Diagnosing thermohaline trends of the Atlantic Inflow from ARGO data

J. Soto-Navarro, J. C. Sánchez-Garrido, F. Criado-Aldeanueva, J. García-Lafuente, C. Naranjo-Rosa, A. Sánchez-Román, E. Bruque, C. Calero, J. Delgado, and J. M. Vargas

Physical Oceanography Group. University of Malaga. Spain (**javiersoto@uma.es**)

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BACKGROUND

The Atlantic inflow through the Strait of Gibraltar is composed by Surface Atlantic Water (SAW) and Eastern North Atlantic Central Water (ENACW). The latter is formed by isopycnal subduction of surface waters at northern latitudes (north to 43°N) and corresponds to the modal water of the permanent thermocline that is incorporated to the Azores Current, the main water source to the strait area (van Aken, 2001) . A recent study (Millot, 2007) has detected a high salinity trend (~0.05 year^{-1}) of the AW from experimental data collected at the Moroccan continental shelf in the period 2003-2007. This value highly exceeds the estimations for the 1990s period in the Atlantic area close to the strait (Poliakov et al., 2005; Boyer et al., 2005). The trend can be consequence of changes in the intrinsic properties of the water masses or vertical displacement of the water column that makes saltier water from the surface sink to deeper layers (Bindorf and McDougall, 1994).

In order to identify the source of these recent changes we have used eight years of salinity and temperature data from ARGO drifters to estimate termohaline trends for different layers of the North Atlantic water in the area adjacent to the strait.

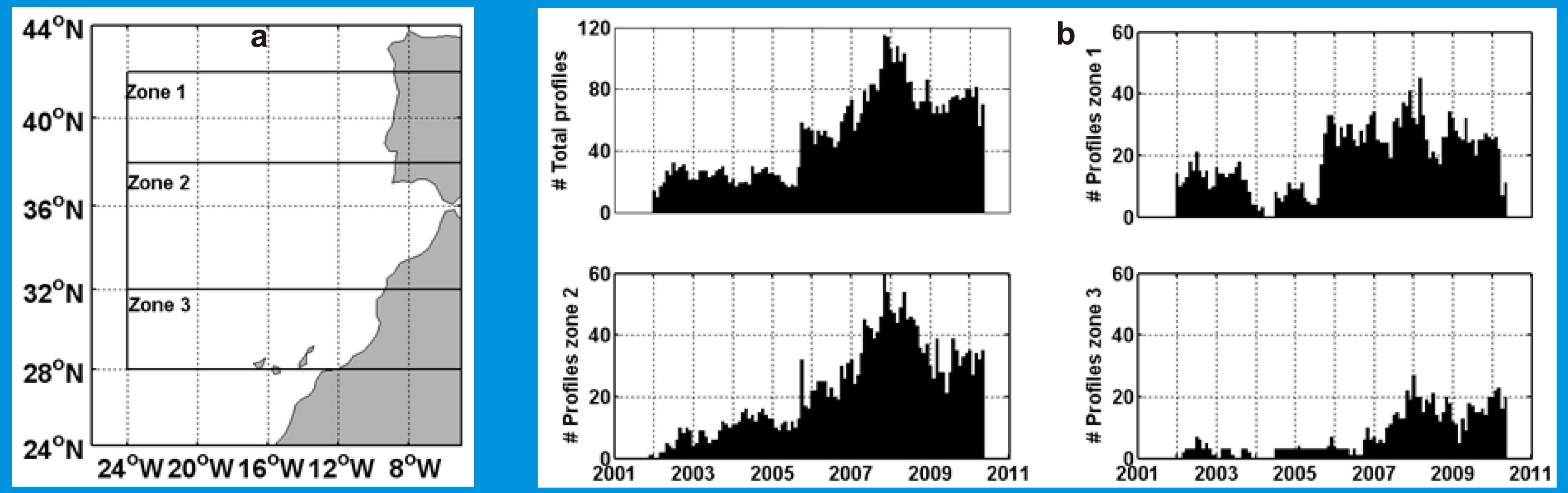

FIGURE 1. a) Selected area of study. It has been divided into zones to separate out the influence of different North Atlantic circulation features in the inflowing waters through the Strait. Zone 1 catches the main pathway of the outflowing Mediterranean waters, zone 2 characterizes the Azores Current and zone 3 the Canary Current. **b)** Number of ARGO profiles per month for the different zones considered.

