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Recent thermohaline trends of the Atlantic waters inflowing to the Mediterranean Sea

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[1] A total of 5077 Argo float profiles in the period 01/2002-05/2010 have been used to analyze salinity and temperature trends in the Atlantic waters adjacent to the Strait of Gibraltar in order to identify the source of recent changes observed in the inflow to the Mediterranean Sea. Positive salinity trends of 0.038 ± 0.009 year^{-1} and 0.013 ± 0.003 year^{-1} have been found for the Surface Atlantic Water and the Eastern North Atlantic Central Water, respectively. For temperature, no significant trend is observed in the surface layer while positive trend of 0.05 ± 0.02 °C/year is obtained for the thermocline waters. The Mediterranean Water layer does not show any significant trend for the entire period, but a switch from positive to negative trends is observed in year 2006. In contrast to previous findings, these thermohaline variations are driven by intrinsic water masses changes, instead of isopycnal vertical displacements, probably related to an enhancement of the net freshwater losses in the area. **Citation:** Soto-Navarro, J., F. Criado-Aldeanueva, J. C. Sánchez-Garrido, and J. García-Lafuente (2012), Recent thermohaline trends of the Atlantic waters inflowing to the Mediterranean Sea, *Geophys. Res. Lett.*, *39*, L01604, doi:10.1029/2011GL049907.

1. Introduction

[2] The Mediterranean Sea is a semi-enclosed basin where the hydrologic budget, mainly dominated by the difference between evaporation (E) and precipitation (P), results in a water deficit that must be compensated by a net inflow of Atlantic Water (AW) through the Strait of Gibraltar, its only connection with the global ocean [*Bethoux and Gentili*, 1999; *Mariotti et al.*, 2002; *Criado-Aldeanueva et al.*, 2012]. Inflowing waters are mostly part of the Azores current, the southeastward flow component of the North Atlantic subtropical gyre, which flows eastward from the Atlantic ridge between 32° and 35° N [*Klein and Siedler*, 1989]. However, local features as the Iberian current, flowing poleward (southward) during winter (summer) along the Iberian continental shelf, or the Canary current, flowing southward off Morocco also contribute to the inflow [*Machín et al.*, 2006].

[3] The inflow is composed by the near surface layers of the adjacent area that comprise Surface Atlantic Water (SAW) and Eastern North Atlantic Central Water (ENACW), the latter formed by isopycnal subduction of surface waters at northern latitudes (north to 43°N). ENACW are the mode waters that constitute the permanent thermocline and are characterized by an almost linear T-S relationship. They stretch down to at least the level of minimum salinity around 35.5 (up to 36.0 at the northern and eastern Gulf of Cadiz) at about 600 m in most parts of the area [*Pollard and Pu*, 1985; *Paillet and Mercier*, 1997; *van Aken*, 2001; *Machín et al.*, 2006]. Below this level, Mediterranean Waters (MW) characterized by a salinity maximum around 36.5 [*Ambar et al.*, 2002] and formed by the Mediterranean water leaving the strait after mixing with the ENACW in the Gulf of Cadiz can be found. MW has an important role in the deep water formation at the Norwegian Sea as source of salinity that enhances the deep convection process, hence affecting the Meridional Overturning Circulation and the global climate [*Reid*, 1979; *van Aken and Beckaer*, 1996; *Sarafanov et al.*, 2008]. Further down, North Atlantic Deep Water (NADW) is observed, mainly composed by Labrador Sea Water (LSW), formed by deep convection at the Labrador Sea, although fractions of Antarctic Intermediate Water (AAIW) can also be found in the lower latitudes [*Machín et al.*, 2006; *Machín and Pelegrí*, 2009].

[4] A recent study [*Millot*, 2007] has detected from experimental data collected at the Moroccan continental shelf in the period 2003–2007 a high salinity trend (~0.05 year^{-1}) of the AW that highly exceeds the estimations for the 1990s period in the Atlantic area adjacent to the strait [*Boyer et al.*, 2005; *Polyakov et al.*, 2005]. However, analyses of the same area in more recent periods show salinity anomalies closer to this higher trend [*Hosoda et al.*, 2009; *Roemmich and Gilson*, 2009] and this implies a salinity input to the Mediterranean Sea that may influence the intermediate and deep water formation processes and, consequently, the hydrological characteristics of the MW. Two main mechanisms may drive this salinity increase: changes in the intrinsic properties of the water masses or vertical displacement of the water column that makes saltier waters from the surface sink to deeper layers, or vice-versa [*Bindoff and McDougall*, 1994]. Here we show that the high salinity trends recorded in the Strait of Gibraltar for the AW can also be found in the adjacent area of the North Atlantic and, in contrast to previous findings, are more likely related to changes in the water masses properties.

