2019 IMEKO TC-19 International Workshop on
Metrology for the Sea
Genoa, Italy, October 3-5, 2019

Estimate of the robustness of XBT temperature measurements from SOOP in the Mediterranean by comparison with ARGO profiles

F. Reseghetti[1], F. Pennecchi[2], G. Raiteri[1*], L. Repetti[3]

[1] *ENEA - Marine Environment Research Centre S. Teresa, 19032 Pozzuolo di Lerici (SP), Italy*
[2] *INRiM - Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, 10135 Torino, Italy*
[3] *IIM - Istituto Idrografico della Marina Militare, Passo dell'Osservatorio 4, 16134 Genova, Italy*

[*] Corresponding author: giancarlo.raiteri@enea.it

***Abstract* – Main purpose of this work is the comparison between XBT (eXpendable BathyThermograph) temperature profiles recorded in the Tyrrhenian Sea during the SOOP (Ship Of Opportunity Programme) activity with commercial ships (since September 1999) and Argo profiles (since May 2004). In particular, analysis was focused on the Genoa-Palermo transect, historically managed by ENEA S. Teresa Research Centre. XBT temperature profiles were matched with Argo quasi-collocated in space (and quasi-simultaneous in time) profiles, in order to assess the reliability of XBT temperature measurements. Space-time matching conditions were chosen to be as strict as possible.**

I. INTRODUCTION

An XBT system, including a probe falling in water, a launcher with a connecting cable and a data acquisition unit, is a well-known instrument to measure temperature (t) profiles in oceanography [1,2,3,4].

XBT can be considered as a cheap, versatile, and *easy* to use transducer. Due to these advantages, between 1970 and 1990, XBTs measured most of the temperature data in the upper 2000 m of the oceans, in particular along the main commercial ship lines (Fig. 1). Consequently, overall XBT literature is very huge [5,6].

Nowadays, the quantity of XBT probes launched annually has been considerably reduced due to the widespread network of temperature/salinity profiling floats, known as Argo, that has become a fundamental component of the ocean observing system [7,8,9,10].

Nevertheless, XBT transects are still considered a useful, complementary source of oceanographic information: they provided up to now, in fact, very long records of temperature observations across ocean basins, that are of crucial importance in research related to ocean heat content and current variability, together with water mass and heat transport [6]. In this context, climatologists highlighted both the importance of historical XBT datasets and the need of accurately evaluating their measurement uncertainties, which are fundamental for climatological analyses [11].

For this purpose, a detailed comparison of XBT vs. Argo temperature profiles was considered critical, in line with specific literature related to XBT data quality improvement [12,13,14].

Comparison between quasi-collocated and quasi-simultaneous XBT and Argo measurements was then focused on both Tyrrhenian and northeastern Ligurian seas, along the MX04 XBT transect (Genoa to Palermo, mapped in Fig. 1), historically managed by ENEA S. Teresa research Centre (since September 1999) in the context of the Ship Of Opportunity Programme [6,15]. To date, about 90 transects have been completed, resulting in over 3000 profiles.

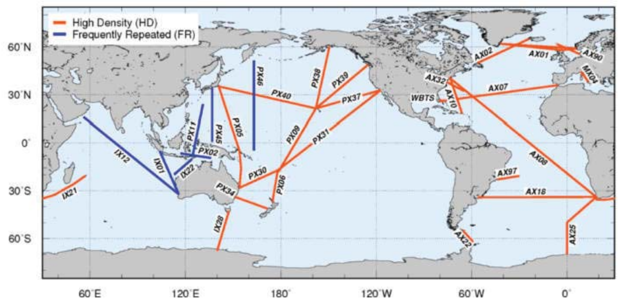

Fig. 1. Location of High Density and Frequently Repeated XBT transects, as recommended by the XBT Science Team during the 5th Science Workshop-2016 [6].

