sector.

time series using the definitions shown in Table 3. All the years when at least one monthly value was available were used (case 1 applied to vertically integrated layers).

Table 3 shows clearly how different definitions of the upper, intermediate and deep layers can lead to different conclusions concerning long term trends in the WMED. Potential temperature trends in the upper layer of the Alboran Sea are not significant for the first and third definition, while they are significant for the second one, 0-100 dbar. If the 300-400 dbar or 300-500 dbar layers are considered, positive significant trends are found for the LIW in the Alboran Sea, and the same result is obtained for the layer 600 dbar-bottom. The temperature trend is only marginally significant for the 1000 dbar-bottom layer and not significant for the 1200 dbar-bottom layer. In the case of salinity, the results obtained are consistent. No significant trends are obtained in the upper layer, while salinity increased significantly in

Table 3. Linear trends and confidence intervals (95%) for potential temperature, salinity and potential density for the three geographical areas considered in this work and for different definitions of the upper, intermediate and deep layers. Figures in bold are statistically significant at the 95% confidence level and figures in bold with asterisks are marginally significant, that is, at the 90% confidence level.

		initial	final	trend ºC yr^{-1}	CI 95% ºC yr^{-1}	trend yr^{-1}	CI 95% yr^{-1}	trend kg m^{-3} yr^{-1}	CI 95% kg m^{-3} yr^{-1}
Alboran Sea									
Atlantic Water									
0	50	1947	1998	0.0143	0.0157	0.0016	0.0056	-0.0018	0.0076
0	100	1947	1998	**0.0131**	0.0100	0.0019	0.0052	-0.0012	0.0068
0	200	1947	1998	0.0040	0.0065	0.0033	0.0045	0.0013	0.0063
Intermediate Layer									
300	400	1947	1998	**0.0037**	0.0022	**0.0033**	0.0018	**0.0018**	0.0016
150	600	1947	1998	0.0016	0.0017	**0.0029**	0.0016	**0.0020**	0.0016
200	600	1947	1998	0.0015	0.0017	**0.0027**	0.0016	**0.0017**	0.0014
300	500	1947	1998	**0.0031**	0.0019	**0.0029**	0.0016	**0.0015**	0.0014
Deep Layer									
600	bottom	1948	1998	**0.0018**	0.0015	**0.0010**	0.0009	0.0006	0.0008
1000	bottom	1948	1998	**0.0014***	0.0014	**0.0011**	0.0009	0.0006	0.0007
1200	bottom	1948	1998	0.0009	0.0014	**0.0011**	0.0010	0.0005	0.0008
Balearic Sea									
Atlantic Water									
0	50	1948	1997	**0.0332**	0.0317	0.0031	0.0042	0.0010	0.0114
0	100	1948	1997	0.0201	0.0285	0.0018	0.0034	-0.0034	0.0082
0	200	1948	1996	**0.0257**	0.0231	-0.0001	0.0025	**-0.0090**	0.0071
Intermediate Layer									
300	400	1948	1997	0.0020	0.0032	**0.0005***	0.0005	0.0002	0.0005
150	600	1948	1997	0.0014	0.0026	0.0006	0.0008	0.0002	0.0009
200	600	1948	1997	0.0015	0.0026	0.0003	0.0007	0.0000	0.0007
300	500	1948	1997	0.0019	0.0028	**0.0006**	0.0005	-0.0001	0.0005
Deep Layer									
600	bottom	1948	1997	-0.0011	0.0021	**0.0008**	0.0005	0.0001	0.0005
1000	bottom	1948	1997	0.0002	0.0022	**0.0006**	0.0005	0.0002	0.0005
1200	bottom	1948	1997	0.0006	0.0021	**0.0006**	0.0005	0.0003	0.0005
Northern Sector									
Atlantic Water									
0	50	1949	1998	0.0129	0.0281	-0.0009	0.0025	0.0039	0.0096
0	100	1949	1998	0.0002	0.0203	-0.0008	0.0021	0.0016	0.0062
0	200	1949	1998	0.0005	0.0112	-0.0005	0.0015	0.0000	0.0036
Intermediate Layer									
300	400	1951	1998	**0.0046**	0.0030	0.0009	0.0018	-0.0003	0.0016
150	600	1949	1998	**0.0039**	0.0025	0.0004	0.0014	-0.0004	0.0013
200	600	1949	1998	**0.0043**	0.0026	0.0006	0.0015	-0.0004	0.0015
300	500	1951	1998	**0.0044**	0.0030	0.0009	0.0018	-0.0002	0.0017
Deep Layer									
600	bottom	1952	1998	**0.0022**	0.0015	**0.0014**	0.0006	0.0002	0.0005
1000	bottom	1952	1998	**0.0018**	0.0014	**0.0010**	0.0006	0.0002	0.0004
1200	bottom	1952	1996	**0.0020**	0.0014	**0.0008**	0.0005	0.0002	0.0004

the intermediate and deep layers, independently of the layer definition.