ARGO DATA ANALYSIS

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 were 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). Data exceeding the mean profile more than three standard deviations were also erased. Once the selection was made a total of 5077 profiles covering the studied area were separated by zones and monthly distributed. This distribution is represented in figure 2. 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 dB) and monthly averaged.

According to figure 2, four different vertically distributed water masses can be found: Surface Atlantic Waters in the first 100 m, Eastern North Atlantic Central Water (ENACW) from 100 to 600 m, Mediterranean Outflowing Water (MOW) from 600 to 1200 m and North Atlantic Deep Water from 1200 to 2000 m, approximately. Taking into account this distribution four vertically averaged time series of salinity and temperature, one for each of the first three layers and another one for the complete profiles, were obtained for the different zones (the deeper layer has not been studied since the profiles do not measure it completely). These time series were least-square fitted to compute their linear trends and the 95% confident intervals of this computation were estimated with a t-student test

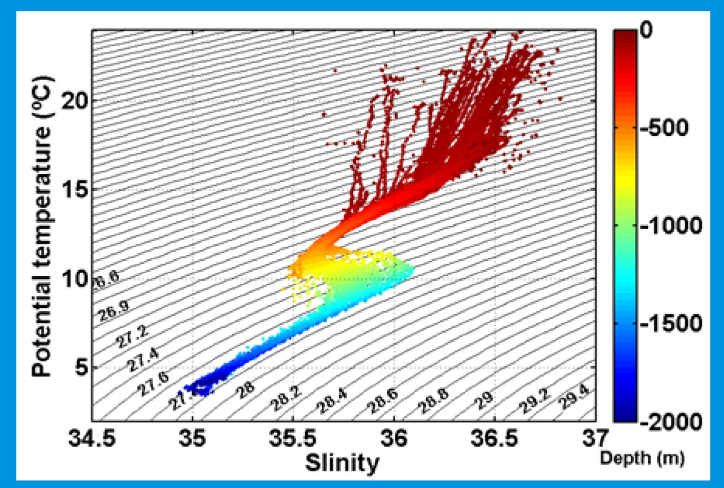

FIGURE 2. T-S diagram for the monthly averaged profiles of the complete studied area. The colours represent the depth in which each T-S point is found.