2. Data and Methods

[5] The area of study, covering from 28°N to 42°N in latitude and from 5°W to 24°W in longitude, has been divided into three zones (Figure 1a) to separate out the influence of the different North Atlantic circulation features in the inflowing waters through the Strait of Gibraltar. The northernmost one (zone 1 hereinafter) catches the main pathways of the MW [*Bower et al.*, 2002; *Sarafanov et al.*, 2008] and

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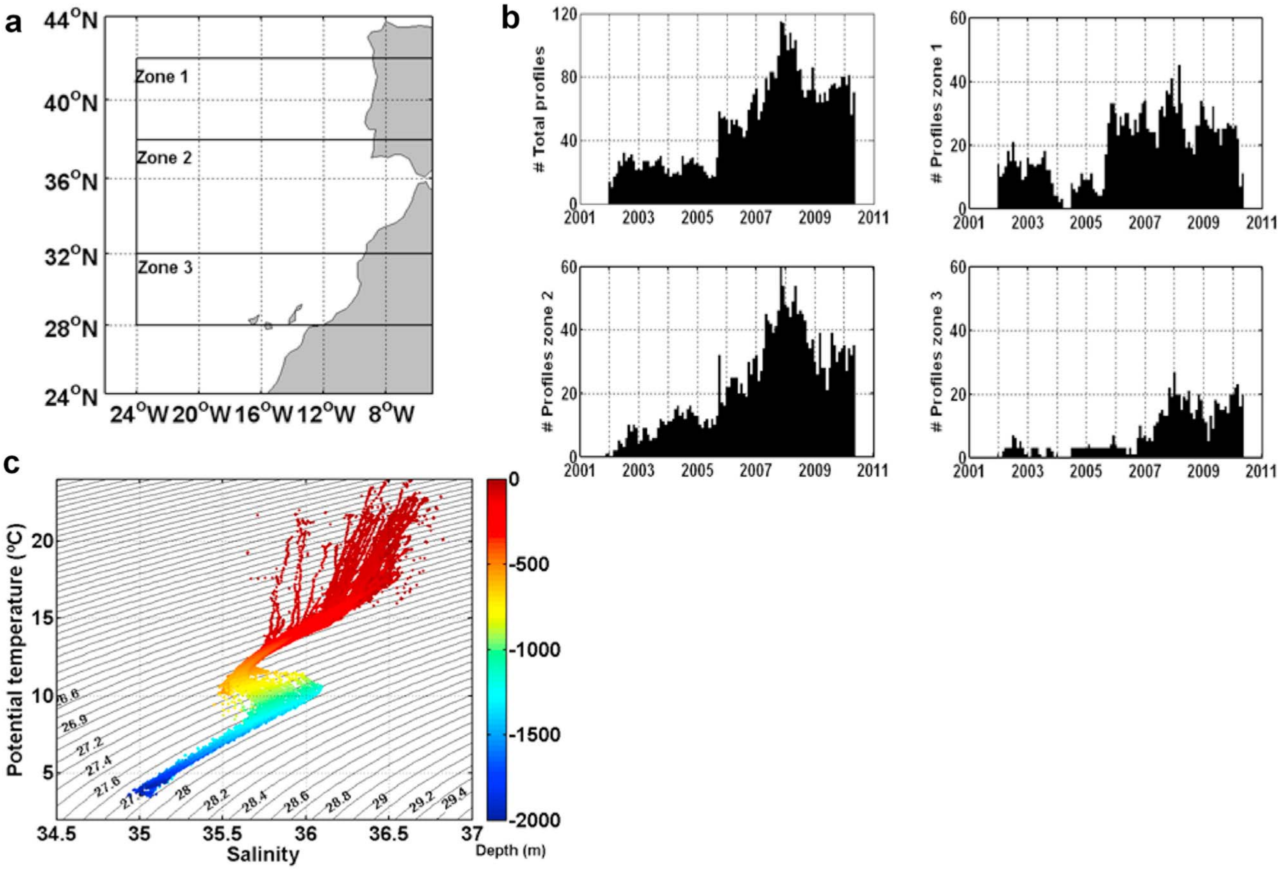