II. DATA AND METHODS

XBT and Argo profiles were downloaded from dedicated online databases ([16] and [7], respectively).

Each XBT profile underwent a quality control process in which a series of tests assessed the quality of the measurements (i.e. presence of spikes, constant value profiles, extreme depth (d) and temperature values, improper dates and locations, vertical gradients and inversions, wire breaks, seafloor contact, etc. [6]).

In particular, for the XBT data starting from the cruise of the 29th of July 2010, a check of performances of the acquisition system was available through the calibration of system itself by a test canister working at two reference temperatures. This control procedure was performed immediately before the XBT launches started and immediately after the launch of the last XBT probe.

A slight deviation from the reference temperature values has often been verified, especially at high temperatures, sometimes even combined with a different result between the values read at the beginning and end of the XBT deployment, a symptom of a possible temporal drift of the system. It was therefore decided to correct the XBT profile data by applying an algorithm that linearly corrects the XBT temperature reading according to the time elapsed since the first launch (to take into account the time drift) combined with a further linear correction as a function of the deviation from the reference temperature values. A detailed analysis of all this correction is in preparation (Reseghetti et al., paper in progress [17]).

Following the indications for the first Rossby radius of deformation indicated in [18], XBT and Argo profiles were matched in pairs, in which the former was considered as the reference in space and time to which the latter was compared (i.e. position and instant of the XBT deployment were considered as the position and time *zero*, respectively).

The matching 3D-space and time conditions were chosen as follows (it has to be underlined that two different time windows were considered, in order to have a first dataset comparable to previous study [12] and a second dataset with a more restrictive matching condition in time):

- ΔLatitude: ± 0.10°
- ΔLongitude: ± 0.15°
- Δtime: ± 7 days and ± 1 day (nominal intervals)
- Δdepth: ± 1 m.

The coordinate differences allowed to have a maximum distance of about 12 km between each XBT profile and the matched Argo one (the Rossby radius in the area of interest is about 10 km), whose typical operating cycle is 5 or 10 days. The considered period spans from the 16th of August 2004 up to the 19th of March 2019.

As a function of the two different time windows, the dataset could be divided as follows.

A. Dataset obtained in the large time window (± 7 days)

A number of 147 XBT vs. Argo paired profiles was found, satisfying the previous matching conditions (spatial matching equal to (9.4 ± 3.1) km). In Fig. 2 and Fig. 3, the spatial distribution of XBT-Argo considered pairs and an example of matched temperature profiles are reported, respectively. The actual number of different XBT probes was equal to 94, mainly Deep Blue type (DB). More in detail, there were thirteen T4, seven T5, one T6, two T10 and seventy-one DB types [19]: this distribution reflected in some way the amount of different deployed XBT probes. The actual number of different Argo floats involved in the comparison was equal to 24, originating 127 profiles.

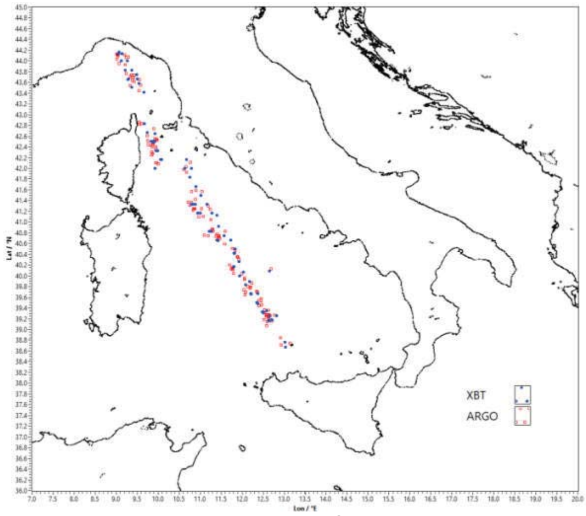

Fig. 2. Spatial distribution of the XBT-Argo pairs analyzed along the MX04 transect in about 15 years.

