DEEP FLOAT EXPERIMENT FINAL EVALUATION AND RECOMMENDATIONS

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EXECUTIVE SUMMARY

This deliverable describes the outcome of the inter-comparison at-sea experiment, under typical Argo float mission parameters, carried out to determine and quantify any biases, temporal drifts or pressure effects in the three CTD sensors (SBE41CP, SBE61 and RBR) currently used for the extension of Argo to the Deep ocean (> 2000 dbar).

During two cruises, in December 2020 and March 2022, two 3-headed and two 2-headed floats were deployed in the Canary Basin, chosen as the deployment area because of its central and deep waters being relatively stable over time. The 3-headed floats have a SBE41 sensor on cap and a SBE61 and RBRconcerto sensors on the sides, while the 2-headed floats have a RBRargo3 sensor on cap and a SBE61 on the side. A total of 56 profiles for the 3-headed floats and 40 for the 2-headed floats has been used in this analysis.

Overall, the pressure sensors show a behavior that lies within the sensor accuracy, although its error increases with depth, and for waters colder than 5°C. The temperature sensors of the SBE41CP, SBE61 and RBR agree within the expected sensor accuracy, that is 0.001 or 0.002°C in the deep layers, although in some cases the error near the surface exceeds sensor accuracy. For the conductivity sensors the analysis reveals that once corrected the SBE sensor with the reference CTD profile carried out at the deployment, the results are within the accuracy. For the RBR, even if progress has been made, the conductivity still exhibits a residual pressure dependence.

Despite the progress done so far by SBE and RBR, as well as by the Argo community in increasing the accuracy and stability of the CTD sensors, it is still necessary to carry out a reference CTD profile at the deployment site. Without this CTD profile, neither the SBE nor RBR sensors would achieve the needed accuracy.

These 3-head and 2-head intercomparison exercises are the only methods to evaluate and help improve the performance of the new generation of deep sensors. Also, the collaboration with manufacturers has been demonstrated to be of great benefit to assess and improve the quality of the observations.

TABLE OF CONTENT

1 Introduction

Extending Argo to the deep ocean

The extent to which the deep interior will continue to absorb anthropogenic heat is an essential question for environmental projections, which requires a most accurate quantification of the deep thermal structure of ocean basins and their changes. The sparsity of hydrographic measurements, however, only allow relatively uncertain estimates of basin-averaged temperature trends, with occupations of coast-to-coast transects spaced out by some years (1 or 2 years at best, but usually 5 to 10 years). Following the evident need of extending the core-Argo array to the ocean bottom, the Argo Steering Team (Johnson et al, 2015) proposed for long-term implementation of a Deep Argo array. Based on decorrelation time scales from core-Argo float time series at 1800m (about 160 days) and deep temperature variance from repeat hydrography sections, they argued that a hypothetical 5° x 5° x 15 days array (about 1200 floats) would substantially reduce uncertainties in global and regional temperature trends. This extension to the deep ocean, Deep Argo, is part of OneArgo, the major expansion of the Argo program. (Roemmich et al 2022).

Pilot experiments carried out by the Argo international community have already led to significant advancements for the future implementation of a global and homogeneous Deep-Argo array. As of October 2022, 178 floats have been deployed, gathering altogether 17644 profiles of temperature and salinity down to either 4000 dbar or 6000 dbar with privileged study zones including the subpolar North Atlantic, the southwestern Pacific and Atlantic, and Southern Ocean seas. Innovative scientific results have already emerged from those first deployments (Johnson et al, 2019; Kobayashi, 2018, Racapé et al, 2019; Petit et al, 2022, Desbruyères et al., 2022), which have contributed to encourage the next phase of the implementation, aimed to be global and coordinated at the international level.

New technologies

Given the indubitable need for a Deep-Argo array, several pilot experiments were aimed to demonstrate the ability of floats to acquire good-quality deep data and evaluate the different available sensors (e.g. precision requirements for climate studies) in order to guide the international community in the global implementation of the network. Possible biases and time drifts in the conductivity sensor, as well as a possible pressure effect on the measurements, are sources of important questions in the community and active efforts are still needed to provide the global Deep-Argo array with the best available technology. We particularly need (1) platforms capable of reaching the deep ocean, (2) temperature, salinity and pressure sensors with the accuracy and stability to address the changes in the deep ocean, and (3) methods to evaluate the quality of the observations and perform corrections when necessary.

Three deep sensors are currently available for the extension of Argo to the deep ocean (>2000 dbar). The SeaBird SBE41CP (0 - 4000 dbar range), the SBE61 (0 - 6000 dbar range; upgrade of SBE41/41CP), and the RBRargo^3 sensor (0 - 6000 dbar range; RBRconcerto^3 for the standalone version), developed with a totally different technological approach by RBR Ltd. To inter-compare the respective capabilities of those three sensors, Ifremer has developed “2-headed” (RBRargo^3 on cap + SBE61 on the side) and "3-headed" (SBE41 on cap + SBE61 & RBRconcerto on the sides) multi-sensor Deep-Arvor floats. For simplification, the RBRargo3 and RBRconcerto will be referred to as RBR in the rest of the document.

Before the Euro-Argo RISE project, IFREMER carried out technological developments and short at sea trials (during Ifremer/LOPS campaigns named MICROCO, from the 9th to the 16th of September 2018 and LOPSTECH19-L1, from the 3rd to the 9th of May 2019) by a 3-headed float to ensure a long-term deployment in 2020. Those trials showed the overall good functioning of the float, as a platform, and have already revealed differences in the behaviors of the 3 sensors (overestimation of salinity by RBR for example, or different pressure response for the SBE41CP) and problems with the housing of the RBR sensors. However, biases, temporal drifts, and pressure effects require to be estimated in a full float mission at sea, with as many profiles as possible.

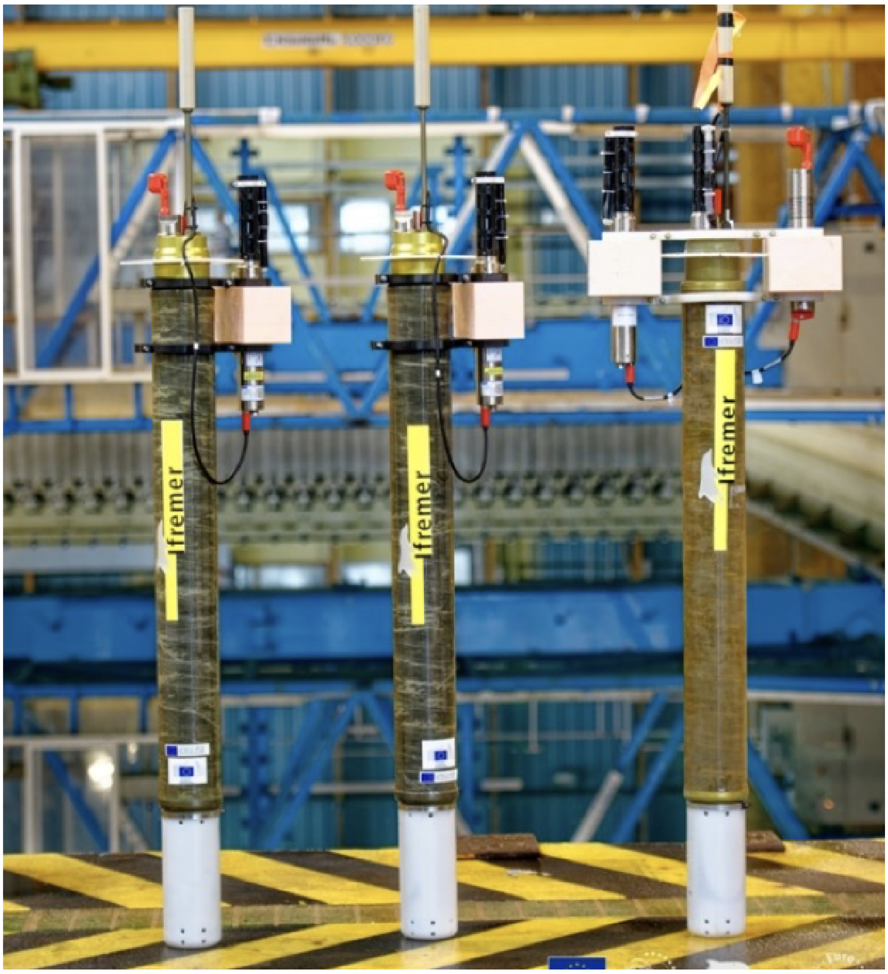


Figure 1. *Picture of the 3-headed-Euro-Argo RISE 2022 float (right) and the two 2-headed-Euro-Argo RISE floats (2 on the left) deployed in March 2022*

Objectives of the deep float experiment

The objective of the full at-sea experiment is to determine and quantify any biases, temporal drifts or pressure effects in the three CTD sensors (SBE41CP, SBE61 and RBR) under typical Argo float mission parameters. Comparisons between these three sensors will enable us to assess whether the SBE41CP and RBRargo3 CTDs meet the accuracy (for salinity primarily, but also for pressure) required for deep-ocean investigations. The SBE61 will be used as reference, together with the shipborne full-depth CTD profile that will be carried out before the deployment (see next section). Evaluation of sensor stability will benefit from the quiescent character of the deployment area and the associated stability of its central and deep water mass properties (temperature and salinity). The stability and accuracy of the pressure and temperature sensors will also be assessed, and facilitated owing to the alignment of the three sensors. However, the RBR concerto sensor mounted on the flank of the 3-headed float is not the final design intended to be mounted on standard deep Argo floats, since they will have the RBRargo3 sensor. Therefore the data analysis of the 3-headed float will only assess the new RBR inductive technology for the conductivity cell rather than the final generation of deep sensors. This is the purpose of using the 2-headed floats, with the RBRargo^3 sensor mounted on top, and the SBE61 sensor on the flank. The comparison between the observations from the new sensors would determine if the new RBR inductive technology satisfies the requirements to explore deep and abyssal layers (Figure 1)

Additionally, here we report the results of the deployment of UK national floats (NOC) in the Atlantic and equipped with either SBE61 or RBR sensors.