Figure 1. Area of study, Argo profile distribution and T-S diagram. (a) Selected area of study and different subzones considered. (b) Monthly distribution of the Argo profiles for the (top left) complete area and for (top right) zone 1, (bottom left) zone 2, and (bottom right) zone 3. (c) T-S diagram of the monthly averaged profiles for the complete area. The colours represent the depth in which each T-S point is found.

the Iberian current. The central area (zone 2 hereinafter) covers the Azores Current and the southern zone (zone 3 hereinafter) covers the Canary Current [*Pollard and Pu*, 1985; *Paillet and Mercier*, 1997; *van Aken*, 2001; *Machín et al.*, 2006]. A total of 5997 ARGO salinity and temperature profiles are available at the Argo data selection web site (http://www.argodatamgt.org/) for the area from 2002 to May 2010. 15% of the profiles have been neglected because they had less than ten values or were shallower than 500 m (the Argo floats cycle provides profiles from the surface to 2000 m approximately in the North Atlantic). All standard corrections detailed in the Argo Data User's Manual have been applied. Moreover, data exceeding the mean profile more than three standard deviations have also been erased. Once the selection has been made, a total of 5077 profiles covering the area of study were separated by zones and monthly distributed (Figure 1b). The profiles were then vertically interpolated in 22 pressure levels (0 10 20 30 50 100 150 200 300 400 500 600 700 800 900 1000 1100 1200 1400 1500 1750 and 2000 dbar) and monthly averaged.

[6] In view of the monthly averaged T-S diagram of Figure 1c, three main water masses will be properly analyzed: SAW in the first 100 m (although not strictly a proper water mass since its thermohaline properties have sources and sinks due to air-sea interactions, we will refer to it as representative of the surface layer [*Criado-Aldeanueva et al.*, 2006]), ENACW occupying the main thermocline from 100 to 600 m and MW extending from 600 to 1200 m. Although MW is found at shallower depths in the Gulf of Cadiz area, where it flows close to the continental shelf of the Iberian Peninsula between 400–600 m [*Ambar et al.*, 2002], this area is very poorly sampled by the Argo floats and does not reflect in the T-S diagram. The deepest 800 m correspond to the upper layer of the NADW, which is not completely sampled and will not be analyzed in this work. Vertically averaged time series of salinity and temperature for the first three layers were constructed and least-square fitted to compute their linear trends. 95% confidence intervals of this computation were estimated with a t-student test.

[7] For comparison purposes, two additional datasets were used: i) a total of 108 CTD profiles from the French Laboratory d'Océanographie de Villefranche Dyfamed project (www.obs-vlfr.fr/sodyf/), collected at (43.25°N, 7.52°E) and covering the period 2001–2009 were analyzed in a similar procedure than for the Argo data, although in this case the trend was calculated only for the surface layer (0–150 [*Rixen et al.*, 2005]), which corresponds to the Atlantic Water (AW) spreading through the Mediterranean Sea; ii) MW salinity and temperature were analyzed from the time series collected at Espartel sill, western Strait of Gibraltar (35°51.70′N,