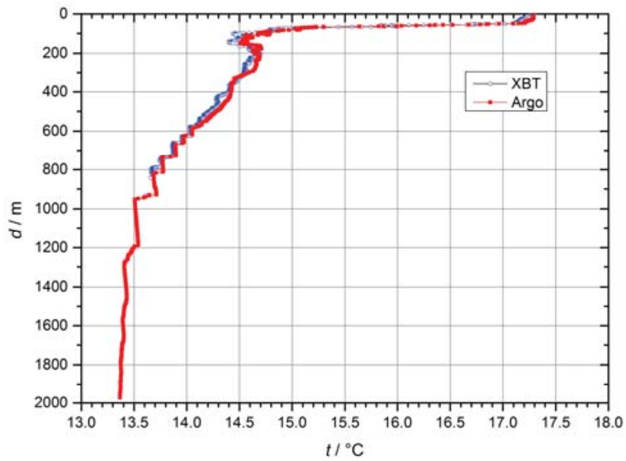

Fig. 3. Example of quasi-collocated and quasi simultaneous XBT and ARGO profiles. XBT (Deep Blue) - Date: 2018/12/11, Time: 14:05:50, Lon: 12.6322°E, Lat: 39.1667°N. ARGO (#6902903) - Date: 2018/12/14, Time: 10:19:00, Lon: 12.6344°E, Lat: 39.2362°N.

As detailed in the next paragraph, full profiles and, separately the 0-100 m and >100 m depth regions of the sea water column were considered. This is due to the well known depth error that affects the XBT measurements (estimated as the greater between 5 m and 2 % of the depth itself [19]), usually well evident at the start of the upper seasonal thermocline. The same analyses were also repeated on different data subsets depending on the XBT types. An overall number of 15740 matched temperature values was found, quasi-collocated in depth along the water column (within ± 1 m). To give evidence of the numerosity of the analyzed sample, in Fig. 4 the number of XBT-Argo pairs is reported, divided per XBT type and depth interval.

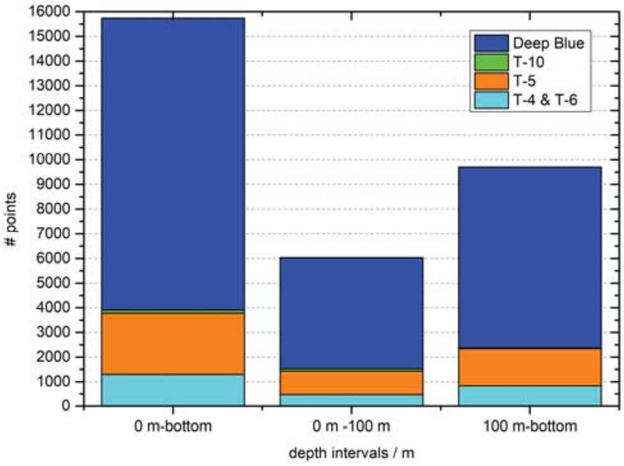

Fig. 4. Number of matches XBT vs ARGO divided per XBT type and depth intervals (time window ± 7 days).

B. Dataset obtained in the strict time window (± 1 day)

By applying the same space matching conditions, but with a stricter time window, a number of 31 XBT vs. Argo paired profiles were found (spatial matching equal to (9.3 ± 3.4) km). The actual number of different XBT probes was equal to 31: six T4, two T5 and twenty-three DB types. The actual number of different Argo floats involved in the comparison was equal to 10, originating 24 profiles. An overall number of 2601 matched temperature values was found, quasi-collocated in depth along the water column (within ± 1 m). This is a subset of the previously analyzed dataset.

III. RESULTS

In analogy with the previous paragraph, results of the comparison are presented taking into account the two different time windows.

A. Results obtained in the large time window (± 7 days)

In Fig. 5, all the temperature differences (XBT-Argo) are reported as a function of depth, while in Fig. 6 an overall summary of the corresponding results is shown.