Other examples in which the significance of the calculated trends depends on the layer definition can be seen in the temperature of the upper layer and the salinity of the intermediate layer of the Balearic Sea.

DISCUSSION AND CONCLUSIONS

Results concerning deep layers indicate that this layer has increased its potential temperature and salinity during the 50-year period corresponding to the second half of the 20th century. Considering the results in Table 3, (case 1 applied to different definitions of upper, intermediate and deep layers), trends calculated from 600 dbar to the bottom seem to be the most consistent of all the layers analysed. Salinity increased in the three geographical areas and for the three different definitions used for this layer. Temperature increased significantly in the deep layer of both the Alboran Sea and the Northern Sector. However, the values obtained show some differences.

In order to determine the real rate at which temperature and salinity have increased, we consider the results in Table 3 and the trends which were significant at the 95% confidence level. If β denotes the linear trend and CI is the 95% confidence interval, the trends can be within the range β–CI, β+CI. If there are several significant trends for an area and layer, we consider the minimum and maximum ones and we state that the trend can be any one in the range β_{min}–CI_{min}, β_{max}+CI_{max}, where the sub-indices *min* and *max* stand for the minimum and maximum significant trends. In the case of the deep layer, this corresponds to a temperature increment for the second half of the 20th century of between 0.02 and 0.19ºC in the Northern Sector and between 0.02 and 0.17ºC in the Alboran Sea. Salinity would have increased in the range 0.02/0.1 in the Northern Sector, 0.01/0.07 in the Balearic Sea and 0.01/0.1 in the Alboran Sea.

Deep layers are supposed to integrate changes occurring in the water masses contributing to their annual formation process. Mixing with waters formed in previous years further contributes to smooth time series in this layer. A well-mixed deep layer should produce similar trends for the different geographical areas. The temperature increases presented above clearly show that this is not the case. This could simply indicate that deep waters are not well mixed throughout the WMED. Nevertheless, this explanation does not fully account for the trends observed. Significant temperature trends are detected in the Alboran Sea and the Northern Sector, but not in the Balearic Sea. Salinity trends in the Alboran Sea are higher than those in the Balearic Sea, and closer to those in the Northern Sector than those in the Balearic Sea. These differences are not consistent with the usually accepted circulation scheme for the WMDW (see Fig. 1). In the case of a non-homogeneous deep layer, the Balearic Sea should be more similar to the Northern Sector than the Alboran Sea. We hypothesise that these differences are simply caused by the scarcity of data and the great uncertainty that this factor introduces in the analysis. This hypothesis would also be supported by the different results obtained depending on the data analysis method, as presented in the results section. As explained in data set section, all the methods used seem to be correct and the only explanation for these differences is the poor spatial and temporal coverage of the available data. Taking into account these considerations, we conclude that the only thing we can assert concerning trends in the deep layers of the WMED is that it increased its temperature between 0.02 and 0.19ºC for the second half of the 20th century, while the salinity increase was between 0.01 and 0.1. It is also important to note that the 1990s were poorly sampled (Fig. 2) and deep layers seem to have undergone a warming rate acceleration after 1995 that would not be captured by MEDATLAS data (Smith and Bryden, 2007; Schröder *et al.*, 2006). This simply shows that decadal variability obscures the detection of long-term changes, evidencing the difficulty of obtaining accurate trend estimations.

The analysis of trends in the intermediate layer is important in itself, as it is indicative of changes in the ocean-atmosphere exchanges in the EMED, but it is also a key factor for understanding the changes observed in the deep layers. According to works by Bethoux *et al.* (1990, 1999), Bethoux and Gentili (1996), Rohling and Bryden (1992) and Rixen *et al.* (2005), the salinity of the LIW increased in the second half of the 20th century, this being one of the causes of the deep water salinity increase. Krahmann and Schott (1998), on the other hand, found no changes in the salinity of this water mass and concluded that the salinity increase in the deep waters was due to the salinity increase in the upper layer. Our analysis shows that the salinity of LIW increased significantly in the Alboran and Balearic Seas. In the Northern Sector salinity trends were positive for the three layer definitions, although in this case they were not significant. Once again, the data analysis method seems to be of great importance. If we consider monthly time series of depth-averaged time series (subtracting a climatological monthly seasonal cycle, not shown), we find that LIW increased its salinity significantly in the three geographical areas. For the case of yearly averaged time series (Table 3), salinity increased by between 0.06 and 0.26 in the Alboran Sea and by between 0.01 and 0.06 in the Balearic Sea during this 50-year period. The temperature of this water mass increased by between 0.06 and 0.3ºC in the Alboarn Sea and between 0.07 and 0.38ºC in the Northern Sector. In this case the LIW temperature in the Balearic Sea increased for all the layer definitions, but not significantly.