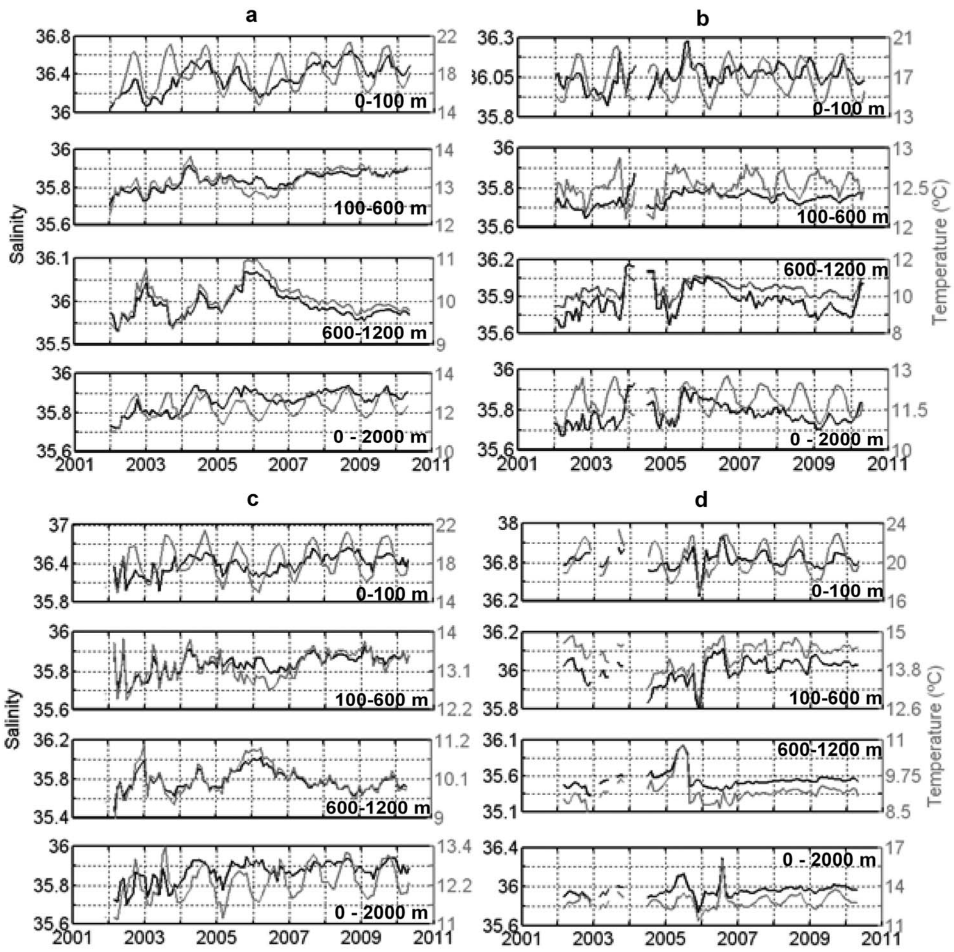

Figure 2. Time series of the monthly averaged salinity (black) and temperature (grey). (a) Complete area, (b) zone 1, (c) zone 2, and (d) zone 3. For each zone the layers corresponding to the main water masses considered are shown: SAW (0–100 m) in the top graph of the panel, ENACW layer (100–600 m) in the second graph of the panel, MW layer (600–1200 m) in the third graph of the panel and the entire profile in the fourth graph of the panel.

5°58.60′W), in the frame of the INGRES projects, at a mean depth of 356 m from October 2004 to February 2010.

[8] The nature of the water properties changes at a given depth can be associated with two main different mechanisms. On one hand, modifications in the intrinsic properties of the water mass along isopycnal surfaces occupying that depth caused by mixing or horizontal advection. On the other hand, vertical displacements of the water column that make water masses of different densities reach deeper or shallower depths without changing their intrinsic properties; this is known as isopycnal heave. It is possible to separate out the influence of these two mechanisms applying a simple decomposition equation [*Bindoff and McDougall*, 1994].

$$\left.\frac{d\xi}{dt}\right|_p = \left.\frac{d\xi}{dt}\right|_n - \left.\frac{dp}{dt}\right|_n \left(\frac{\partial \xi}{\partial p}\right) \qquad (1)$$

The left hand side term of equation (1) represents the time variation at isobaric surfaces of a scalar property, in our case potential temperature and salinity. The first term of the right hand side represents the time variation of the property along isopycnal surfaces, due to either intrinsic changes in the water mass properties or horizontal advection. The second term of the right hand side accounts for changes at a particular pressure level produced by the vertical displacement of the isopycnal surfaces.

3. Results and Discussion

3.1. Estimated Thermohaline Trends

[9] The time series for the different zones and layers are represented in Figure 2 and the fitting results are summarized in Table 1. Whereas no significant temperature trends are observed in the surface layer, clear positive salinity trends are estimated in the complete area, 0.038 ± 0.009 year^{-1}, and also for zones 1 and 2, of 0.010 ± 0.005 year^{-1} and 0.04 ± 0.01 year^{-1} respectively. These values are higher than those obtained for the 90s [*Boyer et al.*, 2005; *Polyakov et al.*, 2005], where positive but smaller anomalies were found. However, recent studies show an increase in the salinity and temperature anomalies of the SAW in the last decade closer to our findings [*Hosoda et al.*, 2009; *Roemmich and Gilson*, 2009] and measurements in the AW reaching the Mediterranean [*Millot*, 2007] provide a salinity trend of 0.05 year^{-1} for the period 2003–2007, a value very close to our result for the complete area of study and even more to that of zone 2, which corresponds to the path of the Azores Current.