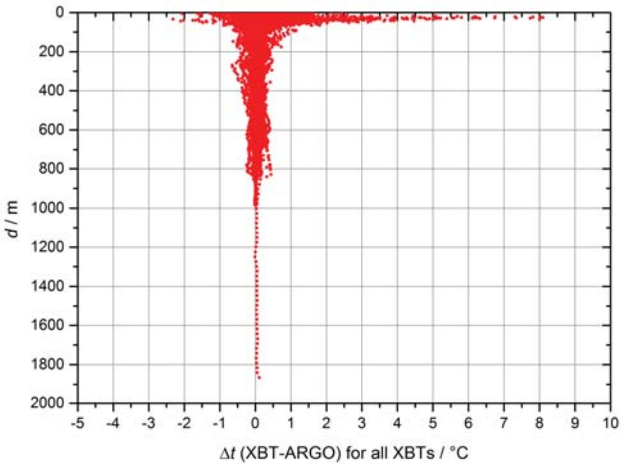

Fig. 5. All temperature differences (XBT-Argo) vs. depth. Note the large values close to the surface.

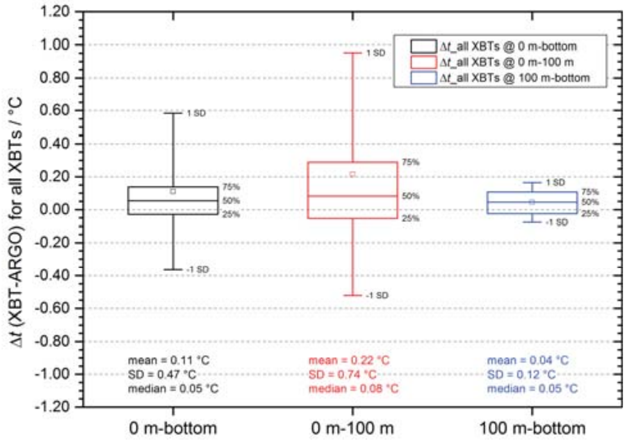

Fig. 6. Box plot of temperature differences (XBT-Argo). Mean values are indicated by the empty squares.

The mean Δ*t* calculated over the whole water column was + 0.11 °C (but the median was + 0.05 °C), with a standard deviation (SD) equal to 0.47 °C.

If the surface layer region 0-100 m (the typical thermocline region) was excluded, then mean Δ*t* would become equal to + 0.04 °C (in practice the same value as for the median), but with a SD value of 0.12 °C.

Detailed results, differentiated by XBT type, are shown in Tables 1, 2 and 3 for depths 0 m-bottom, 0-100 m and 100 m-bottom, respectively.

Table 1. Δt (XBT-Argo) for each XBT type involved. Depth: 0 m - bottom.

quantity	**T-4 T-6**	**T5**	**T10**	**Deep Blue**
# matched points	1301	2481	131	11827
Max Δ*t* (°C)	4.29	8.10	1.20	8.01
Min Δ*t* (°C)	-1.09	-1.65	-0.60	-2.31
Mean Δ*t* (°C)	0.11	0.13	0.33	0.10
SD (°C)	0.36	0.59	0.31	0.46
Median Δ*t* (°C)	0.07	0.02	0.25	0.06

Table 2. Δt (XBT-Argo) for each XBT type involved. Depth: 0-100 m.

quantity	**T-4 T-6**	**T5**	**T10**	**Deep Blue**
# matched points	475	961	100	4502
Max Δ*t* (°C)	4.29	8.10	1.20	8.01
Min Δ*t* (°C)	-1.09	-1.65	-0.60	-2.31
Mean Δ*t* (°C)	0.21	0.31	0.36	0.19
SD (°C)	0.57	0.91	0.35	0.72
Median Δ*t* (°C)	0.01	0.11	0.45	0.07

