

ARGO floats vs. ship-based CTDs: an overall metrological comparison in the whole Mediterranean Sea

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Abstract – The widespread network of temperature/salinity profiling floats, known as Argo, has nowadays become a fundamental component of the ocean observing system. Since Argo floats usually are not recovered and should last up to five years without any re-calibration, their onboard sensors can reasonably suffer some drift and/or offset. During the years, very refined methods have been developed and implemented to post-process the Argo data, in order to correct the response of their profiling CTD (Conductivity – Temperature – Depth) sensors, in particular adjusting the salinity drift. The core of this delayed-mode quality control is the comparison of Argo data with reference climatology. At the same time, it's still considered metrologically fundamental the experimental comparison of Argo profiles with quasi-collocated in space and quasi-simultaneous in time ship-based CTD profiles. In this paper an overall comparison of Argo floats vs. shipboard CTDs was made, in terms of temperature and salinity profiles in the whole Mediterranean Sea and under strict space-time matching conditions.

I. INTRODUCTION

Argo profiling floats (Argo in the following) mainly measure temperature (t) and salinity (S_p , practical salinity) of World Oceans from an array of more than 3000 underwater robots. They drift and are carried by currents at a parking depth of about 1000 m; then, usually at intervals of 5, 8 or 10 days, they go down to a depth of about 2000 m before rising to the surface. During the ascent, t and S_p values are recorded: at the surface, pairs at selected values are transmitted back to the Thematic centres via satellites. Finally, they return to parking depth to start next measuring cycle [1].

Nominal accuracies of CTD probes mounted on Argo floats (model SBE 41/41CP), resulting from on-bench calibration, are actually comparable to accuracies of onboard CTDs [1]. Temperature measures in the Argo CTD profiles are declared to be accurate to ± 0.002 °C,

while pressure ones are accurate to ± 2.4 dbar [2]. For what concerns salinity measures, it has to be considered that the conductivity cell is more sensitive to possible drift and/or offset (due for example to fouling that accumulates over the years, varying the dimension of the cell itself). Therefore, S_p data delivered in real time are declared to be accurate to ± 0.01 PSU [2]. However, in a second stage, salinity measures are post-processed and corrected by expert examination, comparing Argo data vs. historical data (mainly acquired by older Argo floats or ship-based CTD data) used to estimate the background climatological salinity. Salinity data are in this way post-validated (or adjusted) following a method known as Delayed Mode Quality Control [3,4,5]. This refined method is anyway tightly connected to high quality ship-based CTD measures, to which Argo profile should be compared in order to maintain in a reasonable way the necessary metrological traceability [6,7,8].

Aim of the present work is to show and discuss main results obtained from comparing (adjusted and not-adjusted) Argo profiles vs. ship-based CTD profiles, mated under strict space and time matching conditions, not so common in literature on a so large scale [9]. The comparison was performed starting from 2000 (when Argo deployments began) and taking into account the whole Mediterranean Sea, where the overall coordination of profiling float operations is in charge of MedArgo program (together with Argo data control and distribution) [10,11,12,13].

II. DATA AND METHODS

Both Argo and CTD profiles were downloaded from WOD (World Ocean Database [14], release WOD18-March 2019), according to the following searching criteria:

- Year: from 2000 to 2018 (all months and days)
- Longitude range: from 6°W to 36°E
- Latitude range: from 30°N to 44.5°N
- Measured variables: t , S_p
- Dataset: CTD, PFL (Argo Profiling Floats).

As a result, a number of 60838 total casts was obtained by WOD, divided as follows:

- no. 5664 CTD casts
- no. 55174 Argo casts.

Each cast was then checked in order to filter data according to both the available quality flags, i.e. those supplied by WOD itself and those by the data Originator, respectively [15,16]. As a consequence, for each CTD cast, only data flagged by WOD with flag “0” were selected: this check was performed for the entire cast (where “0” means “accepted cast”) and for the individual observations of depth, temperature and salinity (where “0” means “accepted value”). At the same time, applying the method of a logical AND, Argo casts flagged by the Originator with flag “1” (that means “good data”) and by WOD with flag “0” were selected for the comparison.

After collecting these two datasets, following the indications for the first Rossby radius of deformation indicated in [17], Argo and CTD profiles were matched under the following 3D space-time conditions:

- Δ Latitude: $\pm 0.10^\circ$
- Δ Longitude: $\pm 0.15^\circ$
- Δ depth for each temperature and salinity values in the matched profiles: ± 1 m
- Δ time: ± 1 day.

