Report on the evaluation of the RBRargo|2000 OEM sensor from at sea data analysis

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0.9	25.10.2022	Simo Siiriä,Laura Tuomi, Guillaume Maze, Kevin Balem, Ingrid Angel, Birgit Klein, Corinna Jensen	Version for internal review
1.0	07.11.2022	Simo Siiriä	Final Version after comments

EXECUTIVE SUMMARY

Only two sensors are commercially available for Argo floats, and until recently only SeaBird sensors were endorsed by the program. Having to rely on only one provider is a risk for operation in case for some reason the service is not available, or encounters considerable hindrances. For this reason Euro-Argo RISE studies the use of RBRargo^3 CTD on NKE's Argo-floats to increase the options for providers.

Based on the experiments in the Baltic Sea, and Open Oceans, the RBRargo^3 CTD (previously RBRargo|2000 OEM) performance seems acceptable for use in both environments, the possibility to measure even the topmost layer is a clear advantage. The detected drifts and pressure dependencies were able to be corrected with existing correction methods. Based on the pilot project results, the latest AST (Argo Steering Team, 2022) meeting decided to add the RBRargo^3 sensor in endorsed sensors for the Core Argo missions.

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1 Introduction

Most of the CTD sensors currently in operations are produced by SeaBird. Having to rely on only one provider is a risk for operation in case for some reason the service is not available, or encounters considerable hindrances. For this reason Euro-Argo RISE studies the use of RBRargo[3] CTD on NKE's Argo-floats to increase the options for providers.

At-sea tests of the developed Arvor-RBR floats were performed in both Baltic Sea and open oceans.

Baltic Sea was chosen as one test environment as it provides a very different environment compared to open oceans: the profiling depth stays relatively shallow, slightly over 200 metres at maximum, and the area has low salinity. Yet the temperature and salinity gradients can be large within one profile.

The open ocean tests were done in the Northern Atlantic. These floats provided information of the sensor performance in the depth of up to 2000 metres and in higher and more typical salinities. As a reference for the tests performed within Euro-Argo RISE, a description of national work on sensor comparisons is included in chapter 3.

2 Euro-Argo RISE Experiments

2.1 Experiment descriptions

2.1.1 Bothnian Sea Experiment

The Bothnian Sea prototype was deployed on 21/05/2021 (WMO 6903710) from r/v Aranda, and until 28/06/2022 has measured 210 profiles, continuing its mission. The float remained near its deployment location (61.4 °N, 20.18 °E) for the first hundred cycles, then started to drift northwards, reaching (62.63 °N 19.80 °E) at its northernmost point to date. This is rather typical behaviour for the floats in the area (Figure 1).

Other floats were operating on the same area, and can be used as comparison, together with CTD measurements taken from the ship. Suitable Argo missions are WMO 690711, which has followed a similar route than the prototype, and floats WMO 6903699 and 6903702, which have stayed relatively stationary between 21/05/2021 - 28/06/2022. Float WMO 6903698 was also active during the time, but is not suitable for comparison, since it didn't end up near the prototype. The routes are plotted together with the WMO 6903710 in Figure 1.