2 Deployments

The floats used during the deep evaluation experiments were deployed (table 1) during two cruises, in December 2020 and March 2022, carried out by the IEO/CSIC as parts of its long-term Ocean Observing program in the Canary Islands, the Radial Profunda de Canarias (Raprocan) (Tel at al, 2016).

The Canary Basin was chosen as the deployment area for the two 3-headed and the two 2-headed floats because of its central and deep waters being relatively stable over time. This was demonstrated by a 22-year long time series of temperature and salinity of North Atlantic Central Waters (NACW) and the North Atlantic Deep Waters (NADW) in the area (Figure 2), as derived from repeated bi-annual hydrographic surveys carried out by the Spanish Oceanographic Institute (IEO) since 1997 (Tel et al., 2016)). Such a weak interannual variability of the deep Canarian Basin, as well as its frequent surveying by IEO/CSIC will ensure a rigorous assessment of the long-term stability of the float sensors at depth. The NACW and NADW have a long term trend in salinity over potential temperature of -0.001 ± 0.003 and -0.002 ± 0.001 per decade, respectively. These values, per year, are smaller than the accuracy of the conductivity sensors in the present generation of Argo floats.

Table 1: *Deployments of the specifically designed 2-headed and 3-headed Argo floats.*

Type of float	Code name	Deployment	Cruise	Number of cycles
3-headed	**3-head-NAOS-2020**	December 2020 Recovered in March 2022	RAPROCAN2012	57, only 35 cycles are usable
3-headed	**3-head-Euro-Argo RISE-2020** (recovered)	December 2020 Recovered in April 2021	RAPROCAN2012	41, only 13 cycles are usable (not shown here)
3-headed	**3-head-Euro-Argo RISE-2022** (Re-Deployed)	March 2022	RAPROCAN2203	21 cycles, still Active on October 2022
2-headed	**2-head-Euro-Argo RISE-01**	March 2022 Recovered in September 2022	RAPROCAN2203	19 cycles
2-headed	**2-head-Euro-Argo RISE-02**	March 2022	RAPROCAN2203	21 cycles, , still Active on October 2022

In December 2020, during the Raprocan2012 cruise, two 3-head floats were deployed, one belonging to the Euro-Argo RISE project (3-head-Euro-Argo-RISE-2020 hereinafter) and one belonging to the NAOS project (3-head-NAOS-2020 hereinafter), a French project that set up a Deep-Argo pilot experiment in the North-Atlantic over the period 2011-2019 (Le Traon et al., 2020). On December 11th 2020, the two 3-headed floats were deployed at station 25 (Figures 2 and 3), at 29° 10.00' N - 018°29.80' W, with a bottom depth of 4244 m. The deployments were together with core floats equipped with RBR sensor on top from the WP2.

Before the deployment of the float, a full-depth CTD cast using a SBE911+ with dual CT sensors, and calibrated after the cruise, was carried out.

In the description of the work of the Grant agreement it was planned that IFREMER would deploy the NAOS 3-head deep Argo float in the Eastern North Atlantic Subpolar Gyre. However, we experienced delays in having the deep RBRsensor, and given that the Canary basin area is regularly surveyed by IEO oceanographic cruises, as indicated, and because its central and deep waters are being relatively stable over time, we decided to relocate the deployment to the Canary basin (see D3.1). This change did not affect the objective of the experiment, that is to assess the stability and accuracy of the deep Argo CTD sensors.

For the initially deployed 3-headed floats, the 3-head-NAOS-2020 float carried 35 good quality cycles before shortage of the battery recommended its recovery. In March 2022 it was successfully recovered. Due to water intake in the RBR sensor, we lost communication with the 3-head-Euro-Argo-RISE-2020. Fortunately, it was successfully recovered and refitted with new RBR sensors and a re-calibrated SBE sensors for redeployment in 2022. During this first at sea experiment, the float realized only 13 cycles and the RBR data were not usable. Data from this first deployment (3-head-Euro-Argo-RISE-2020) are not presented in this report.

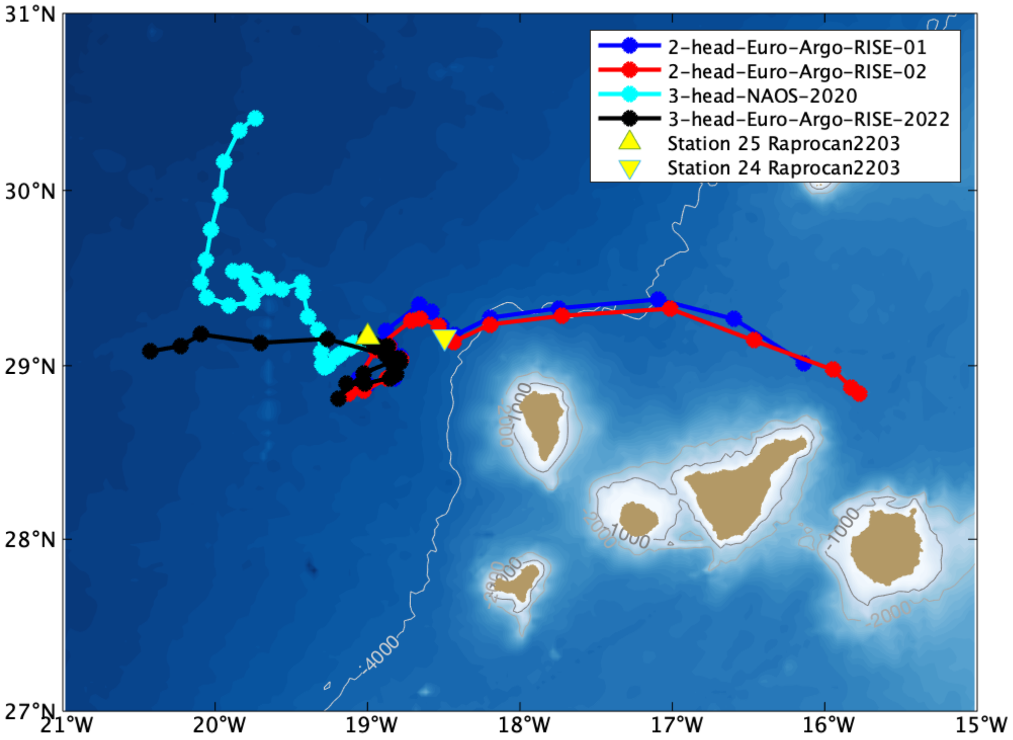


Figure 2. *Trajectories of the two 3-headed and the 2-headed floats used in this report, and the stations 24 and 25 from the Raprocan cruises.*

The refitted Euro-Argo RISE 3-head float (3-head-Euro-Argo-2022 hereinafter) and the two 2-head deep Argo floats (2-head-Euro-Argo-01 and 2-head-Euro-Argo-01 hereinafter) were deployed on 6th March 2022 during the Raprocan2203 cruise (Table 1). The three floats were deployed also at station 25 (Figure 2), at 29°10.00’N - 19°00.11’W, with a bottom depth of 4244 m. Before the deployment of the float, a full-depth CTD cast using a SBE911+ with dual CT sensors, and calibrated after the cruise, was also carried out.

After 19 cycles, the 2-head-Euro-Argo-01 float increased its energy consumption, and was recovered in September 2022. At the time of this report, the 2-head-Euro-Argo-02 is still active.

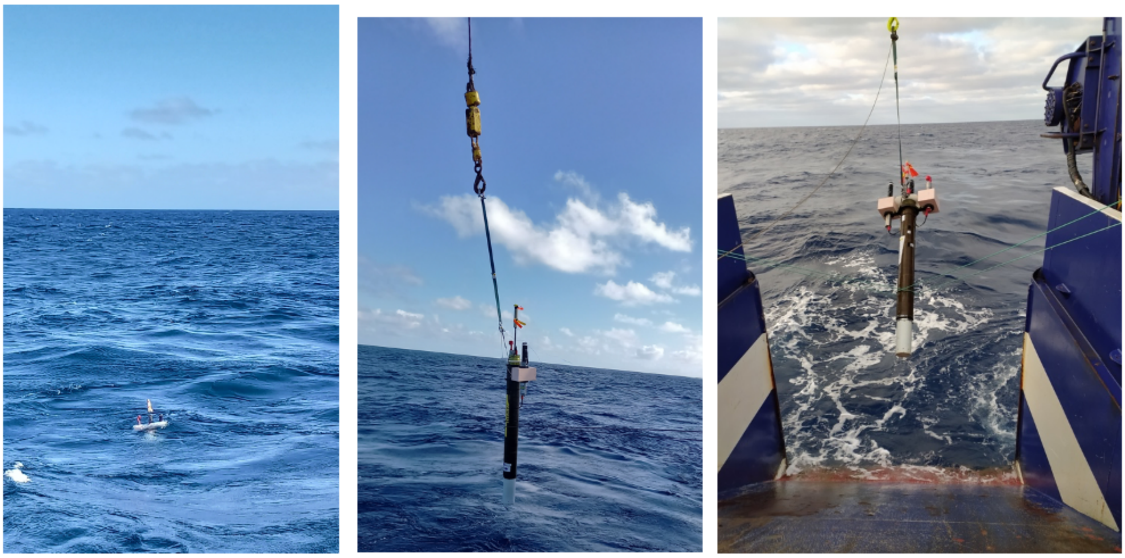


Figure 3. *Picture of the 3-headed floats (right 2020 and left 2022) and the 2-headed float (center) deployments*

Additionally, 5 UK funded Deep APEX floats, with SBE61, were deployed by NOC in January/February 2020 in the subtropical Atlantic, along the 25.5ºN hydrographic section. A UK funded Deep APEX float with 6000 dbar RBR CTD was deployed in December 2020 in the North Atlantic, however the float suffered early failure after 7 cycles, and therefore, unfortunately, nothing was learned about the performance of the RBR CTD. Five Deep APEX with SBE61 were deployed in the Argentine Basin between December 2020 and January 2021.