By adding the requirement that each couple of Argo and CTD profiles satisfying the previous conditions has in common at least ten values matched along the entire profile, the dataset was at last restricted to:

- Longitude range: from 3.097°E to 32.720°E
- Latitude range: from 33.563°N to 43.533°N
- Time period: from the 2nd of April 2006 to the 6th of June 2018
- no. of profiles matched (Argo vs. CTD): 360
- no. of Argo individual profiles: 96
- no. of (ship-based) CTD individual profiles: 135 (for each profile, the CTD type is declared as “unknown” in the WOD database)
- no. of Argo floats involved: 47 (whose subdivision into models is reported in Table 1).

In the box chart reported in Fig. 1, the actual distances in space and time between Argo and CTD profiles are reported: it can be noted that about 75% of matched profiles were separated by less than 12 km in space (mean 7.5 km) and about 24 h in time (mean 16.6 h).

Taking also into account the relatively high number of matching profiles, these can be considered as reasonably strict space-time matching conditions, if compared with those reported in literature: e.g. five Argo-CTD matched profile were considered in [18], where distance varies

from 3.0 km to about 17.4 km (mean 8.2 km) and separation in time spans from 26.9 h to 41.9 h (mean 35 h). In other works, the space-time limits are taken as 100 km and 10 days [19] (for 38 matched profiles) or six days [20] (but for more than 500 matchups).

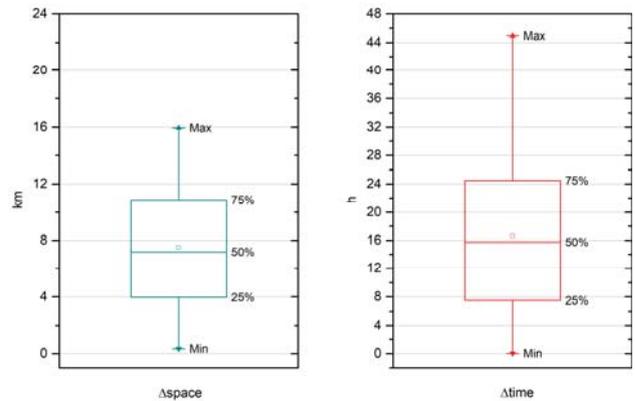


Fig. 1. Distances in space (left) and time (right) between collected Argo and CTD profiles.

In the map in Fig. 2, the distribution in space and time of involved Argo floats is reported.

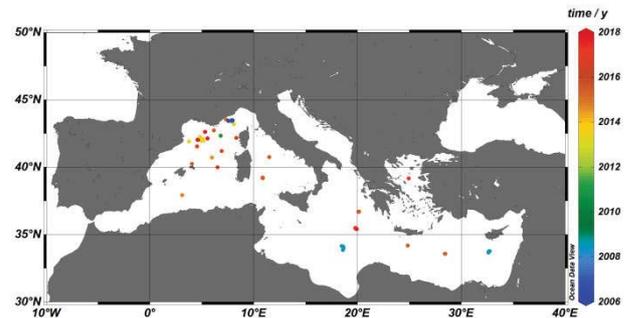


Fig.2. Positions of considered Argo floats, per year, in the Mediterranean Sea.

In Table 1, Argo models involved in this comparison are listed and counted (for more details, see [21]).

Table 1. Argo different models considered.

Argo model	# PFL	Argo model	# PFL
APEX	1	PROVOR	7
ARVOR	5	PROVOR CTS2	2
ARVOR A3	1	PROVOR CTS31-DO	2
ARVOR DO	2	PROVOR CTS3-DO	3
ARVOR-I	2	PROVOR-II	1
ARVOR-N	3	PROVOR-III	18

III. RESULTS

The matched Argo vs. CTD profiles resulted subdivided as follows:

- no. of matches with not-adjusted Argo profiles: 199 (with a total number of matched points equal to 40571, for both t and S_p values)
- no. of matches with adjusted Argo profiles: 161 (with a total number of matched points equal to 10455, for both t and S_p values).

It should be specified here that, as literally reported in [15], the adjustment is a real value (i.e. decimal number) and is the mean difference between original (real-time) and adjusted (delayed-mode) profile of pressure, temperature or salinity for all values below 500 m depth. If a profile has an adjustment value, even if this value is 0.0, it indicates that the profile has gone through additional quality control by the Argo project and is considered either adjusted real-time or delayed-mode data. It has to be underlined that only in 75 pairs of matched profiles (of 161 with adjusted Argo values) an adjustment different from zero was reported: adjustments were applied only to salinity, with negative values ranging from -0.0018 to -0.031 PSU.