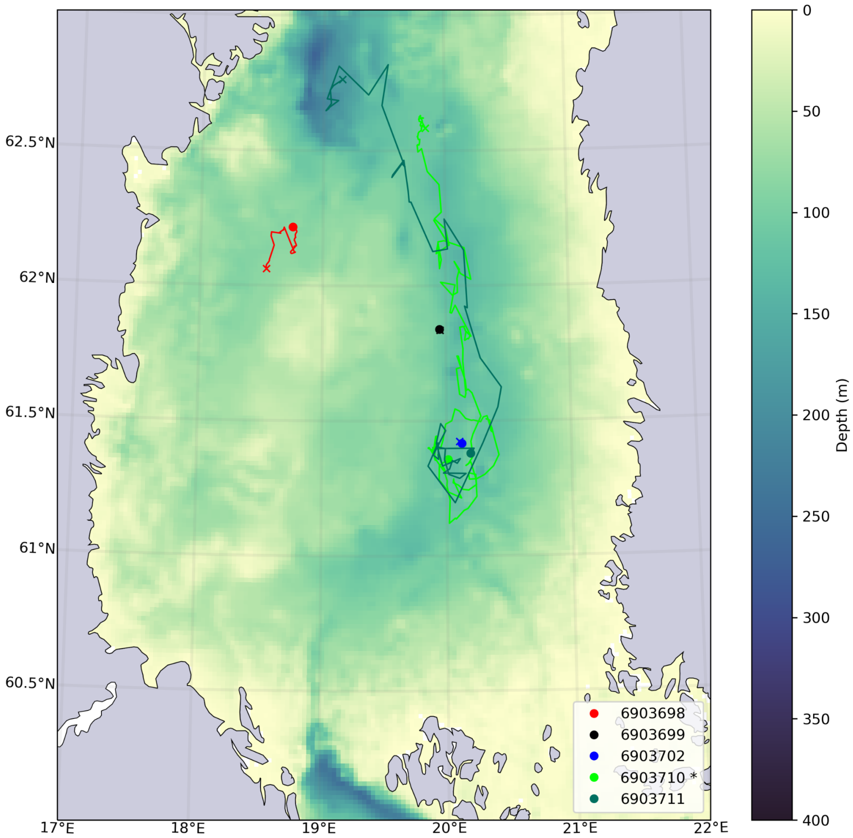

Figure 1: Trajectory of the prototype (WMO 6903710, bright green), and the other floats active during the mission. Dot shows the point of the first measurement of the period and x the last.

2.1.2 Baltic Proper Experiment

The Baltic Proper prototype was deployed on 19/05/2021 (WMO [6903709]) from r/v Aranda, and measured 262 profiles, until 10/10/2022 when it was recovered. During its mission, the float remained within the Gotland Deep area (Figure 2)

Gotland Deep area in the Baltic Proper is the most active Argo operation area in the Baltic Sea. As such, there are several floats that can be used for comparisons. Floats and trajectories active during the mission are shown on Figure 2. WMO 6903708 is an APEX float deployed by FMI at the same time as the prototype, WMO 6903706 another Euro-Argo RISE project prototype with RAMSES sensor (further explained in deliverable D4.12) and WMO’s 3902110, 6904116, 6904117, 6904226, 7900587 are active floats operating in the area.

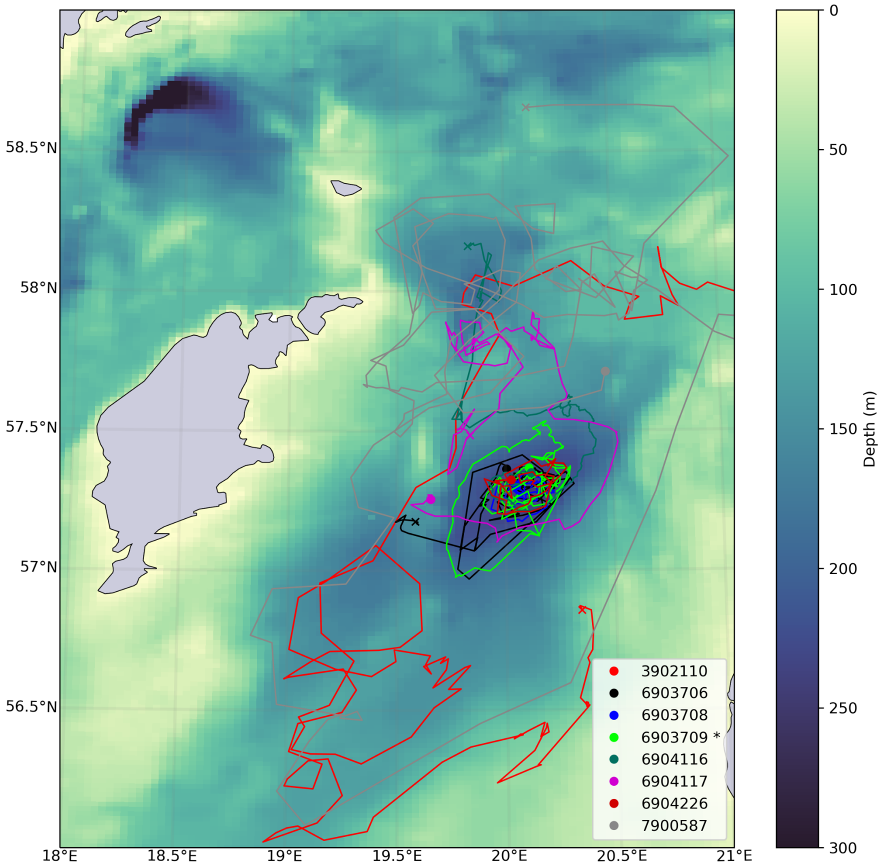

Figure 2: Trajectory of the prototype (WMO 6903709, bright green), and the other floats active during the mission. Dot shows the point of the first measurement of the period and x the last.