Table 1. Estimated Linear Trends for the Complete Area and for the Zones Considered[a]

	Complete Area		Zone 1		Zone 2		Zone 3	
	S Trend (year^{-1})	T Trend (°C/year)	S Trend (year^{-1})	T Trend (°C/year)	S Trend (year^{-1})	T Trend (°C/year)	S Trend (year^{-1})	T Trend (°C/year)
0–100 m	0.038 ± 0.009	n.s.	0.010 ± 0.005	n.s.	0.04 ± 0.01	n.s.	n.s.	n.s.
100–600 m	0.013 ± 0.003	0.05 ± 0.02	0.005 ± 0.003	0.02 ± 0.01	0.013 ± 0.004	0.06 ± 0.03	0.010 ± 0.005	n.s.
00–1200 m	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
0–Bottom	0.014 ± 0.003	0.05 ± 0.04	n.s,	n.s.	0.015 ± 0.004	0.07 ± 0.04	0.007 ± 0.006	n.s.

[a] Each row corresponds to the different water masses analyzed: SAW layer (0–100 m), ENACW layer (100–600 m), MW layer (600–1200 m) and the entire profile. The 95% confidence intervals have been computed by a *t*-student test where *n.s.* means that the fitting is not significant.

[10] In the ENACW layer, positive trends are observed both for salinity (with values ranging 0.005–0.013 year^{-1}) and temperature, about 0.05 °C/year (Table 1). These results are also higher than those historically observed in this layer [*Boyer et al.*, 2005; *Polyakov et al.*, 2005], but are in good agreement with more recent estimations [*Leadbetter et al.*, 2007; *Benítez-Barrios et al.*, 2008]. Numerical studies also predict a high intensification of the salinity anomalies for the upper 500 m of the North Atlantic in the first half of 21st century [*Stott et al.*, 2008]. For the MW, even though the computed trends for the entire period are not significant, their values are of the same order than those estimated from time series at the monitoring station of Espartel sill, the last gateway of Mediterranean waters towards the Atlantic. A positive trend of 0.0017 ± 0.0003 °C/year is observed for temperature and a negative trend of −0.0022 ± 0.0003 year^{-1} for salinity in the period October 2004–February 2010 at this location (Figure 3a). However, it is worth to mention two different periods for this layer in the whole area and zones 1 and 2: first significant positive trends from 2002 to 2006, with common values of 0.06 ± 0.02 year^{-1} and 0.2 ± 0.1 °C/year for salinity and temperature respectively, and a switch to negative trends from then onwards, with values around −0.05 ± 0.02 year^{-1} for salinity and −0.2 ± 0.04 °C/year for temperature. The positive trend continues that of the previous period 1992–2002 in the intermediate waters of the subpolar North Atlantic, where values of 0.0088 ± 0.0026 year^{-1} for salinity and 0.049 ± 0.010 °C/year for temperature at 53°N were found and attributed to a combination of MW salinification and a low North Atlantic Oscillation (NAO) phase [*Sarafanov et al.*, 2008].

[11] To further investigate the influence of these results in the evolution of the thermohaline properties of the first 150 m along the Mediterranean basin, salinity and temperature time series from the Dyfamed station corresponding to the AW layer (the first 150 m) are represented in Figure 3b, where a positive trend of 0.016 ± 0.008 year^{-1} can be observed for salinity (no significant trend is found for temperature). Even though this trend is smaller than our estimation for the inflowing waters, it must be taken into account that the cyclonic circulation of the Mediterranean Sea makes the AW reaching the Ligurian Sea differ from the AW entering the Mediterranean [*Millot*, 1999]. However, this result is one order of magnitude higher than the previous estimation for the last decade of the 20th century from the MEDAR-MEDATLAS dataset [*Rixen et al.*, 2005; *Vargas-Yáñez et al.*, 2010].