In the following diagrams, an overview of Argo (adjusted and not-adjusted) and matched CTD profiles, together with main results obtained from the comparison, is reported.

Profiles of both t and S_p versus depth (d) were first plotted for all the Argo-CTD matched profiles, in order to have an overall indication of the space-time variability of the thermohaline properties in the area (all Mediterranean Sea) and period of interest (about 12 years): diagrams are shown in Fig. 3 and Fig. 4, respectively.

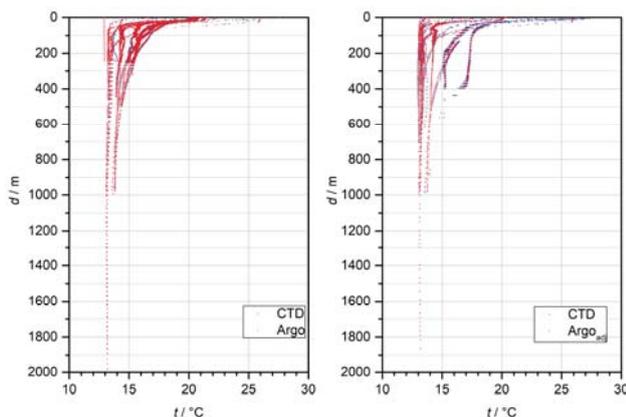


Fig.3. Overall Argo (red dots: not-adjusted, left, and adjusted, right) and CTD (blue dots) matched temperature profiles.

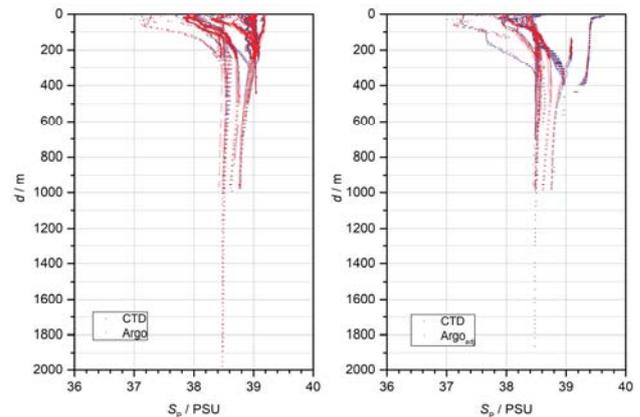


Fig.4. Overall Argo (red dots: not-adjusted, left, and adjusted, right) and CTD (blue dots) matched salinity profiles.

Values of t and S_p from the surface to 100 m depth are comprised substantially in the range of 13-28 °C and 37-39 PSU, respectively. At greater depths, i.e. below 500 m, values converge in the interval 13.00-14.50 °C and 38.43-38.98 PSU, respectively.

All the paired values Argo vs CTD in the matched profiles were then analyzed through histograms (with associated means and standard deviations, indicated by s.d.) of t and S_p differences: results are reported in Fig. 5 and Fig. 6, respectively, taking into account all data in the water column.

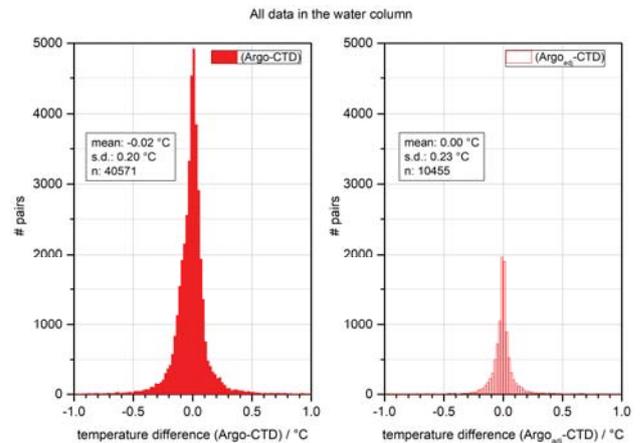


Fig.5. Temperature difference distributions: Argo (not-adjusted, left, and adjusted, right) vs CTD.