Table 3. Δt (XBT-Argo) for each XBT type involved. Depth: 100 m-bottom.

quantity	T-4 T-6	T5	T10	Deep Blue
# matched points	826	1520	31	7325
Max Δt (°C)	0.48	0.57	0.42	0.93
Min Δt (°C)	-0.62	-0.26	0.09	-0.65
Mean Δt (°C)	0.05	0.01	0.23	0.05
SD (°C)	0.12	0.12	0.08	0.12
Median Δt (°C)	0.06	-0.01	0.22	0.05

By considering Table 3, T5-type XBTs showed the best results in accuracy below 100 m (where also the dispersion value is reduced, due to a smaller temperature variability with depth along the water column).

B. Results obtained in the strict time window (± 1 day)

In Fig. 7 a summary of the obtained results is shown.

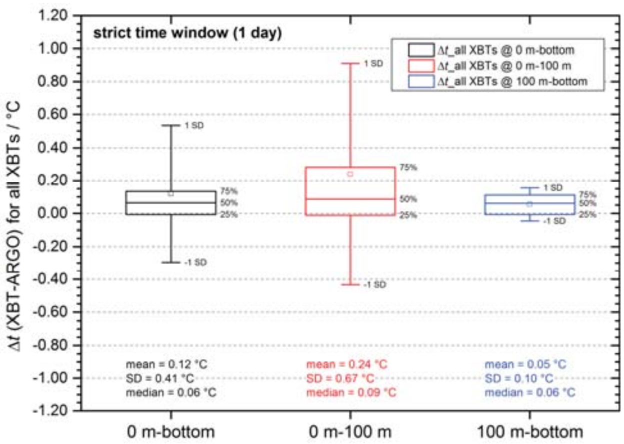

Fig. 7. Box plot of temperature differences (XBT-Argo). Mean values are indicated by the empty squares.

By comparing values reported in Fig. 6 and Fig. 7, it can be noted that a more strict matching condition on time has no significant influence on mean or median of temperature differences (for each depth interval considered); on the contrary, a reduction of SD values is evident (about 10 %), showing an improved agreement between XBT and Argo measurements which are matched in a stricter time window. Detailed results, differentiated by XBT type, are shown in Tables 4, 5 and 6 for depths 0 m-bottom, 0-100 m and 100 m-bottom, respectively. Here again, T5-type XBTs showed the best results in accuracy below 100 m. In order to give evidence to the best behaviour of T5 type, if compared with other XBT types, values of differences of the matched temperature values were plotted vs. depth (d > 100 m) in Fig. 8.

Table 4. Δt (XBT-Argo) for each XBT type involved. Depth: 0 m - bottom.

quantity	T-4 &T-6	T5	Deep Blue
# matched points	322	475	1804
Max Δt (°C)	4.29	4.68	6.33
Min Δt (°C)	-0.43	-0.84	-1.55
Mean Δt (°C)	0.12	0.09	0.13
SD (°C)	0.44	0.40	0.41
Median Δt (°C)	0.07	0.01	0.07

Table 5. Δt (XBT-Argo) for each XBT type involved. Depth: 0-100 m.

quantity	T-4 & T-6	T5	Deep Blue
# matched points	128	143	635
Max Δt (°C)	4.29	4.68	6.33
Min Δt (°C)	-0.37	-0.84	-1.55
Mean Δt (°C)	0.18	0.27	0.24
SD (°C)	0.68	0.69	0.67
Median Δt (°C)	0.05	0.06	0.10

Table 6. Δt (XBT-Argo) for each XBT type involved. Depth: 100 m-bottom.

quantity	T-4 & T-6	T5	Deep Blue
# matched points	194	332	1169
Max Δt (°C)	0.48	0.37	0.32
Min Δt (°C)	-0.43	-0.16	-0.49
Mean Δt (°C)	0.07	0.01	0.06
SD (°C)	0.11	0.10	0.10
Median Δt (°C)	0.08	-0.01	0.07