One conclusion that we can extract from our analysis is that the salinity increase in LIW, together with the salinity increase in the deep layers, is one of the most robust results in the WMED. This coincides with the time evolution of salinity reported by Rixen *et al.* (2005) for the 150-600 m layer and finally supports the hypothesis that the deep water salinity increment is—at least partially—linked to the salinity increase in LIW. LIW temperature also increased in the WMED from approximately 1950 to 2000. It is well documented that this water mass underwent a strong cooling from the late 1970s to the early 1980s in the EMED (Brankart and Pinardi, 2001). The signal of this event is clearly detected in the WMED.

According to Brankart and Pinardi, this event was initiated in 1979 and reached minimum temperature values in 1983. Low temperature values persisted at least until 1985 (see Fig. 3 in Brankart and Pinardi, 2001). Figures 4E and 4F show that, regardless of the data analysis method, this abrupt cooling is also observed in the WMED at 600 dbar. Some indications of this event are still observed at 1000 dbar (Figs. 4G and 4H), whereas none are detected at 1750 dbar (Figs. 4I and 4J). The beginning of the temperature decrease in the WMED also occurred around 1979 or 1980, indicating a fast transmission of anomalies in LIW from the eastern to the western basin, and persisted in the Northern Sector of the WMED until the late 1990s. Our interpretation is that there was a continuous warming of the LIW from 1950 to the late 1970s. This was interrupted by the anomalous event described by Brankart and Pinardi (2001) and then temperatures recovered the previous positive trend. As already stated in the introduction, these singular events can have a large impact on the trend calculations. Nevertheless, the trends estimated over periods of time much longer than the typical time scale of such events can provide an estimation of the mean long-term increment. Upper and intermediate layers undergo clear oscillations, which make it difficult to detect long-term changes. As these are the two water masses contributing to the WMDW formation (at least up to 1996, Millot *et al.*, 2006), the same kind of variability should be observed in WMDW. It is interesting to note that this time variability seems to be filtered out and smoothed in the deep layers (Fig. 4I and 4J), and this is probably the reason why deep water trends show the most robust and consistent results both in the present work and in the literature.

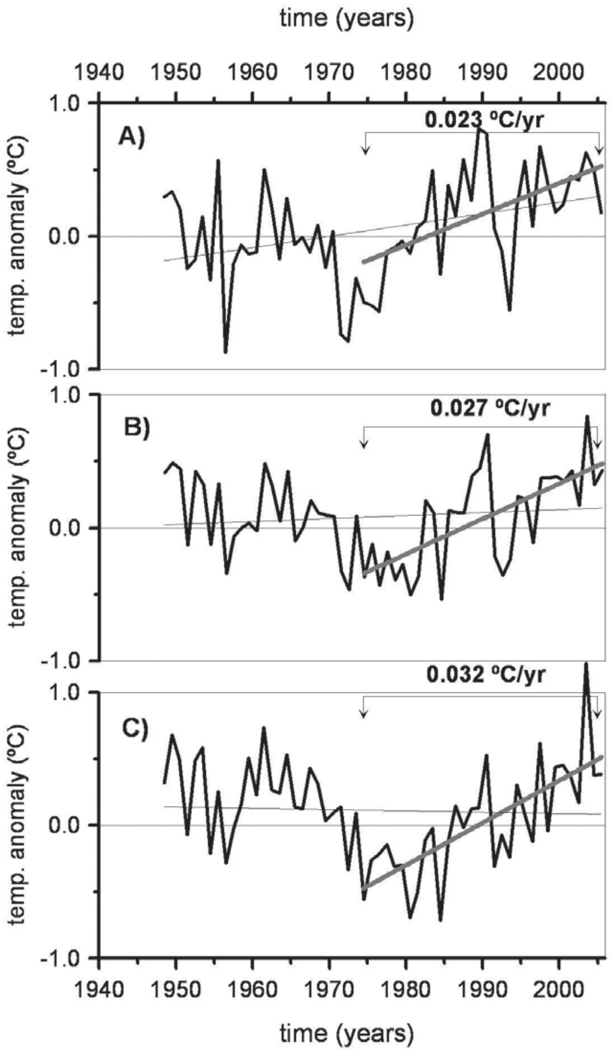

FIG. 12. – Sea surface temperature anomalies from the NCEP. A, Alboran Sea, B, Balearic Sea, and C, Northern Sector. The thick line is the linear trend for the period 1974-2005. The corresponding figure is inserted for comparison with Salat and Pascual (2002, 2006). The thin black line is the linear trend for the period 1950-2005, for comparison with Krahmann and Schott (1998).