3 Float configurations

Strategy

For both, the 3-headed and 2-headed floats, the mission was divided into two stages:

- The first stage objective was to determine the coherence of the acquisitions between the SBE41, SBE61 and RBR sensors, and therefore, the sensors were configured to have high-resolution acquisition with observations every 30 s in the descent and ascent profiles, and every hour during the drifting at the parking depth. This stage lasted 3 cycles of the float with a 2 day period. The parking depth and profile depth was 4000 m

- The second stage objective was to determine the long-term stability of the sensors, and therefore the sensors were configured to measure high resolution profiles only during the ascent, at prefixed depths and every 6 hours during the drifting. Additionally, and to maximize the life expectancy of the float, the float cycle periods were lengthened to 10 days to evaluate the stability of the sensor with long temporal time series. The parking depth was 3000 m and the profile depth 4000 m

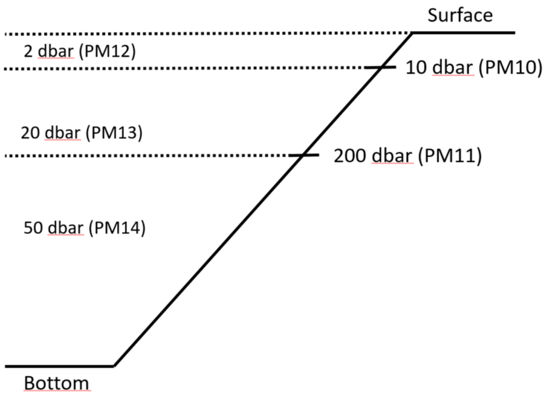
Sampling configuration

The floats had two sampling configurations, managed by two different electronic boards:

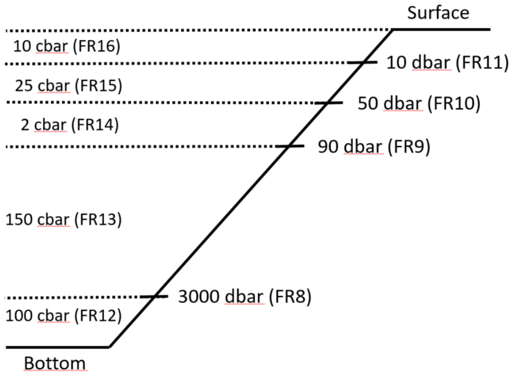
- one dedicated to the core-Argo mission, and only for the SBE41CP sensor;
- one dedicated to the 2-headed/3-headed sensor comparison, which powers and communicates with the two/three sensors: SBE41CP, SBE61 and RBR*argo*[3].

The following graphs shows the depth sampling strategies for both boards:

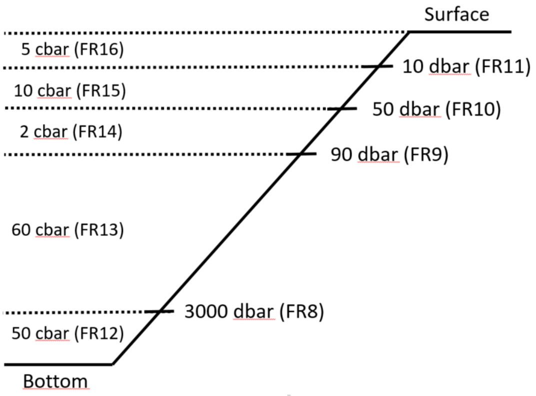
- for the Core-Argo, the SBE41CP acquisition (float mission parameters : PM10 to PM14) for both stage 1 and stage 2 would be :



- for the SBE41CP, SBE61 and RBR acquisition (acquisition PCB parameters : FR8 to FR16), stage 1 only:



- for the SBE41CP, SBE61 and RBR acquisition (FR8 to FR16), stage 2 only :



4 Pressure sensor assessment

The raw data reported by each pressure sensor was first corrected of any bias through surface pressure measurements that deviate from the expected zero value. The surface pressure measurement is realized at each float surfacing through a reset-offset command. The correction is either done internally or on shore through surface pressure measurements transmitted by the float. This procedure also corrects for the pressure difference due to the sensor position. As the surface measurements were not available for the SBE61 sensor on the 3-head floats, we applied a correction of 0.32 dbar to the SBE61 data to correct for the position of the SBE61 pressure sensor compared to that of the SBE41. Once the raw pressure data were corrected, we estimated the top to bottom mean value of the sensor difference averaged over all the cycles. The absolute value of the sensor to sensor difference is less than 2 dbar when considering the SBE41 and the SBE61 sensors. It is less than 0.5 dbar when considering the RBR and the SBE61 sensors, except on the NAOS float for which the difference was 4.1 dbar (Table 2).

Table 2. Top to bottom mean value and standard deviation of the pressure sensor difference in dbar averaged over all the cycles for the two 3-head and the 2-head floats.

	P_{RBR}-P_{SBE61}(dbar)	P_{SBE41}-P_{SBE61}(dbar)	P_{RBR}-P_{SBE41}(dbar)
3-head-NAOS-2020	4.1 +/- 3.2	2.0 +/- 2.0	2.1 +/- 1.4
3-head-Euro-Argo RISE-2022	0.5 +/- 0.8	1.7 +/- 1.4	-1.1 +/- 1.5
2-head-Euro-Argo RISE-01	- 0.3 +/- 1.1	-	-
2-head-Euro-Argo RISE-02	0.4+/- 1.1	-	-

The vertical structure of the difference (Figure 4) exhibits a non-linear pressure dependent pattern. The absolute value of the difference increases from 0 to about 5 dbar, except when comparing the SBE61 and RBR sensor on the 3-head-NAOS float. For this float, the pressure difference reaches about 10 dbar at 4000 dbar. Except in this latter case, the pressure difference between the sensors lies within the sensor accuracies.

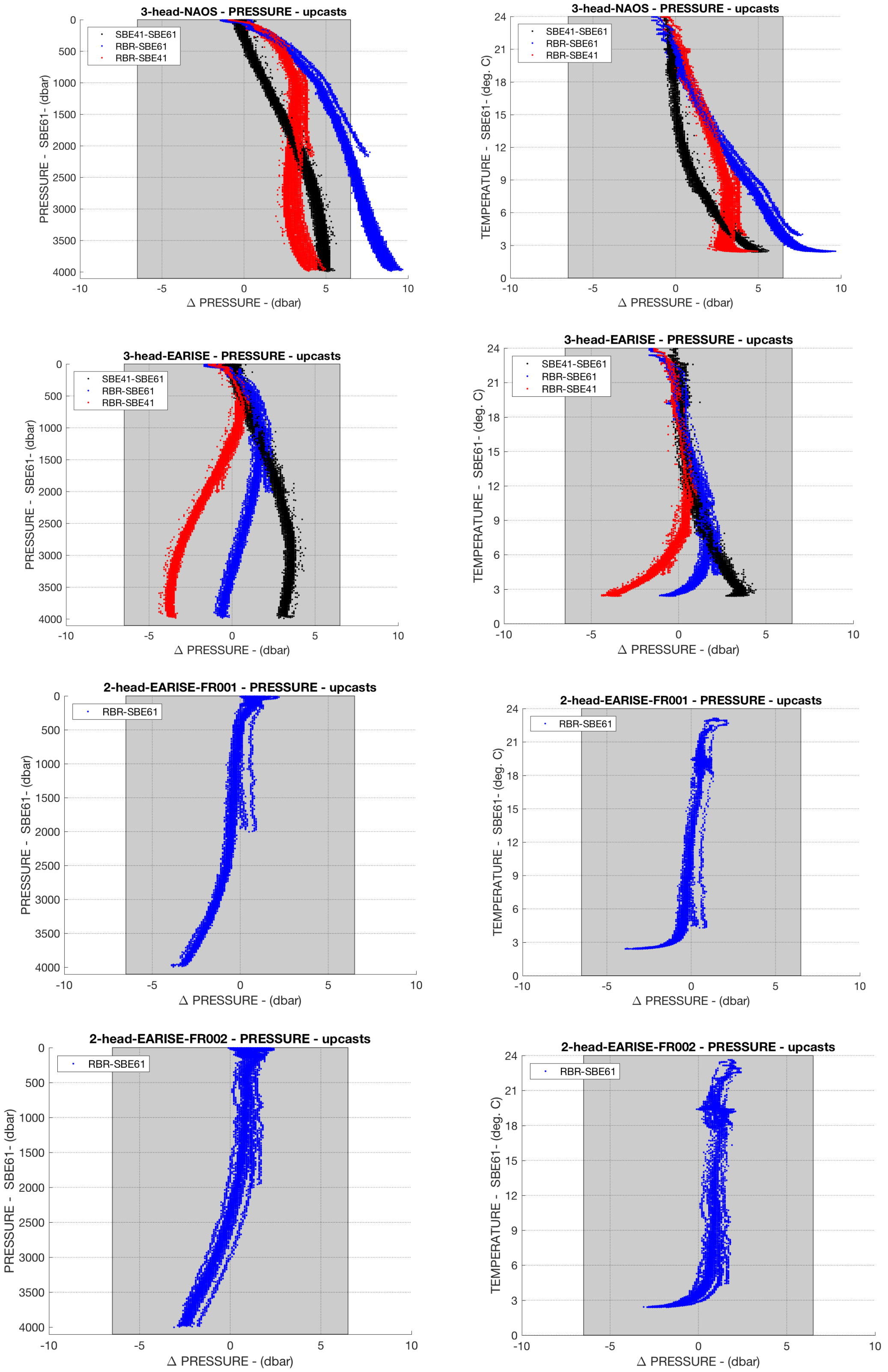


Figure 4. *Vertical structure of the pressure difference between the sensors as function of the SBE61 pressure (left panels) or SBE61 temperature (right panels). (Black dots) Difference between the SBE41 and the SBE61 sensors (panels (a),(b), (e) and (f)). (Blue dots) Difference between the RBR and SBE61 sensors. (Red dots) Difference between the RBR and the SBE41 sensors (panels (a),(b), (e) and (f)). The shading represents the sum*

of the SBE61 and RBR sensors accuracy (+/- 6.5 dbar). (a, e) 3-head-NAOS-2020 float. (b, f) 3-head-Euro-Argo-RISE-2022 float. (c,g) 2-head Euro-Argo-RISE-01 float. (d,h) 2-head Euro-Argo-RISE-FR002 float.