3.2. Mechanisms Controlling Changes

[12] The decomposition results of equation (1), displayed in Figure 4, reveal that the observed trends are strongly related to changes along isopycnal surfaces (blue), while the vertical displacements (green) have a secondary role. For the complete area and zone 2 (Figures 4a and 4c), which exhibit similar patterns, the influence of the former mechanism is clearer, with a monotonic decrease from 0.03 year^{-1} for salinity and 0.12 °C/year for temperature at 50 m to almost zero at 800 m (the shallower 50 m are not

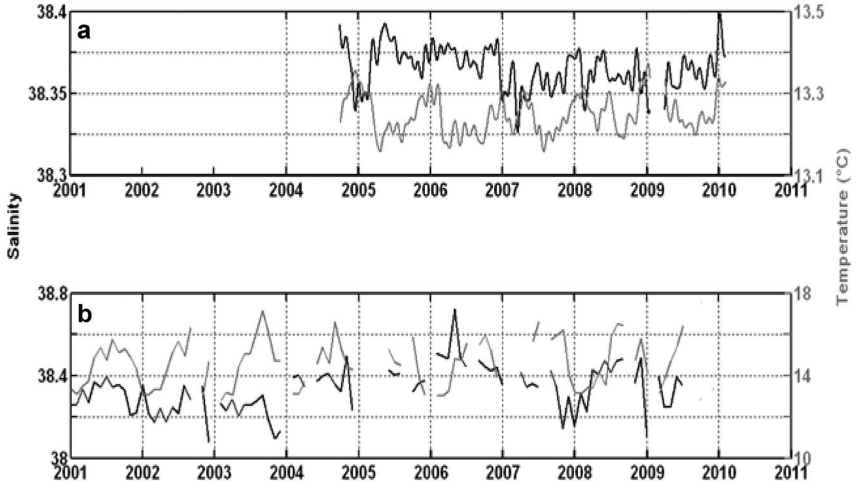

Figure 3. Time series of salinity and temperature (a) from the permanent station of Espartel sill and (b) from the Dyfamed station.