Temperature differences are negative on the average (mean equal to -0.02 °C) with a s.d. equal to 0.20 °C in the case of not-adjusted Argo profiles. If adjusted Argo profiles are considered, even if on temperature a null adjustment were declared in the considered casts, a slight improvement on the mean difference can be noted, with a substantially identical dispersion: mean and s.d. values are in fact equal to 0.00 °C and 0.23 °C, respectively. This fact can reasonably imply that data on which an

additional quality control is not applied may be subjected to a potential systematic error. For what concerns salinity data, again, a slight improvement in the mean difference Argo vs CTD can be noted when adjusted Argo data are considered: mean values change in fact from -0.013 PSU to -0.009 PSU (with s.d. equal to 0.041 PSU and 0.038 PSU, respectively). It should be underlined that for both t and S_p values, mean differences (Argo-CTD) are negative, in agreement with [18].

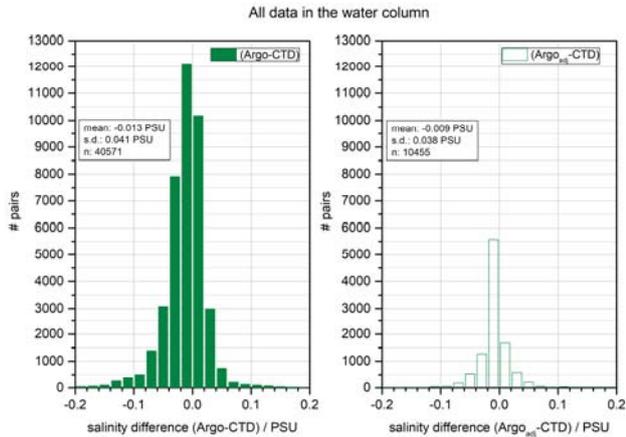


Fig.6. Salinity difference distributions: Argo (not-adjusted, left, and adjusted, right) vs CTD.

Matched profiles were then sorted in depth intervals distributed along the water column (at 100 m step down to 1000 m, then a single step at deeper depths down to 2000 m): for each depth interval, mean and s.d. of both t and S_p differences were calculated. Results are plotted in Fig.7 and Fig.8, where n indicates the number of considered pairs in each interval.

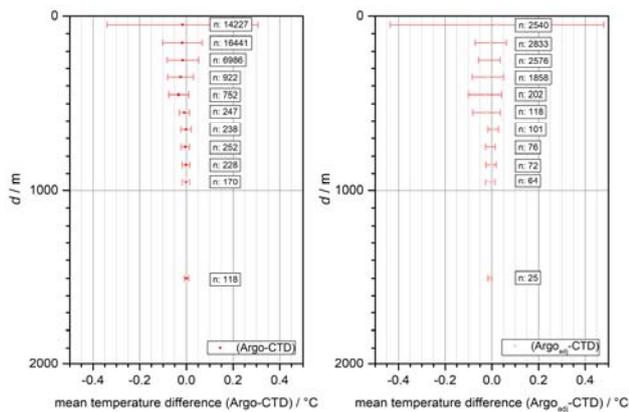


Fig.7. Mean temperature differences and s.d. at depth intervals: Argo (not-adjusted, left, and adjusted, right) vs. CTD.

The results show that the temperature difference (Argo vs CTD, in both cases), averaged in the intervals, spans in

the range (-0.03, +0.02) °C in the layers down to 500 m. From 600 m down, this difference becomes less equal to -0.01 °C. The s.d. values substantially decrease toward deeper depths, due to the reduction of sea water temperature variability with depth itself: values span from about 0.4 °C near the surface to about 0.01 °C at the bottom of the profiles. For what concerns salinity, the mean differences from surface down to 500 m have values ranging in (-0.016, -0.005) PSU. Deeper in the water column, the differences typically converge to -0.005 PSU. Values of s.d., again, are greater near the surface (up to about 0.070 PSU), reaching a minimum at bottom depth (about 0.010 PSU).

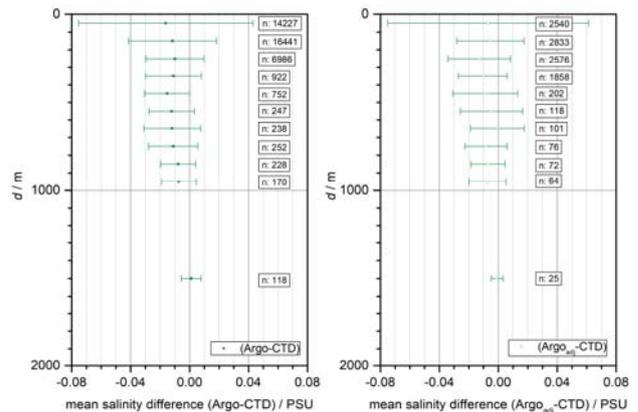


Fig.8. Mean salinity differences and s.d. at depth intervals: Argo (not-adjusted, left, and adjusted, right) vs. CTD.