In Figure 4 it is shown the sensor to sensor difference as a function of the temperature. For the Euro-Argo RISE floats, that have the most recent SBE and RBR sensors, the difference between the RBR and the SBE61 sensor is rather constant from 24 to about 5°C. In this temperature range, the mean value (standard deviation) of the difference is 0.6 (0.9) dbar, 0.3 (0.5) dbar and 1 (0.4) dbar for the Euro-Argo-RISE 3-head, and 2-headed, FR001 and FR002 floats, respectively. At temperatures lower than 5°C, the difference abruptly increases to approximately 4 dbar. A similar structure is observed when comparing the SBE41 pressure sensor with that of the SBE61 on the Euro-Argo RISE 3-head float, with a mean difference (standard deviation) of 0.7 (0.8) dbar. We note that the difference starts to increase at 9°C, warmer than the 3°C for the SBE61, which reflects the difference in pressure calibration between the two SBE sensors. The SBE61 pressure receives a 4-point temperature compensation for pressure, while only two points are used for the SBE41CP.

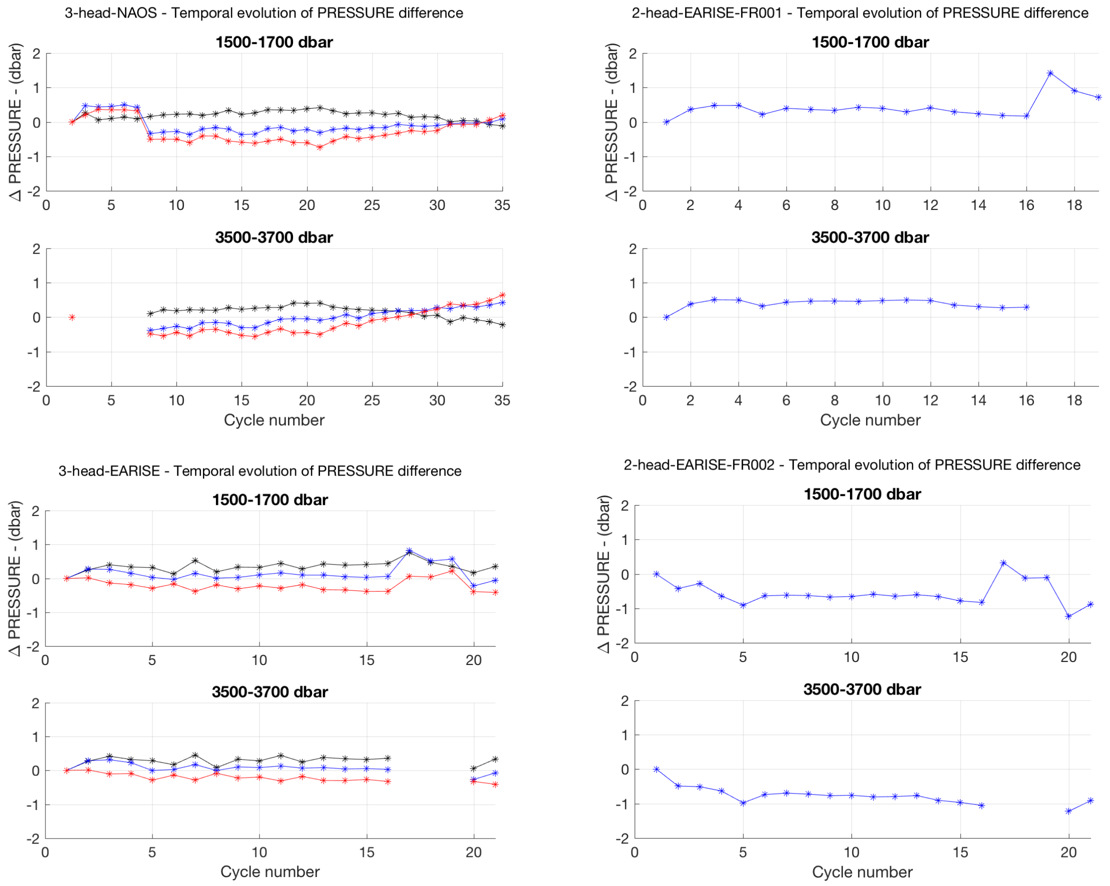


Figure 5: *Time-series of the pressure difference between the SBE41 and the SBE61 sensor (black dots), between the RBR and SBE61 sensors (blue dots) and between the RBR and the SBE41 sensors (red dots) in the 1500-1700 dbar layer and in the 3500-3700 dbar layer. (Upper left panel) 3- head-NAOS-2020 float. (Lower left panel) 3-head-Euro-Argo-RISE-2022 float. (Upper right panel) 2-head-Euro-Argo-RISE-01 float. (Lower right panel) 2-head-Euro-Argo-RISE-02 float.*

Regarding the stability over time, the difference between the pressure sensor (Figure 5) does not vary by more than ± 1.5 dbar over the cycles. The largest changes are observed between the RBR and SBE61 sensors when the profiling depth of the float changed from 4000 to 2000 dbar (Figure 4.1 and 4.2) revealing an hysteresis of at least one of the pressure sensors, although it is not possible to know which sensor is affected by the hysteresis, and longer time series are required to detect any significant long-term drift of the sensors.

The comparison between the RBR pressure sensor and the SBE61 pressure sensor is consistent for the three Euro-Argo RISE floats deployed in 2022 but differs, both in amplitude and vertical structure, from that of the 3-head-NAOS-2020 float deployed in 2020. The pressure difference was larger for the 3-head-NAOS-2020 float than for the Euro-Argo RISE floats. No significant changes can be noticed in the vertical structure of the difference between the SBE41 and the SBE61 sensors on the 3-head-NAOS-2020 and 3-head-Euro-Argo-RISE-2022 floats. This suggests that the performance of the RBR pressure sensor changed and improved with the second batch of floats.

5 Temperature sensor assessment

We first estimated the top-to-bottom median value of the temperature differences between the sensors. We considered the first 19 profiles for each float to ensure that the same number of profiles are taken into account in the average (Table 3).

Table 3: *Median value of the temperature differences between the sensors, considering the first 19 profiles for each float.*

	RBR-SBE61	SBE41-SBE61	RBR-SBE41
3-head-NAOS	0.001 ± 0.002 °C	- 0.001 ± 0.002 °C	0.002 ± 0.002 °C
3-head-Euro-Argo RISE-2022	0.002 ± 0.003 °C	- 0.001 ± 0.007 °C	0.003 ± 0.006 °C
2-head-Euro-Argo RISE-01	- 0.001 ± 0.003 °C	-	-
2-head-Euro-Argo RISE-02	- 0.001 ± 0.003 °C	-	-

We verified that the number of cycles considered do not affect the median and standard deviation values. The difference between the three temperature sensors lies between the sensor uncertainty (+/- 0.002°C) except when comparing the RBR sensor with the SBE41CP sensors for which the difference reaches 0.003°C on the 3-head-Euro-Argo-RISE-2022 float.

We also computed a mean vertical profile of the difference (Figure 6) considering the first 19 cycles and the median value of the temperature difference between the sensors over these cycles and in 20-dbar layers. For each sensor, the temperature values were taken at the same time stamp and reported at the pressure value of the SBE61 sensor.

For the 3-head-NAOS, 2-head-Euro-Argo-RISE-01 and -head-Euro-Argo-RISE-02 floats, the median value of the temperature difference between the sensors lies within ± 0.002°C, although it occasionally exceeds this value in the near surface layer. For the Euro-Argo RISE floats, the difference between the temperature sensors lies within ± 0.002°C but exceeds this range at shallower depths. The median value of the difference remains less than 0.004°C when comparing the RBR with the SBE61 sensor but exceeds ± 0.005°C in the upper 0-500 dbar layer when comparing the SBE41CP sensor with the two other sensors. Except for the 3-head-Euro-Argo RISE-2022 float, the three sensors provide temperature values that agree within the expected sensor accuracy, that is 0.001 or 0.002°C.

The temperature difference between the sensors is stable over time for the four floats and does not exhibit a significant trend (not shown).