THERMOHALINE TRENDS

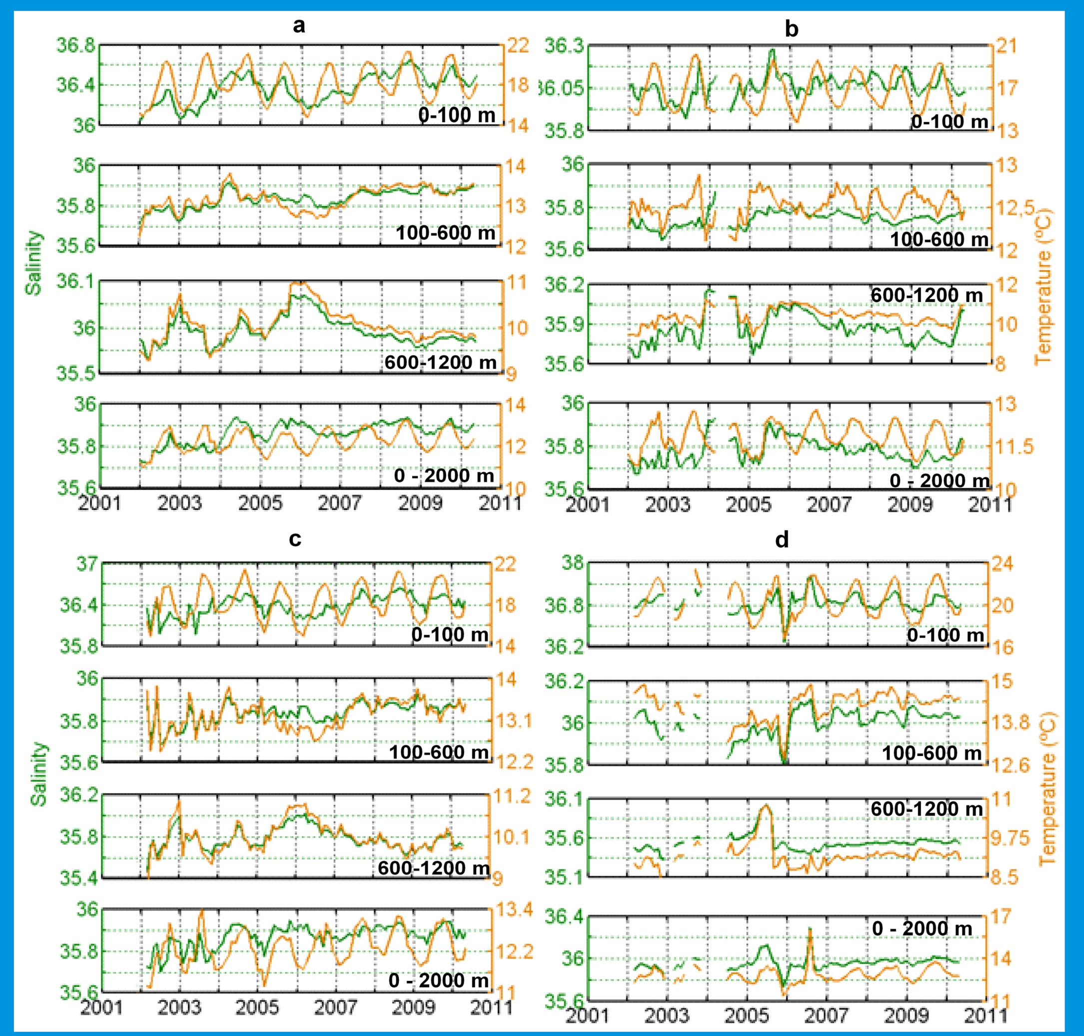

FIGURE 3. Time series of the monthly averaged salinity (green) and temperature (orange) for the complete area of study (panel a), and for the zones 1 (panel b), 2 (panel c) and 3 (panel d). For each zone the layers corresponding to the main water masses considered are shown: Surface Atlantic Water (0-100 m) in the top graph of the panel, NACW layer (100-600 m) in the second graph of the panel, MOW layer (600-1200 m) in the third graph of the panel and from 0 to 2000m in the fourth graph of the panel.