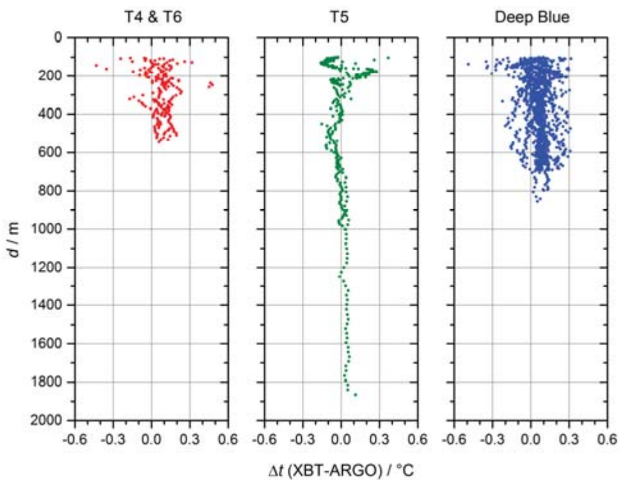

Fig. 8. Temperature differences vs. depth (> 100 m) for all the (XBT-Argo) pairs separated less than 10 km in space and within a 1 (nominal) day time window.

Scatter diagram and linear regressions (1:1 line) were then applied on XBT vs. Argo values (d > 100 m): slope a and the coefficient of determination r^2 showed no significant departure from the linearity (Fig. 9).

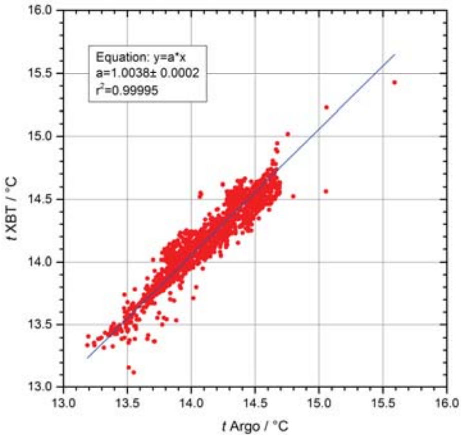

Fig. 9. XBT vs. Argo values linear fit.

IV. ANALYSIS AND CONCLUSIONS

Aim of the present work was to assess the temperature difference between XBT probes and Argo profiling floats, quasi-collocated and quasi-simultaneous along the SOOP Genoa-to-Palermo transect, in a period of about 15 years (up to March 2019) [20,21,22].

The depth of an XBT probe is not measured directly but estimated through a fall rate equation with empirical coefficients (based on tests carried out by the manufacturer [19]) which change with the XBT type but which are independent of any other factor such as water temperature, launching height and so on. The manufacturer also indicates in 5 m or 2 % of the depth (whichever is greater) the accuracy value to be associated with the XBT depth (as anticipated in paragraph II).

Therefore, up to a depth of 250 m, for each depth value the associated uncertainty is equal to 5 m. This value has no significant influence on the temperature change measured at deeper depths, but can have dramatic consequences at the beginning of the structures of the upper thermocline, where gradients greater than 2 °C/m can be measured in the Mediterranean. An example of this can be verified in Fig. 5, where the maximum of temperature differences occurs in the surface and sub-surface layers. In the depth value 0-100 m, a small variation in depth could in fact correspond to a very important variation in temperature, so that the comparison with Argo values wouldn't be significant.

In a significant part of measurements, the XBT calculated depth overestimates the actual depth in the first tens of meters of the fall. Therefore a wrongly calculated depth (deeper than the real one) is combined with a temperature actually measured at a slightly less deep depth. Nevertheless, in the present work, this fact was not taken into account nor corrections to the XBT depth were applied. Therefore, the results obtained herein (which are still affected by an error on the read t value, attributable to an incorrect d value calculated by the fall equation) could be certainly improved, in terms of temperature mean difference and standard deviation.