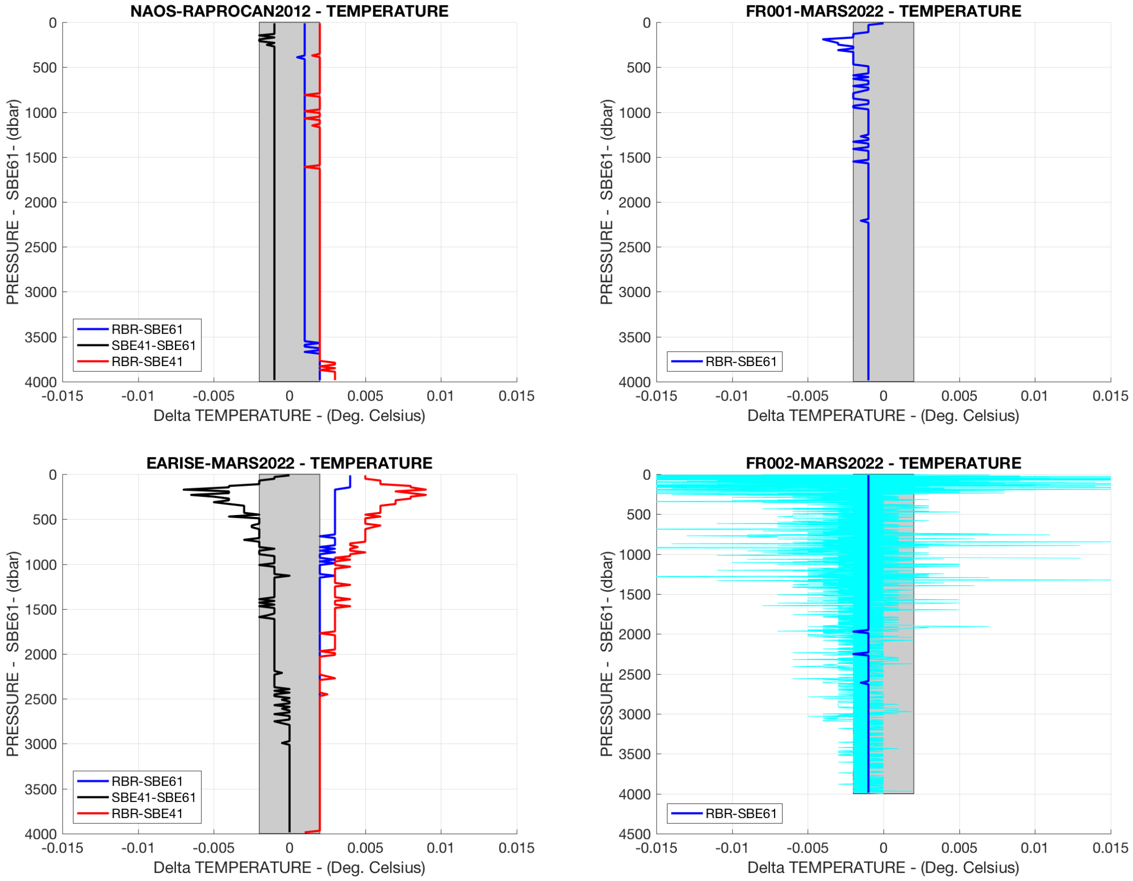


Figure 6. *Vertical profile of the temperature difference (deg. Celsius) between the SBE41 and the SBE61 sensor (black lines), between the RBR and SBE61 sensors (blue lines) and between the RBR and the SBE41 sensors (red lines). The median value is computed over the first 19 cycles of each float and in 20-dbar bins. (Upper left panel) 3-head-NAOS-2020 float. (Lower left panel) 3-head-Euro-Argo-RISE-2022 float. (Upper right panel) 2-head-Euro-Argo-RISE-01 float. (Lower right panel) 2-head-Euro-Argo-RISE-02 float. For this float, all cycles and pressure levels are plotted.*

6 Salinity and conductivity sensor assessment

6.1 SBE sensors: comparison to reference cast and CPcor correction

For each float and each sensor, the salinity data are compared on isotherms to the calibrated reference cast of the RAPROCAN2012 cruise (station 25, STA25 hereafter) (Figure 7).

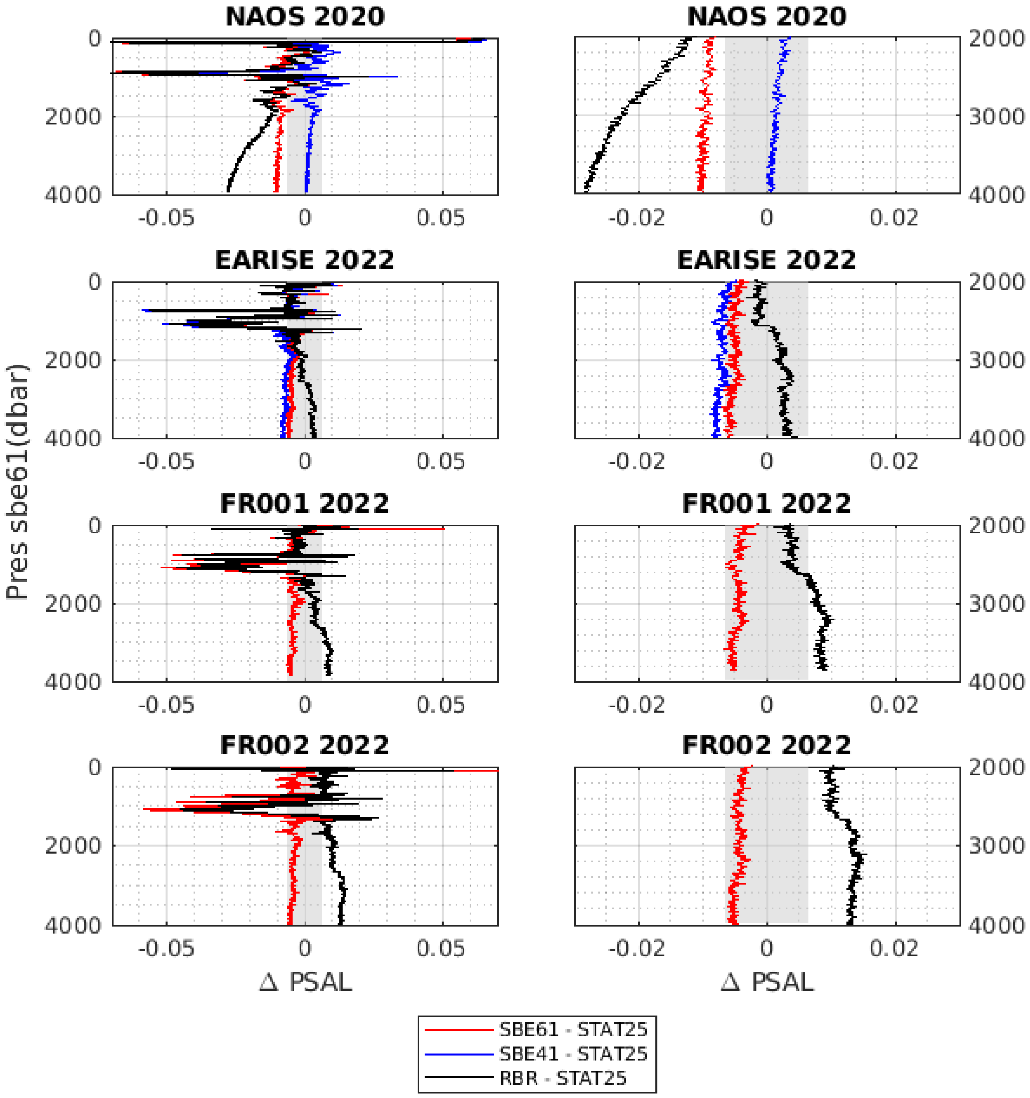


Figure 7. *(Left panels) Comparison of the salinity data of the first available ascending profile of the 3-head-NAOS-2020, the 3-head-Euro-Argo-RISE-2022 float, the 2-head-Euro-Argo-RISE-01 float and the 2-head-Euro-Argo-RISE-02 float (cycle 2 for the 3-head-NAOS-2020 float, cycle 1 for the other floats) with station STAT25, the calibrated ship-based CTD cast done at float deployment (station 25 of RAPROCAN2012 cruise). The comparison is made on float theta levels and the pressure of the SBE61 is used as the vertical axis. (Right panels) Same as the left panels but zoomed in the 2000 - 4000 dbar layer.*

The comparison reveals that the SBE sensors exhibit a pressure dependent bias compared to the CTD deployment cast, with a at 4000 dbar is about 0.002 fresher than the bias at 2000 dbar. In addition to this pressure dependency, most of the SBE sensors are biased toward fresher values, except for the SBE41 sensor on the 3-head-NAOS-2020 float, which is slightly saltier than the reference CTD profile On average, between 2000 dbar and 4000 dbar, the SBE61 sensor is biased fresh on the four floats. The averaged bias is -0.0096 on the 3-head-NAOS-2020 float, -0.0051 on the 3-head-Euro-Argo-RISE-2022 float and about -0.0040 on both 2-head Euro-Argo-RISE floats. The SBE41 salinity is saltier by 0.0014 on the 3-head-NAOS-2020 float and by 0.0071 on the 3-head-Euro-Argo-RISE-2022 float.

The SBE conductivity cell is known to have a pressure dependent response, and though SBE corrects this response through the use of a compressibility coefficient for the conductivity cell, referred to as CPcor, a residual pressure dependency of the SBE conductivity sensor has however been observed for deep floats and attributed to an incorrect value of CPcor (Kobayashi et al, 2021). The initial nominal value provided by SBE for CPcorr was -9.57e-08, although later on, SBE recommended a new standard CPcor coefficient (-11.6e-8) for both sensor types. The Argo Data Management Team thus recommends recomputing the float salinity using an updated CPcor coefficient (ArgoQCManual, Wong et al., 2022). New standard CPcor coefficients have been obtained by the Deep-Argo team by comparing a set of deep profiles with reference CTD data. These new standard CPcor coefficients are -13.5e-08 for the SBE41 sensor and -12.5e-08 for the SBE61 sensor. The reason for the difference between the two sensor types still remains unknown.