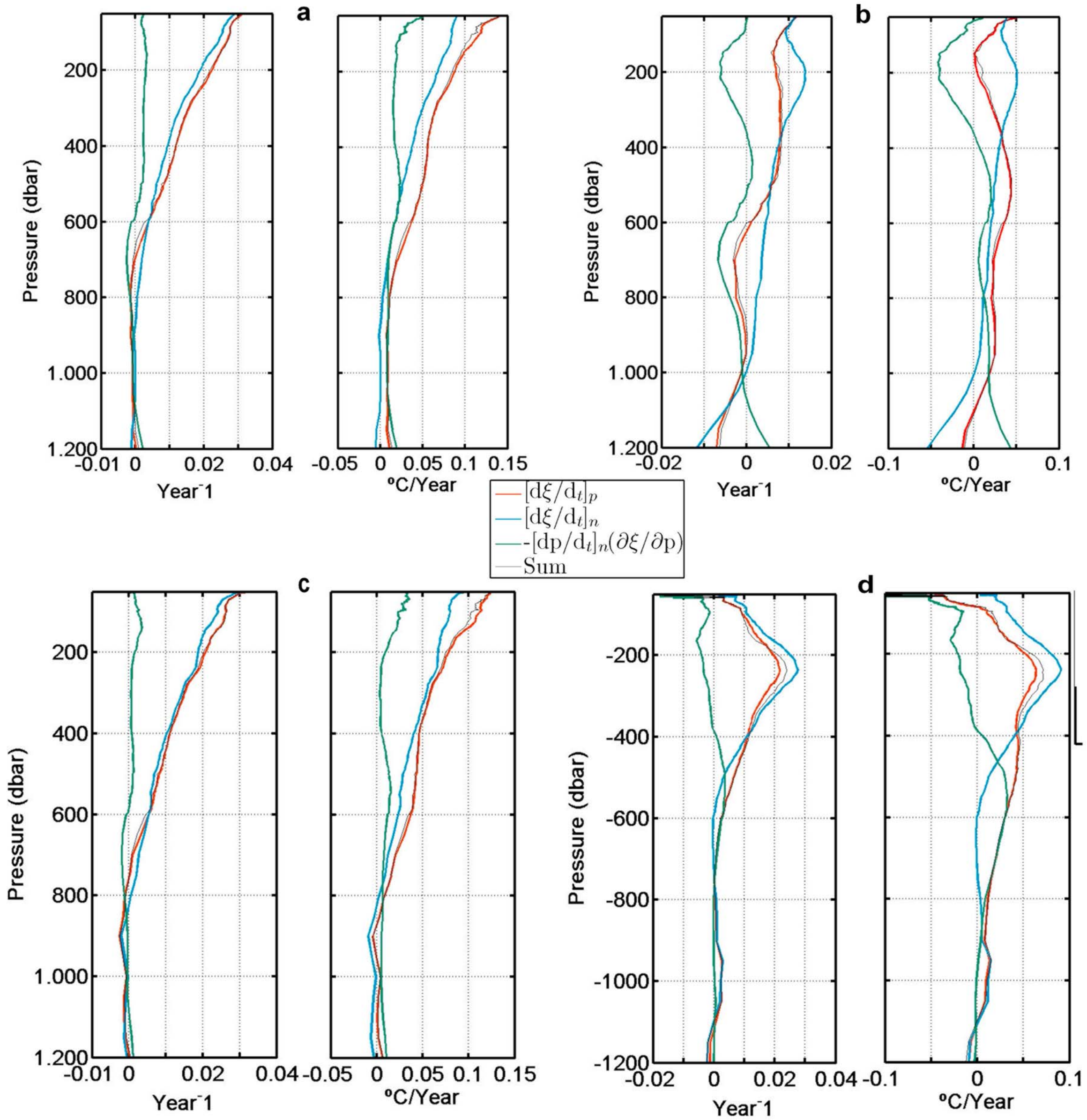

Figure 4. Results of the equation (1) decomposition for salinity and temperature. (a) Complete area, (b) zone 1, (c) zone 2, and (d) zone 3. On each panel the red line represents the trend along isobaric surfaces, the blue line the contribution of changes along isopycnal surfaces and the green line the contribution of the vertical displacements. The grey line is the sum of these two latter contributions. The left graph of each panel represents salinity trends and the right graph temperature trends.

considered because equation (1) does not apply in the strong near-surface gradients [*Arbic and Owens*, 2001]). In a previous study from CTD data collected at the 36°N section, lower temperature trends were obtained for the period 1981–2005 [*Leadbetter et al.*, 2007]. But the main contrast with the present work is the mechanism responsible of the trend, which in that case was the isopycnal displacement. Even taking into account the differences between the sampled areas, the authors estimated a negative sign (opposite to our results) for the isopycnal changes term in the first 800 m, which means an important change in the thermocline water characteristics of this area in the last years.

[13] For zone 1 (Figure 4b) the isopycnal heave is more important; in the first 400 m it has negative sign that, for temperature, compensates the positive intrinsic changes making the total trend zero at 200 m. For salinity, the weakening of the isopycnal changes term below 600 m makes the heave responsible for the negative sign of the trend in the MW layer. In zone 3 (Figure 4d) the highest trend is not found at the surface but at about 250 m, and is again caused by changes in the neutral surfaces, with negative contribution of the isopycnal displacements in the shallower 400 m, more important for temperature. From this depth, the heaving term becomes positive while the intrinsic changes term tends to zero, this leading to a small positive trend in the deeper layer for temperature. As for zone 2, studies referred to earlier periods found lower trends in this area [*Vargas-Yáñez et al.*, 2004; *Cunningham and Alderson*, 2007; *Benítez-Barrios*

et al., 2008] with the isopycnal displacement mechanism controlling the process, especially in the ENACW layer.

[14] The results described above emphasize that the observed trends in the SAW and in the ENACW filling the permanent thermocline, the main components of the Atlantic inflow to the Mediterranean, are the result of an intrinsic warming and salinification process. The existence of a salinity minimum in the bottom of the thermocline (Figure 1c) discards the mixing with the Mediterranean water as the source of salinity for the upper layers. The most likely hypothesis for the salinity increase is an enhancement of the freshwater evaporative losses in the surface layer that increases the salinity in both SAW and ENACW by subduction processes. For the complete area, the necessary trend in the net evaporation (E-P) to match the obtained salinity trend is about 10 cm/year, a value similar to previous estimations for the 90s, which can be a consequence of an intensification of the trade winds related to a high NAO index state [*Curry et al.*, 2003].

4. Conclusions

[15] We have found that the historically observed salinity (and, in a lesser extent, temperature) trends of the Atlantic inflow in the Strait of Gibraltar correspond to a similar salinification/warming in the first 600 m of the surrounding Atlantic waters. The highest salinity trends are found in the surface layer of the Azores current area (0.04 year^{-1}), although positive values are also found northward and southward. Lower but positive values are computed in the main thermocline (around 0.01 years^{-1}), which in all cases exceed previous estimations. But the main novelty presented here is that, in contrast to other studies for earlier periods, trends are mainly related to intrinsic changes in the water masses instead of isopycnal displacements. The changes in the water masses properties are probably linked to a recent increase in the net evaporation that may affect salinity in the surface layer and also in the main thermocline by subduction and advection processes.

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