In this work, a first time window of ± 7 days was initially chosen to build a first, conspicuous database of (XBT-Argo) pairs. Then, a more strict matching condition in terms of time was applied, by choosing a window of ± 1 day (with the same space matching conditions, equal to about 10 km). Results in terms of t mean difference, calculated on all XBTs, are not significantly dissimilar in the two considered time windows: for depth greater than 100 m, in fact, values of 0.04 °C and 0.05 °C were found, respectively (with SD values equal to 0.12 °C and 0.10 °C).

Some statistical analysis was then applied to temperature differences related to each XBT type involved in this comparison. The population of (XBT-Argo) differences, exclusively associated to the smaller time window, was in fact analyzed by means of a paired sample t-test [23], 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 [24]. Obtained conclusions can be summarized as follows. By comparing T4 and T6 XBT measurements with Argo ones, in a strict statistical sense (i.e. neglecting the associated measurement uncertainties), the agreement is good, but just in the range [100, 200] m (55 pairs, p-value equal to 0.24). For what concerns T5 type, again without considering the instrumental uncertainties, the agreement is very good in the following two ranges: [200, 400] m (83 pairs, p-value equal to 0.44) and [700, 900] m (28 pairs, p-value equal to 0.33). In general, for T5, the statistical agreement with Argo is good all along the water column below 200 m (222 pairs, p-value equal to 0.64). It can be concluded that, in this case, the two instruments give the "same measure": this fact can be considered as a good indicator of the interchangeability of these two instruments (also indicating that, under these space-time conditions, the sea behaves reasonably like a thermostatic bath).

A further metrological step was to consider at least one of the two involved instruments with its associated standard uncertainty. For this purpose, neglecting the instrumental Argo uncertainty on temperature (XBT readings are intrinsically less accurate than Argo ones), the standard uncertainty of 0.1 °C was assigned to XBT measurements, obtained dividing by two the overall XBT accuracy of 0.2 °C as stated by the manufacturer [6,25]. This standard uncertainty can be considered as obtained "in field" (i.e. during working condition in sea, in a typical XBT launch from shipboard). Well, in this condition XBT and Argo measurements are consistent also at depths in which, when neglecting uncertainty, the statistical test did not show a sufficient agreement. XBT and Argo, within the considered uncertainty, can be judged as measuring the same quantity already from 100 m down, in the sense that, in the water column, there is at least a 90 % percentage of normalized differences (i.e. |*t*_XBT-*t*_Argo|/U(*t*_XBT), where *U* is the expanded uncertainty) lower than 1. This result is valid as for all the XBTs as for each specific model (i.e. T4 and T6, T5 and Deep Blue).

In summary, temperature profiles collected in the Western Mediterranean Sea by XBT probes launched by commercial vessels have proven not to differ too dramatically from the values recorded by Argo profilers, considering position differences smaller or similar to the local Rossby radius. By varying the time windows of the comparison from daily to weekly scale, differences do not change significantly. If the complete profile of the different types of XBTs usually launched is considered, the agreement between the values recorded by Argo and XBTs is poor. However, if the superficial region is eliminated (usually identified in the 0-100 m layer), where generally significant and strong thermal structures are present and which are critical for the XBTs, the agreement in the lower layers becomes much more consistent, also because the characteristics of the water column tend to resemble more and more those of a thermostat bath. In this case, temperature values supplied by the XBTs show a slight excess that, combined with its SD, is fully compatible with the accuracy declared by the manufacturer. The application of a more accurate description of the falling motion of the probe should consequently allow a small reduction of the differences between the reading by XBTs and Argo profilers. This aspect will be analyzed in subsequent works.