2.1.3 North Atlantic Experiment

Two ARVOR-I RBR floats, equipped with an RBRargo[3] CTD, were deployed on Dec. 11[st] 2020 during the IEO cruise RAPROCAN2012 in the Canary Basin (see Figure 3 below). During this campaign, two 3-headed Deep-Arvor, equipped with SBE41CP, SBE61CP and RBRconcerto[3] CTDs, have also been deployed, which could be helpful for inter-comparison of the results.

The deployment was the following:

- The two Arvor-I RBR were deployed during station 24, where we have a long time series, and along one Arvor-I SBE41 and the two 3-headed floats (from Euro-Argo RISE WP3) ;

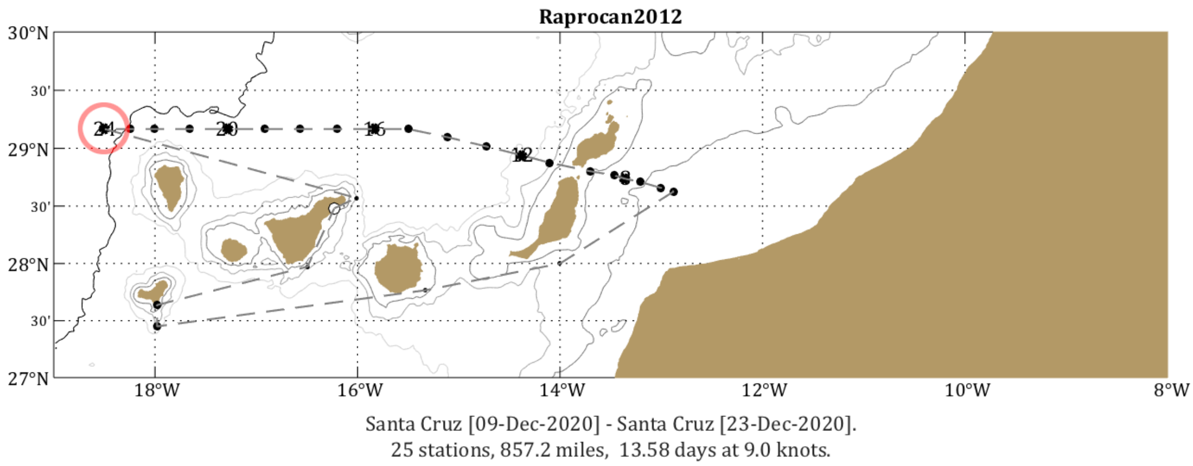

Figure 3: Map of the planned deployment in the Canary Basin during Raprocan2012 cruise in December 2020, Station 24 highlighted with a red circle.

Deployments were made after a CTD cast using a SBE911+ with dual CT sensors. The deployment has been carried out using a crane, ensuring the floats were deployed smoothly and safely (Figure 4).

All technical details on the floats configuration can be found in the Euro-Argo RISE Deliverable 2.2 "[RBRargo|2000 OEM sensor and float experiment description]".

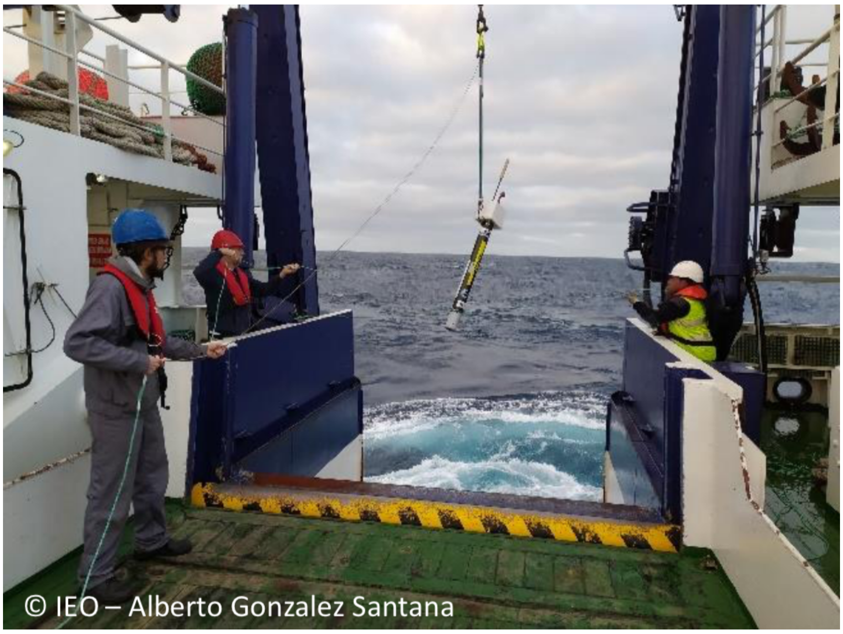

Figure 4: Arvor-I/RBR float deployment on the morning of Dec. 11st 2020.