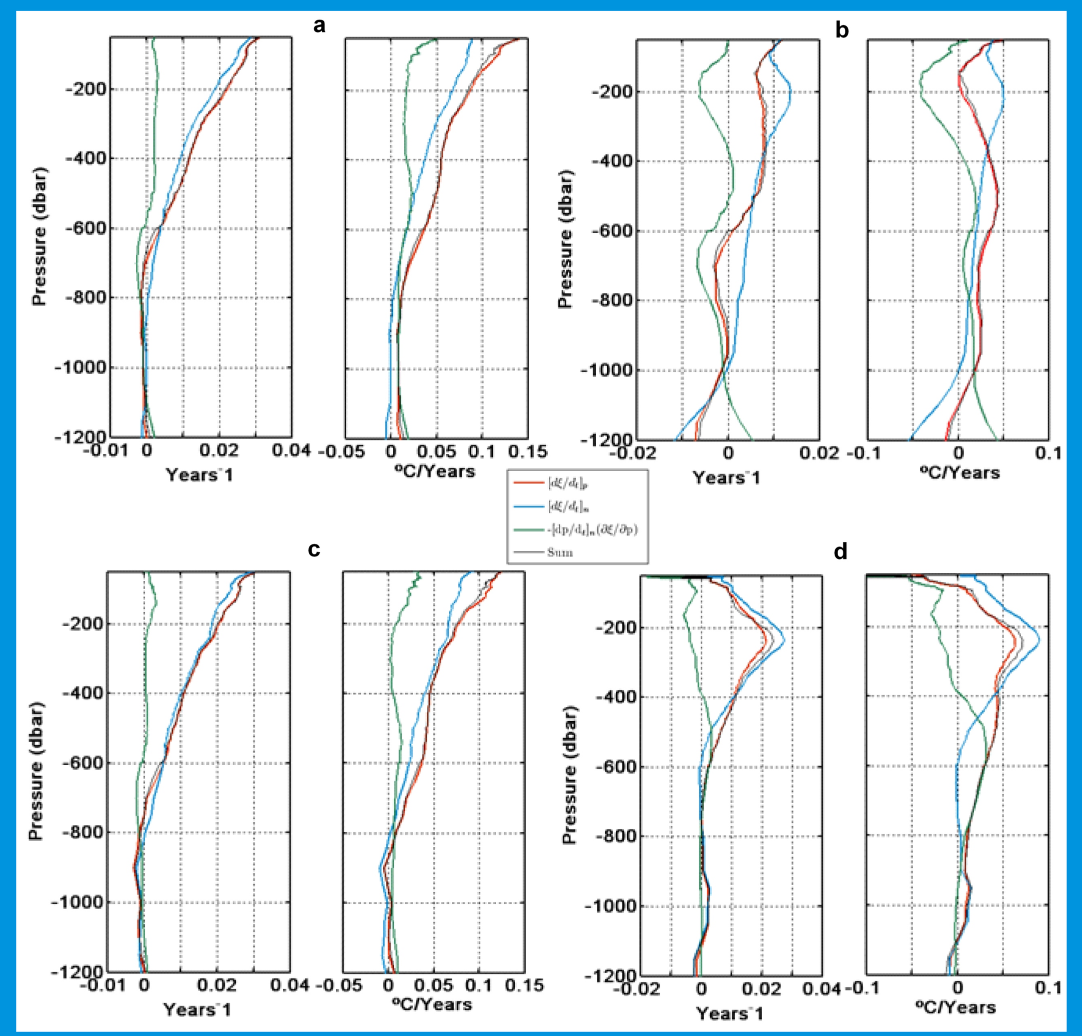

FIGURE 4. Decomposition of the salinity (left graph of each panel) and temperature (right graph of each panel) trends. Red line represents changes at constant depth, blue line changes at isopycnal surfaces and green line changes due to neutral surfaces displacement. Panels a), b), c) and d) correspond to the complete area and zones 1 to 3 respectively.

	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 ± 0.03	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.
600 – 1200 m	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
0 – 2000 m	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.

Table 1. Estimated linear trends for the complete area of study and for the different considered zones. Each row corresponds to the different water masses considered: SAW (0-100 m), ENACW layer (100-600 m), MOW (600-1200 m) and 0-2000 m. The trends have been obtained by least square fitting the monthly averaged time series of the ARGO profile for each zone. The 95% confidence intervals have been computed by a t-Student test. n.s. stands when the fitting is not significant.

MECHANISMS CONTROLLING CHANGES

The model proposed by Bindoff and McDougall (1994) was applied to separate out the contribution of the two main mechanisms that could explain the observed trends.

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

The left hand side term of Eq. 1 represents the time variation at isobaric surfaces of a scalar magnitude, in our case potential temperature and salinity. The first term of the right hand side represents the time variation of the magnitude 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. The results of the decomposition are showed in figure 4.

CONCLUSIONS

- High positive salinity trends are observed in the surface layer, especially in zone 2 (0.04±0.01year^{-1}), where the results match with the obtained by Millot (2007) at the Moroccan continental shelf.

- The ENACW layer, corresponding to the main thermocline, also shows positive trends, for both temperature and salinity. The obtained values exceed the previous estimation in the area by Poliakov et al. (2005) and Boyer et al. (2005).

- The MOW layer does not show any significant trend neither in salinity or temperature. This is in good agreement with the observation at the monitoring station of Espartel sill, western Strait of Gibraltar, where very low trends are computed in the time series of salinity and temperature for the Mediterranean outflow (-0.0022±0.0003 year^{-1} and 0.0017±0.0003 °C/year respectively, not shown).

- In the time series corresponding to the upper 150 m of the Dyfamed station, at the Ligurian Sea (not shown), a positive trend of 0.010±0.008 years^{-1} is found for salinity (no significant trend is found for temperature). This value is smaller but of the same order than our estimation for the inflowing waters. On the other hand, this result is one order of magnitude higher than the previous estimation of Rixen et al. (2005) and Vargas-Yáñez et al. (2010) for the last decade of the 20th.

- The observed trends are mainly related to changes along isopycnal surfaces, while the vertical displacements of the isopycnals have a secondary role, except in zone 1 where its influence is noticeable in the first 400 m. This means that the inflow salinification is more likely related to changes in the intrinsic properties of the water masses caused by advection.

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