Acknowledgments
This work was performed thanks to SeaDataCloud project (European Union's Horizon 2020 Research Infrastructures Programme, grant agreement No. 730960) that manages the European Portal SeaDataNet, making available data deriving from in situ ocean measurements (https://www.seadatanet.org/).

REFERENCES

[1] W. J. Emery, R. E. Thomson, "Data analysis methods in physical oceanography", Pergamon, 1997.
[2] Sippican Corporation manual, "Instructions for installation, operation and maintenance of Sippican Expandable Bathythermograph System", 1968.
[3] Sippican Inc. manual, "MK-21 Bathythermograph Data Acquisition System: Installation, Operation and Maintenance Manual", P/N 308195, Rev. A, 2003.
[4] NOAA manual, "AOML high density XBT system setup instructions and troubleshooting manual", 2016.
[5] https://www.aoml.noaa.gov/phod/goos/xbtscience/faqs.php#q3
[6] G. Goni et al., "More than 50 years of successful continuous temperature section measurements by the global expendable bathythermograph network, its integrability, societal benefits, and future", Front. Mar. Sci. 6:452, doi: 10.3389/fmars.2019.00452.
[7] http://www.argo.net/
[8] http://www.argo.ucsd.edu/
[9] https://floats.pmel.noaa.gov/
[10] P.-M. Poulain at al., "MedArgo: a drifting profiler program in the Mediterranean Sea", Ocean Sci., 3, pp. 379-395, 2007.
[11] V. Gouretski, V., K. P. Koltermann, "How much is the ocean really warming?", Geophys. Res. Lett., 34, L01610, 2007.
[12] P.-M. Poulain, R. Barbanti, "Comparison between VOS/XBT and MEDARGO temperatures", REL 61/2005-OGA-31, 2005.
[13] DiNezio, P. N., and Goni, G., "Identifying and estimating biases between XBT and Argo observations using satellite altimetry. J. Atmos. Oceanic Tech. 27, pp. 226–240, 2010.
[14] F. Reseghetti et al., "Assessment of quality and reliability of measurements with XBT Sippican T5 and T5/20", Journal of Atmospheric and Oceanic Technology, 35, pp 1935-1960, October 2018.
[15] https://www.aoml.noaa.gov/phod/goos/xbt_network/
[16] https://www.seadatanet.org/
[17] F. Reseghetti et al, " A possible way to improve the accuracy on XBT temperature reading", paper in progress.
[18] F. Grilli, N. Pinardi, "The computation of Rossby radii of deformation for the Mediterranean Sea", MTP News, 6, p. 4, March 1998.
[19] https://www.lockheedmartin.com/en-us/products/oceanographic-instrumentation.html
[20] Manzella, G. M. R., Scoccimarro, E., Pinardi, N., and Tonani, M., "Improved near real time data management procedures for the Mediterranean ocean Forecasting System – Voluntary Observing Ship Program", Ann. Geophys., 21, pp. 49–62, 2003. https://doi.org/10.5194/angeo-21-49-2003
[21] Pinardi, N., Allen, I., Demirov, E., deMey, P., Lascaratos, A., Le-Traon, P. Y., Maillard, C., Manzella, G., and Tziavos, C., "The Mediterranean ocean forecasting system: first phase of implementation (1998–2001) ", Ann. Geophysicae, 21, pp. 3-20, 2003. https://doi.org/10.5194/angeo-21-3-2003
[22] F. Reseghetti, M. Borghini, and G. M. R. Manzella, "Factors affecting the quality of XBT data - results of analyses on profiles from the Western Mediterranean Sea", Ocean Sci., 3, 59–75, 2007. https://doi.org/10.5194/os-3-59-2007
[23] Hoel, P. G. 1984. Introduction to Mathematical Statistics. 5th ed. New York: Wiley.
[24] https://cran.r-project.org/
[25] E. R. Anderson, "Expandable bathythermograph (XBT) accuracy studies", Tech. Rep. 550, Naval Ocean System Center, California, June 1980.