For each float, in delayed mode, it is also possible to determine an optimized value of CPcor based on a comparison with the calibrated reference profile made at float launch (STAT25). Optimized CPcor values have been computed for each float and each Seabird sensor and are given in Table 6.2. The optimized CPcor values obtained for the SBE41 sensors on the 3-head-Euro-NAOS-2020 and the 3-head-Euro-Argo-RISE-2022 floats (-11.66e-08 and -11.80e-08 respectively) are very close to the new standard CPcor value given by Seabird. The optimized CPcor values obtained for the SBE61 sensors on the 3-head and 2-head floats are slightly larger, ranging from -10.80 e-8 to -11.39e-8. Using the optimized CPcor value or the Seabird new standard CPcor value (-11.6e-08) clearly removed the pressure dependent salinity bias (see Figure 8). In contrast, the new standard CPcor values provided by the deep Argo team seems a slightly low, so that pressure dependency is over-corrected for some floats (e.g. SBE41 or SBE61 sensors on the 3-head-NAOS-2020 float or SBE41 sensor on the 3-head-Euro-Argo-RISE-2022 float). Therefore, we used the new standard CPcor value given by Seabird (-11.6e-08) to correct the salinity of both SBE41 and SBE61 sensors on the 2-head and 3-head floats.

Table 4. *CPcor and M values obtained by comparing the first ascending profile to the reference station (STA25) below 1500 dbar. A) optimized values and B) M values obtained when Ccpor is set to -11.6-08*

		A) Optimized values		**B) New Standard CPcor value (from SBE)**	
		CPcor_new	M	CPcor_new	M
3-head-NAOS	SBE41	-11.66e-08	0.999899	-11.6e-08	0.99990
	SBE61	-10.80e-08	1.000206	-11.6e-08	1.000109
3-head-Euro-Argo RISE-2022	SBE41	-11.80e-08	1.000103	-11.6e-08	1.000108
	SBE61	-10.91e-08	1.000087	-11.6e-08	1.000068
2-head-Euro-Argo RISE-01	SBE61	-11.30e-08	1.000065	-11.6e-08	1.000057
2-head-Euro-Argo RISE-02	SBE61	-11.39e-08	1.000058	-11.6e-08	1.000052

Once the CPcor value was applied, a conductivity ratio M obtained by comparison with STA25 below 1500 dbar was calculated (Table 4) and applied to the conductivity of SBE sensors. Using the new standard CPcor and M values there is an excellent agreement with the ship-based reference profile (Figure 8).

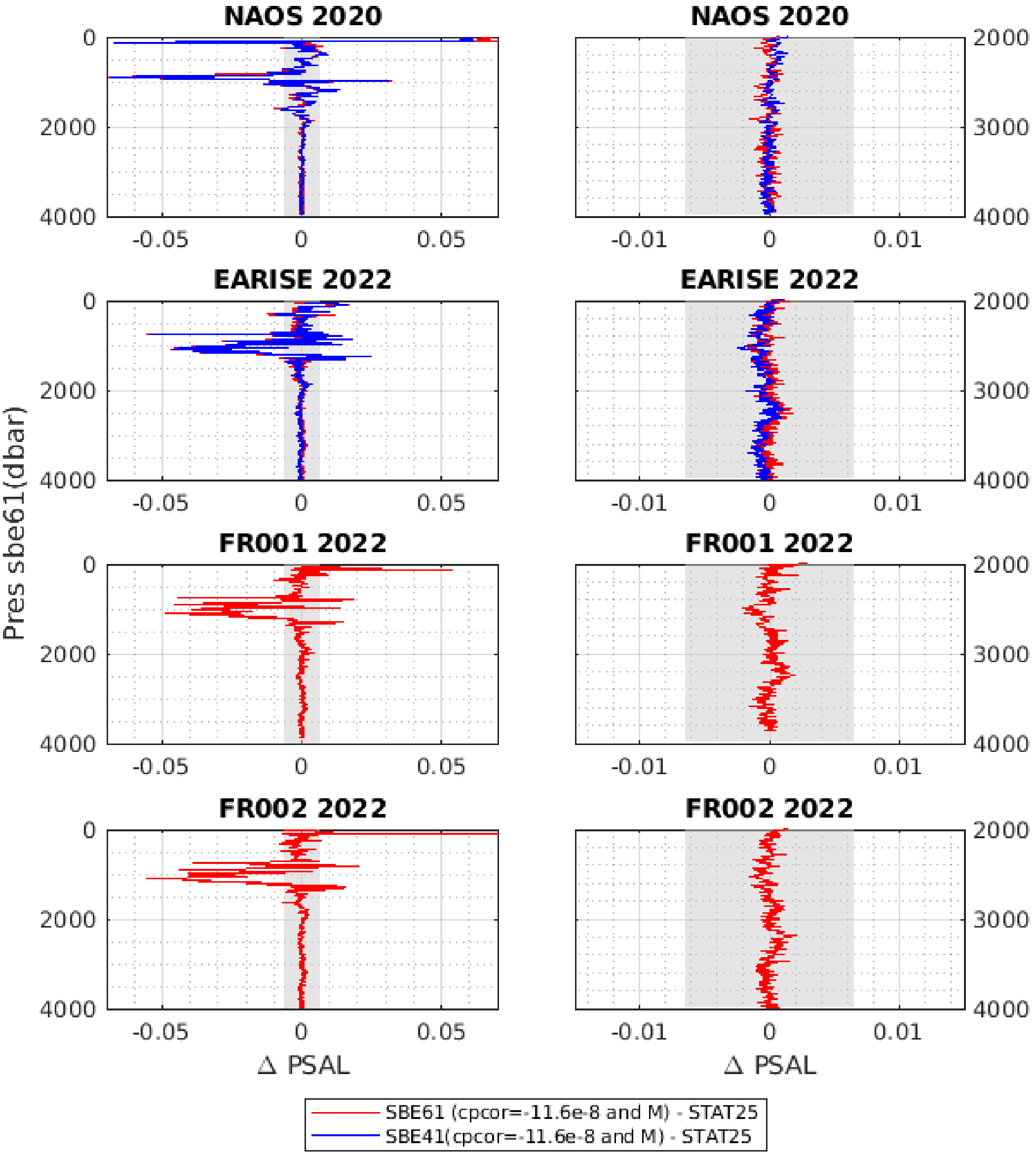


Figure 8. *(Left panels) Comparison of the salinity data of the first available ascending profile of the 3-head-NAOS-2020 float, the 3-head-Euro-Argo-RISE-2022 float, the 2-head-Euro-Argo-RISE-01 float and the 2-head-Euro-Argo-RISE-01 float (cycle 2 for the 3-head-NAOS-2020 float, cycle 1 for the other floats) with STA25, the calibrated ship-based reference cast done at float deployment (station 25 of RAPROCAN2012 cruise). The conductivity of the SBE sensors have been recomputed with the new CPcor value recommended by SBE (CPcor_new = -11.6e-8). A conductivity ratio M obtained by comparison with STA25 has been applied to the conductivity of SBE sensors (table 4). The comparison is made on float theta levels and the pressure of the SBE61 is used as the vertical axis. (Right panels) Same as the left panels but zoomed in the 2000 - 4000 dbar layer.*

6.2 RBR sensor: comparison to reference cast

The RBR sensor on the 3-head-NAOS-2020 float exhibits a much larger pressure dependency compared to the SBE sensors (Figure 7). The bias varies between -0.012 at 2000 dbar to -0.028 at 4000 dbar. This pressure dependency was the result of a compressibility coefficient that was not obtained to each sensor. After the deployment of the floats in 2020, RBR performs a pressure calibration of each sensor. Indeed, the pressure dependency of RBR sensors for the three floats deployed in 2022 is lower than for the 3-head-NAOS-2020 float, it varies between them and shows a knee shape at around 2600 dbar. The salty biases observed for 2-head-Euro-Argo-RISE-01 and 2-head-Euro-Argo-RISE-01 are 0.0067 and 0.0125, respectively, and within the accuracy for the 3-head-Euro-Argo-RISE-2022 float. The reason for this pressure response is not yet known, but RBR has been informed and is working on it.

It has to be noted that no further correction has been done to the RBR data in this report, while that for the SBE data, a CPcor and M coefficients were computed with the reference CTD cast performed at the deployment, as described in the previous section.

6.3 Sensors intercomparison

Once corrected with the new CPcor value recommended by Seabird (-11.6e-08) and the M coefficient (table 6.2), the averaged salinity difference between the SBE41 and SBE61 sensor is less than 0.001 at depths deeper than 1500 dbar for the two 3-head floats (figure 9). However, this difference is larger in the upper layer. For the 3-head-NAOS-2020 float, the difference is negative and close to -0.005 near the surface while for the 3-head-Euro-Argo-RISE-2022 float, the difference is positive and close to 0.004 near the surface. Since the salinity is calculated from conductivity, temperature and pressure, it is interesting to calculate the ratio of conductivity between the different sensors in order to rule out the effects of pressure and temperature differences between the two sensors (see the differences in figure 4 for pressure and figure 6 for temperature). The conductivity ratios between the SBE41 and the SBE61 sensor show a similar variation with pressure for both 3-head floats, they both decrease from the bottom to the surface to reach values < 0.9999 around 200 dbar. Therefore, the ΔS values observed in the upper layers for the 3-head-Euro-Argo-RISE-2022 float are mainly due to the difference in pressure and temperature of the two SBE sensors.

The averaged salinity difference between the SBE61 (or SBE41) sensor and the RBR sensor is also shown on figure 9. The same observations are made as when comparing the RBR data first profile to the STA25 reference station (see Figure 7), a residual dependence on pressure is visible and a knee shape is found around 2500 -2600 dbar. This knee shape is also visible for the 3-head-NAOS-2020 float whereas it was less obvious when the first profile was compared to the STA25 reference station. The conductivity ratios between the RBR and the SBE61 (or SBE41) sensor show very similar features, which demonstrates that the residual pressure dependence and knee shape are not the result of the temperature or pressure differences of the different sensors.