Scatter diagrams and linear regressions (1:1 line) were then applied on both Argo t and S_p values versus the matched values obtained with ship-based CTDs: results are shown in Fig. 9 and Fig. 10, respectively. The slope a of the regression model shows again a slight improvement in the 1 to 1 relationship for adjusted Argo values (for both t and S_p): anyway, in general, no significant departure from the linearity was observed for any of the two quantities under study.

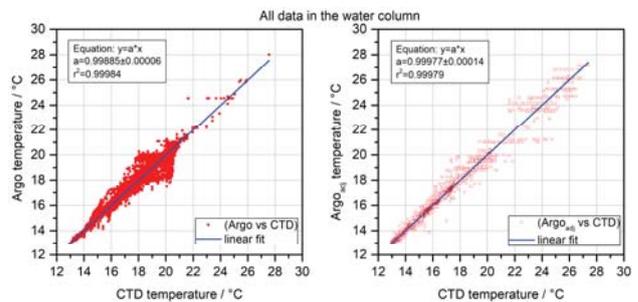


Fig.9. Scatter diagram and linear regression (slope a , coefficient of determination r^2) of Argo (not-adjusted, left, and adjusted, right) vs. CTD values: temperature.

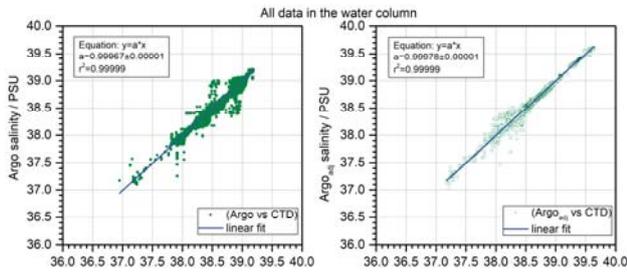


Fig.10. Scatter diagram and linear regression (slope a , coefficient of determination r^2) of Argo (not-adjusted, left, and adjusted, right) vs. CTD values: salinity.

Finally, for each involved Argo float, mean differences vs CTD values, for $d > 100$ m, were plotted as a function of the time elapsed since each float deployment, in order to give evidence of possible drifts of overall Argo population. Diagrams are reported in Fig. 11.

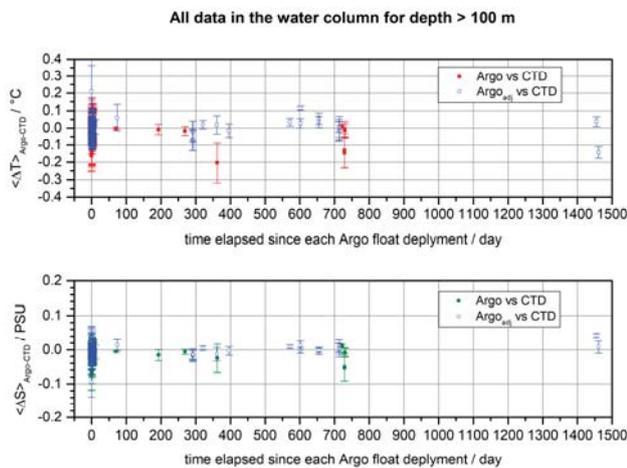


Fig.11. Argo(not-adjusted and adjusted) vs. CTD: temperature and salinity mean differences under 100 m plotted vs. time elapsed since Argo deployment.

IV. ANALYSIS AND CONCLUSIONS

Aim of the present work was to assess the differences in both temperature and salinity between Argo profiling floats and ship-based CTD casts quasi-collocated and quasi-simultaneous, in all the Mediterranean Sea and in a period of about 12 years (up to half 2018). Strict space-time matching conditions allowed to build a conspicuous database of Argo-CTD pairs. Some conclusions are presented in the following, based on data shown in the previous paragraph on which the population of Argo-CTD differences was analyzed by means of a paired sample t -test [22], used to determine whether the mean difference between two sets of observations is zero (i.e. the null hypothesis, meaning that the measures of the two instruments can be reasonably considered as equal to each other). The null hypothesis is rejected when the p -

value is less than the significance level (0.05); t -tests were performed by means of R software [23].