It is clear that the upper layers, which show a continuous dependence on depth, have the largest variance and therefore the largest confidence intervals (Fig. 6 to 11), and it is difficult to detect significant trends in them. Depth-averaged temperature and salinity time series showed no significant trends for salinity in any of the three geographical areas. On the other hand, temperature increased in the upper layer of the Alboran and the Balearic Seas, at least for one definition of this layer. The temperature increase was between 0.16 and 1.16ºC in the Alboran Sea and between 0.13 and 3.25ºC in the Balearic Sea. Note that such large values do not indicate that the warming reached such high values. They only indicate the great uncertainty caused by the noise variance. Temperature did not increase in the Northern Sector, coinciding with Krahmann and Schott (1998), but contrary to Salat and Pascual (2002, 2006). In this case the explanation seems to be simply the different periods considered by these authors and the multidecadal variability contained by these time series. Figures 12 A to C show the surface temperature evolution in the same areas analysed in this study and using data from the National Centre for Environmental Prediction Reanalysis. It seems clear that from 1948 to the mid-1970s there was a cooling period with a strong negative trend. From the mid-1970s or early 1980s there was a strong positive trend. It is worth mentioning that Rixen *et al.* (2005) found that the upper layer temperature increased in the WMED from the early 1980s to 2000. Trends estimated for the surface waters from 1974 to 2000 are between 0.023 and 0.032ºC/yr (see insert in Fig. 12). It is noteworthy that these are the same values found by Salat *et al.* (2002, 2006) for the same period on the Catalan Sea continental shelf. This indicates that trends from the mid-1970s in the upper layer of the WMED are very strong, which is a very robust result. When the time series in Figure 12 are analysed in their complete extension, we also find some agreement with the results presented in this work. The negative or cooling phase from 1948 to the mid-1970s in the Alboran and Balearic Seas seems to be less intense than the warming phase. For the complete 1948-2000 series we find significant trends in these two areas, with a mean increase of 0.45 and 0.1ºC, respectively. In Northern Sector the cooling and the warming phase seem to balance each other out and no significant trends are detected for the complete period. This is in agreement with the present results from the MEDATLAS/2002 data base and with the results reported by Krahmann and Schott (1998).

In summary, there seems to have been a warming of the upper, intermediate and deep layers of the WMED from 1948 to 2000. In the upper layer the warming was not uniform over the whole period. Multidecadal variability is evident, with a cooling period from the beginning of the series to the mid-1970s and a warming after this time. The total temperature increase is likely to represent long term changes, as represented in the difference between two relative maxima. The temperature increase shows latitudinal variations ranging from zero in the Northern Sector to 0.45 and 0.1ºC in the Alboran and Balearic seas, respectively. The mid-point within this interval would be 0.23ºC. Intermediate and deep layers also increased their temperature by between 0.06 and 0.38ºC, with a mean value of 0.22ºC. Regional differences and the large range for this temperature increase seem to be linked to the scarcity of data, which makes results very sensitive to the data analysis method. The increase for deep waters is between 0.02 and 0.19ºC, with a mid-point value of 0.11ºC. Once again, the uncertainty in these values is very likely caused by the irregular time and spatial sampling. No salinity trends have been found for the upper layers, while intermediate and deep layers increased their salinity by between 0.01 and 0.26 for LIW (mean value 0.14) and by between 0.01 and 0.1 for WMDW (mean value 0.06). Our results indicate that the LIW salinity increase is the most likely cause for the deep layer salinity trend.

We finally conclude that by using one single method of analysis and using a certain depth or pressure level we could obtain narrower confidence intervals for the trend calculations and therefore an apparently more accurate estimation of warming and salting trends. Nevertheless, the differences among methods of analysis and geographical areas or depth intervals suggest that these accurate intervals are not likely to represent the true uncertainty concerning long-term changes in the WMED. Larger intervals should be considered for the moment. The analysis of long-term trends by means of numerical modelling forced by high-resolution ocean-atmospheric fluxes (Somot *et al.*, 2006; Hermann and Somot, 2008; Sotillo *et al.*, 2005), and some ongoing efforts devoted to the systematic collection of existing data sets and the high quality control of the marine data such as the project SeaDataNet (www.seadatanet.org), could help to improve the range of uncertainty of the present estimations. Nevertheless, we believe that systematic sampling programmes and longer time series are necessary to increase our knowledge of long-term changes in the Mediterranean.

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