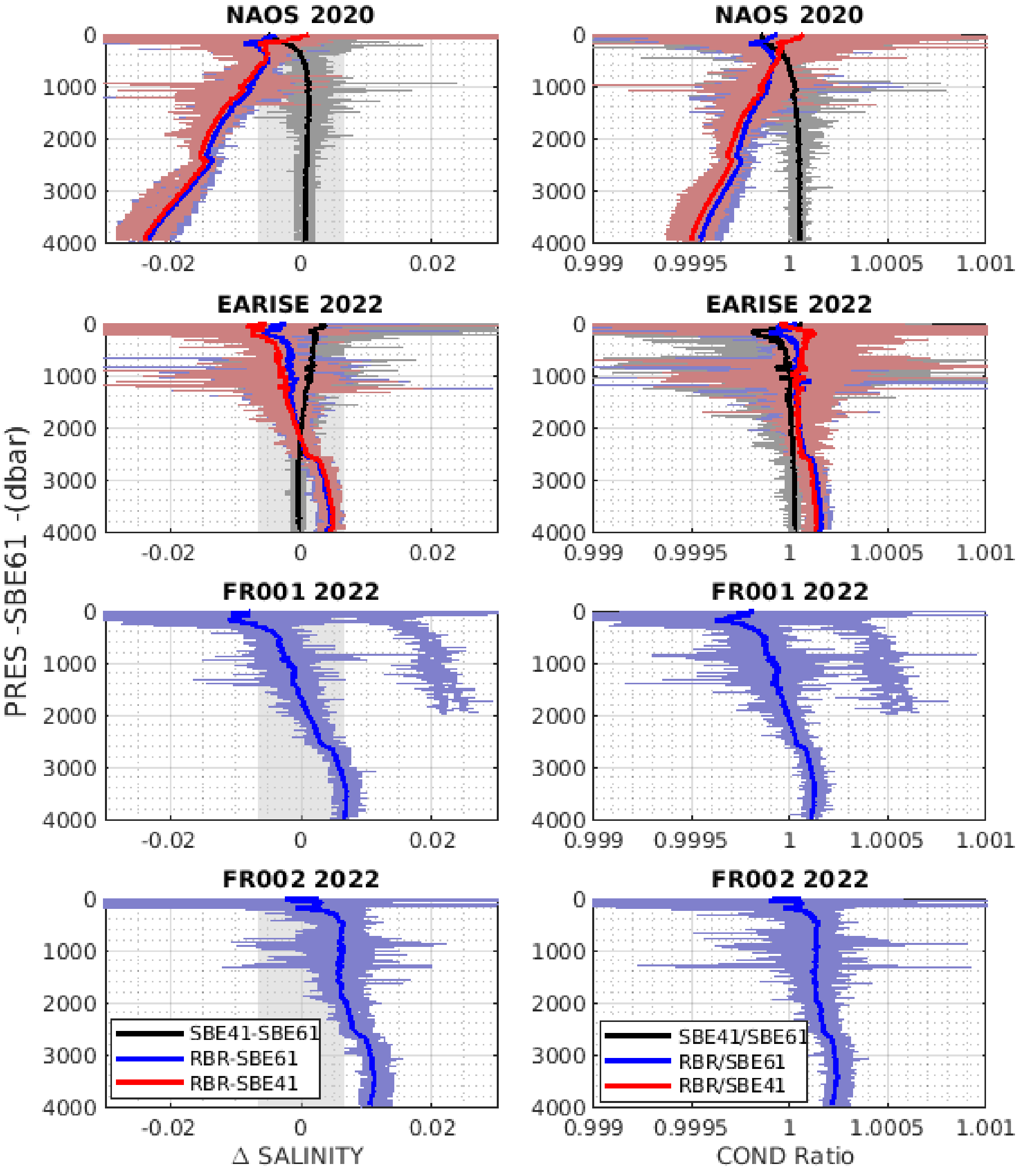


Figure 9. *Vertical profiles of the salinity differences (left panel) or the conductivity ratio (right panels) between the SBE41 and the SBE61 sensor, (gray lines) and the averaged vertical profile (black line), between the RBR and the SBE61 sensor, (shaded-red lines) and the averaged vertical profile (red line) and between the RBR and the SBE41 sensor, (shaded-blue lines) and the averaged vertical profile (blue line). The averaged vertical profiles have been computed from cycles 2-30 for the 3-head-NAOS-2020 float, from cycles 1-21 for the 3-head-Euro-Argo-RISE-2022 float, from cycles 1-16 for the 2-head-Euro-Argo-RISE-01 and from cycles 1-21 for the 2-head-Euro-Argo-RISE-02 float. The pressure axis is that of the SBE61. The conductivity of the SBE sensors have been recomputed with the new CPcor value recommended by SBE (CPcor_new=-11.6e-8). A conductivity ratio M obtained by comparison with STA25 has been applied to the conductivity of SBE sensors (table 4).*

6.4 Stability

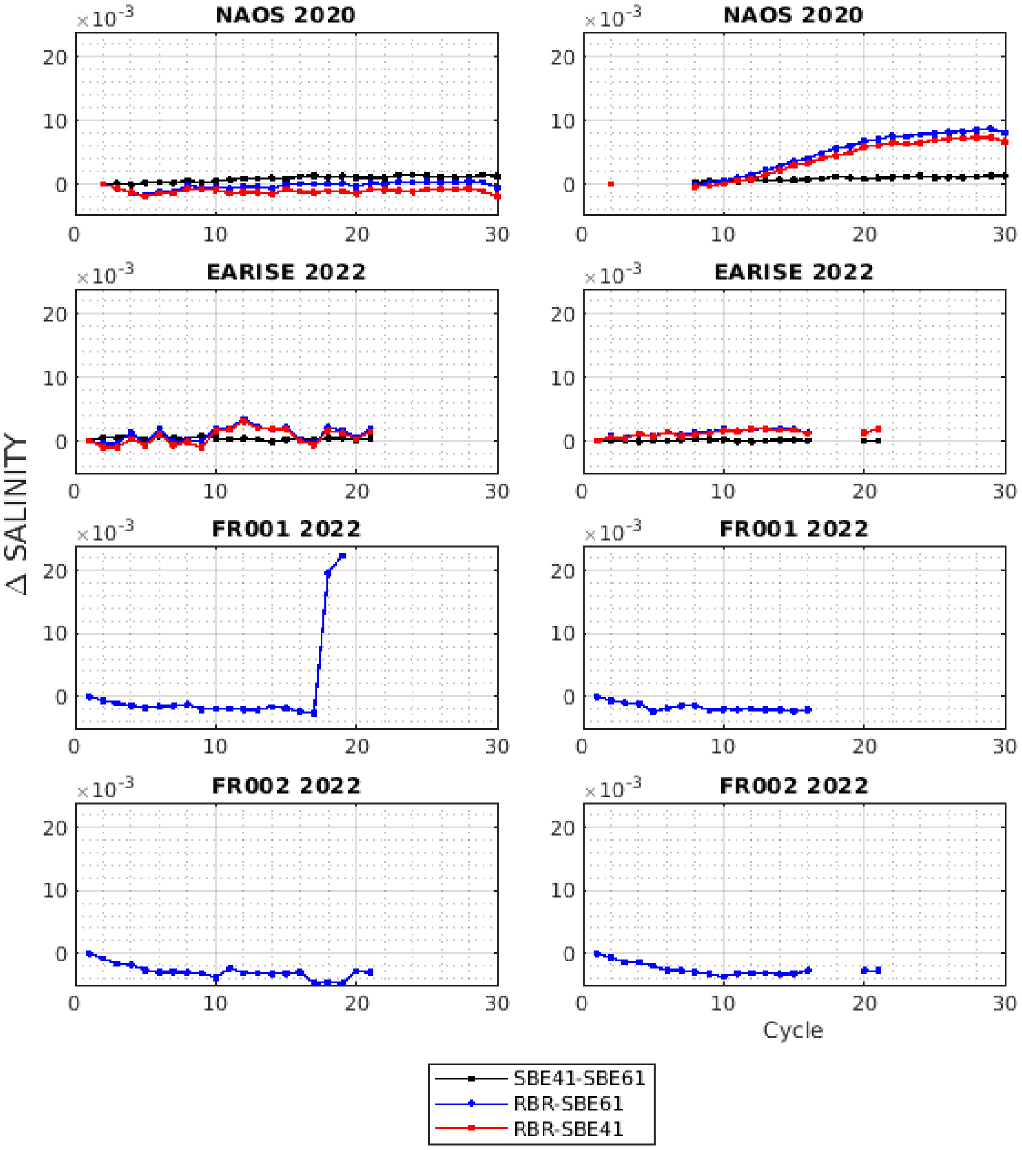


Figure 10. *Temporal evolution of the salinity difference, plotted as function of cycle number, and relative to the salinity difference of the first cycle. Differences between the SBE61 and the SBE41 sensors (black lines), between the RBR and the SB61 sensors (blue line) and between the RBR and the SBE41 sensors (red line) for the 3-head-NAOS-2020 float, the 3-head-Euro-Argo-RISE-2022 float, the 2-head-Euro-Argo-RISE-01 float and the 2-head-Euro-Argo-RISE-02 float. The salinity difference is averaged in the 1500-1700 dbar layer (left panels) and in the 3500 - 3700 dbar layer (right panels). The conductivity of the SBE sensors have been recomputed with the new CPcor value recommended by SBE (CPcor_new=-11.6e-8). A conductivity ratio M obtained by comparison with STA25 has been applied to the conductivity of SBE sensors (table 4).*

The temporal evolution of salinity differences between sensors is shown in Figure 10 for the 1500-1700 dbar and the 3500 - 3700 dbar layers. The salinity difference between the SBE41 and SBE61 sensors on the 3-head-NAOS-2020 and 3-head-Euro-Argo-RISE-2022 floats is overall very stable in both layers (there is a very slight increase of about +0.001 over 30 cycles for the 3-head-NAOS-2020 float).