Obtained conclusions can be summarized as follows.

A. Argo vs CTD in terms of temperature

By comparing not-adjusted Argo and CTD measures, it can be concluded that at $d > 800$ m the two instruments give the "same measure", in a strict statistical sense, even neglecting the associated measurement uncertainties (with a slight tendency of the CTD measurements to be greater than the PFL, being the mean difference at these depths equal to about -0.001 °C). This also indicates that, in this zone of the water column, the sea behaves reasonably like a thermostatic bath (the natural variability of the thermohaline properties is reduced, [18]). On the contrary, by comparing adjusted Argo and CTD measures, again without considering their instrumental uncertainties, the null hypothesis has to be rejected along the whole water column (i.e. there is no evidence of equal behavior, in a strictly statistical sense, between the two instruments). This fact could be due to the smaller sample numerosity available for each depth interval; anyway, for $d > 800$ m, the mean temperature difference (Argo-CTD) is about -0.006 °C, that can be considered as a good indicator of the interchangeability of these two instruments.

A further metrological step was to consider at least one of the two instruments with its associated standard uncertainty, as obtained "in field" (i.e. during working condition in sea, in a typical ship-performed cast). For this purpose, neglecting the instrumental Argo uncertainty on temperature, the standard uncertainty of 0.023 °C was assigned to CTD measures, as reported in [24]. Well, in this condition Argo (both not-adjusted and adjusted) and CTD measures are consistent also at depth intervals in which, when neglecting uncertainty, the statistical test did not show a sufficient agreement: Argo and CTD, within the considered uncertainty, can be considered as measuring the same quantity already from 500 m down, in the sense that, in this water column, there is at least a 90 % percentage of normalized differences (i.e. $|t_{Argo-t_CTD}|/U(t_CTD)$, where U is the expanded uncertainty) lower than 1. For $d < 500$ m, mean differences are anyway large as -0.02 °C, but with greater s.d. due to the natural variability of sea temperature towards surface layers. Therefore, any significant offset between Argo and ship-based CTD can hardly be identified, due to the fact that mean differences are of the same magnitude order of the standard uncertainties of instrument in field.

B. Argo vs CTD in terms of salinity

Following the same criterion as in the previous paragraph, neglecting instrumental uncertainties, not-adjusted Argo salinity measurements were compared with CTD ones. The null hypothesis can be accepted only for

depths greater than 1000 m; from surface to 1000 m the mean difference is about -0.01 PSU. The delayed mode control quality causes a slight improvement: for adjusted Argo values, in fact, the statistical agreement under 1000 m is stronger (i.e. showing higher p -values) and a good agreement is reached also in the band (600, 700) m. From surface to $d = 1000$ m the mean difference is lowered to about -0.007 PSU.

By considering again the CTD uncertainty in field for salinity, equal to 0.01 PSU as reported in [24], not-adjusted Argo and CTD can be considered as reasonably measuring the same quantity already from 500 m depth. For adjusted Argo data, a good agreement (in the sense of metrological data consistency) is reached only at $d > 800$ m. It can in any case be concluded that also for salinity any significant offset between Argo and ship-based CTD would be masked by transducer standard uncertainty.

C. Assessment of Argo float stability

A Weighted Least Squares linear fit was applied to data reported in Fig. 11 [25]: the purpose was to assess if the parameter b (slope) of the model $y = a + b * x$ (where x indicates the time, expressed in days), is significantly different from zero (i.e. indicating the presence of drift) or not (i.e. absence of drift). The slope is different from zero when its standard error is small compared to the numeric value $|b|$, and consequently the associated t -test test gives a p -value smaller than 0.05 (i.e. the null hypothesis of a slope equal to zero cannot be accepted). Results are shown in Table 2: even adjusted data are affected by drift, but this is negligible (reasonably comparable with standard uncertainty) when considered on the mean lifetime of an Argo float (about 4 years).

Table 2. Statistical estimates of Argo drifts on temperature and salinity measures.

Argo data	Slope b	t -test
not-adj_temp	$(-0.6 \pm 1.4)E-05$ °C/day	NO drift
yes-adj_temp	$(6.2 \pm 1.0)E-05$ °C/day	YES drift
not-adj_sal	$(21 \pm 9)E-06$ PSU/day	YES drift
yes-adj_sal	$(29 \pm 2)E-06$ PSU/day	YES drift

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