The salinity difference between the RBR and the SBE61 (or SBE41) sensor shows a large increase for the 3-head-NAOS-2020 float in the deeper layers (about +0.008 between cycle 10 and 30), which is not observed in the shallower layers. RBR identified this problem and modified the sensor design to address it. As described before, the floats deployed in 2022 included this new version of the RBR conductivity sensor and the salinity difference between the RBR and the SBE61 (or SBE41) sensor is more stable in the deepest layer for these floats launched in 2022. For the 3-head-Euro-Argo-RISE -2022 float, we note a slight increase of about +0.002 over 20 cycles in the deepest layer.

The salinity differences between the RBR and the SBE61 sensor for the 2-head-Euro-Argo-RISE-01 and 2-head-Euro-Argo-RISE-02 floats exhibit a small decrease during the first 10 cycles (-0.002 to -0.004) and tend to stabilize thereafter. This could be caused by an anti-biofouling product leak onto the SBE61 sensor that was washed off after a few cycles. Indeed, this type of substance usually produces a fresh offset that gradually returns to normal (Argo QC manual, Wong et al 2022), so that the salinity difference between the RBR and SBE61 sensors would show a negative trend. The three Euro-Argo RISE 2022 floats (3-head and two 2-head floats) were programmed to profile at 2000 dbar for cycles 17-19. For the 2-head-Euro-Argo-RISE-01 float, the salinity of the RBR or SBE61 sensor shifted significantly (~ 0.02) on cycle 17 and 18 before the float was recovered on cycle 19.

Similarly, the temporal evolution of the salinity over the 2.5°C theta isoterm (Figure 11) shows an overall stability of the floats deployed during 2022. For the SBE sensors the difference with the reference CTD profile is within the accuracy for the three floats, and also the variability during the mission is within its accuracy. In the 2-head-Euro-Argo-RISE-01, the SBE61 sensor exhibits a slight initial trend that could be attributed to the anti-biofouling leak, which is washed off after a few cycles. The RBR sensors exhibit remarkable stability, within the accuracy of the sensors. All the RBR sensors exhibit an offset larger than the accuracy of the sensor, however it has to be noted that the RBR sensors were not calibrated against the reference CTD data, while that for the SBE data, a CPcor and M coefficients were computed with that reference CTD cast performed at the deployment.

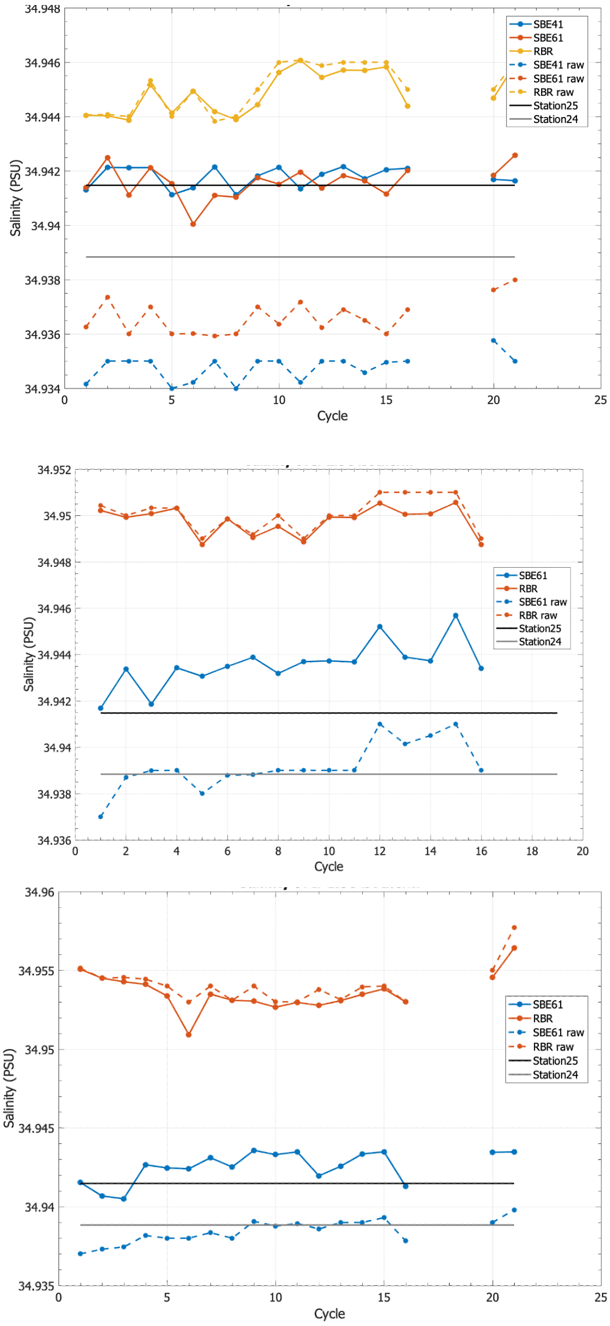


Figure 11. *Temporal evolution of the salinity over the 2.5ºC theta isoterm, plotted as function of cycle number, for the (top) 3-head-Euro-Argo-Rise-2022 float, the (middle) 2-head-Euro-Argo-Rise-01 and (bottom) 2-head-Euro-Argo-Rise-02 floats. The solid blue (SBE41), red (SBE61) and green (RBR) lines were computed using the corrected values (Pressure for all sensors and CPcor and M for SBE), while the dashed lines correspond to the uncalibrated values. The thick black (gray) line corresponds to the values for the reference CTD cast carried out at station 25 (24).*

Regarding the UK national experiments by NOC, of the 5 Deep APEX floats with SBE61 deployed in the subtropical Atlantic, 4 floats failed early, so that only one float provided a longer term test of the SBE61. That float has shown slow but correctable drift of the SBE61 conductivity. Data from this float support the conclusion that the value of CPcor originally recommended by SeaBird would lead to a small fleet-wide bias, and the data from the floats support the need to calibrate with in-situ observations to obtain the precise CPcor value.

Regarding the Deep APEX with SBE61 deployed in the Argentine Basin, the five floats are still working correctly in depths down to 6000 dbar, with small or correctable drift in conductivity, mostly associated with the need of a correct CPcor value.

7 Conclusion and final recommendations

Overall the difference between the pressure sensors lies within the sensor accuracy. The absolute value of the mean difference is less than 1 dbar when comparing the SBE61 and the RBR sensor (except for the *3-head-NAOS-2020* float). It is larger and reaches up to 2 dbar when comparing the SBE41 with the SBE61 sensor. The pressure difference between the sensors is stable in warmer temperatures (from 24 to about 5°C) and is less than 1 dbar on average. This difference increases in waters colder than 5°C where it can reach up to 5 dbar in absolute value. In the area where the floats were deployed, a large proportion of the water column were concerned by those largest differences as the isotherm 5°C was shallower than 2000 dbar there.
Recommendation: work with the manufacturer to improve the pressure sensor calibration in cold waters.

The temperature sensors of the SBE41CP, SBE61 and RBR agree within the expected sensor accuracy, that is 0.001 or 0.002°C in the deep layers. The differences can exceed sensor accuracy in the near surface layer and even exceed 0.005°C in absolute value when comparing the SBE41 with the two other floats.

Recommendation: investigate origin of the differences in temperature measurements in the near surface layer.

The pressure dependence of the SBE conductivity sensors is well corrected by applying the new standard CPcor value provided by SBE (-11.6e-08), and when this pressure dependence is removed, a conductivity ratio M can be calculated by comparison to the reference cast made at deployment. Once corrected for CPcor and M, the conductivity measured by the two SBE sensors are in very good agreement, and within the accuracy. Even if progress has been made (individual calibration and design modification), the conductivity of the RBR sensor still exhibits a residual pressure dependence and a knee shape at around 2500 dbar. For now, this pressure response prevents the conductivity from being adjusted to the reference cast by a M ratio as done for the two SBE sensors. It must be noted that it took 5 years for the Argo community to establish procedures to compute the CPcor and M values, while for the RBR a significant progress has been achieved between the deployments in 2020 and 2022.

Recommendation: **Continue interactions with RBR to solve the conductivity pressure response issue and reach the same level of accuracy as the SBE sensors after correction with the reference CTD profile carried out at the deployment.**

The time-serie of the 4 floats is too short to detect any significant trend in the sensors. Two floats are still active and the sensor behavior will be monitored. For pressure and temperature sensors, the monitoring would be achieved by a sensor to sensor comparison. For conductivity/salinity, we will also compare the salinity data to a reference database as described in Deliverable 3.4 (Euro-Argo RISE D3.4) and 3.5 (Euro-Argo RISE D3.5).

Recommendation: investigate long-term evolution of the sensor on the two last active floats.

These 3-head and 2-head intercomparison exercises are the only method to evaluate and help improve the performance of the deep RBR and SBE CTD sensors. The 3-head NAOS float revealed an issue with the initial design and calibration process of the RBR sensor, which was corrected, to the extent that RBR provided us with a newly designed RBR sensor that equips the floats deployed in 2022. Individual calibration of the conductivity is also done. While conductivity data of the RBR sensor still need to be improved, the pressure and temperature are already of the same quality as the SBE61 sensor. The collaboration between Euro-Argo RISE partners and the RBR company was of great benefit to assess and improve the quality of the deepRBR CTD sensor.

Recommendation: continue intercomparison exercises to evaluate future sensor design and calibration process (both RBR and SBE sensors). This could be done through the refit of the two recovered floats (3-head-NAOS-2020 float and 2-head-Euro-Argo-RISE-02 float) with new CTD sensors.

Despite the progress done so far by SBE and RBR, as well as by the Argo community in increasing the accuracy and stability of the CTD sensors, it is still necessary to carry out a reference CTD profile at the deployment site. Without this CTD profile, neither the SBE nor RBR sensors would achieve the needed accuracy.

Recommendation: calibrate deep Argo data with the reference CTD profile at the deployment site. Without this profile it is not recommended to deploy Deep Argo floats equipped with the actual RBRargo[3], SBE41 and SBE61 sensors.

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