Table 1: Coordinates of deployments of the 3 core Argo floats

	AI3500-20FR001 Arvor-I/RBR WMO 6903075	AI3500-20FR002 Arvor-I/RBR WMO 6903076	AI2600-19FR105 Arvor-I/SBE WMO 6903010
Date time	11/12/2020 8:45	11/12/2020 8:19	10/12/2020 16:29
Latitude	29°09.9928N	29°09.9928N	29°09.975N
Longitude	18°59.8373W	19°00.1417W	19°00.252W

2.2 Results

The performance of the RBRargo[3] sensor in the Baltic Sea was analysed by comparing the profiles acquired by the RBRargo[3] sensor, with the closest profiles acquired by Argo floats with SeaBird CTD sensor. The closest matches were selected from the available floats (shown in figure 1 for Bothnian Sea experiment, and in figure 2 for Baltic Proper experiment) using weighted distance in time and location as described in (Siiria et al. 2019). In brief, the time difference in days is multiplied by 3 and added to the profile distance in kilometres. Figure 5 shows an example of the time/space and total distance determined this way as an example between floats WMO 690709 and 690708. Each profile from the studied float was matched with the closest profile from each float in the area. All these matches were then sorted by proximity, and 15 closest matches of all were used to further check sensor comparability.

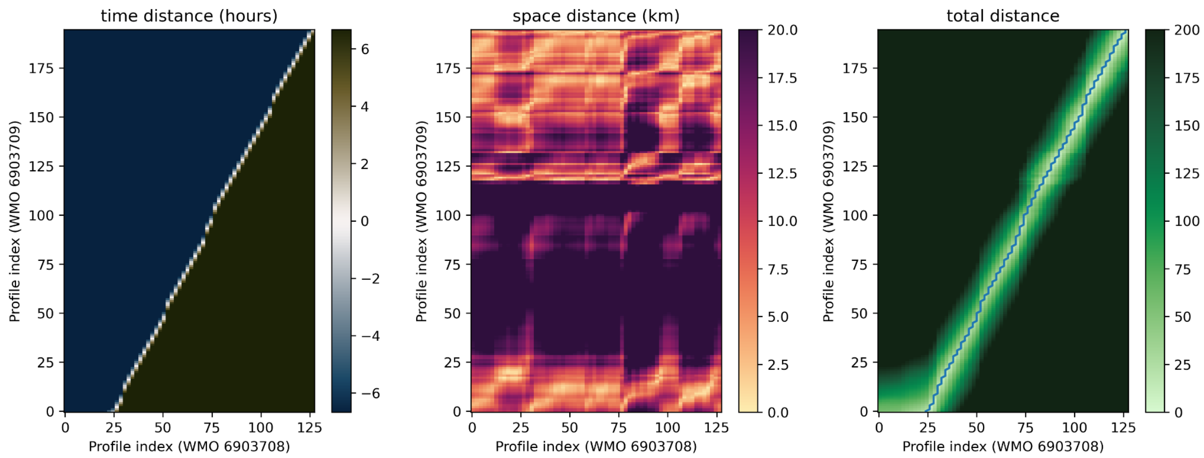

Figure 5: Example of the float distance development for floats WMO 6903709 (The Baltic Proper RBR float) and WMO 6903708 (Finnish national float). Leftmost shows the time difference (-6 to 6 days) between floats, middle one the distance in kilometres (up to 20 km). Rightmost illustrates the combination of the two, the blue line shows the best matching profile from WMO 6903708 for each of the WMO 690709's profiles.

2.2.1 Bothnian Sea

First year profiles of the float WMO 6903710 are shown on Figure 7, and in Figure 8 as a timeline. Overall, the float performed well. After the initial tests, it didn't require any changes in the mission parameters, and as of writing keeps profiling in the area. Clear advantage for RBRargo[3] CTD compared to the SeaBird one, is the ability to measure the very surface of the water column (Figure 9). The time-line presentation of the mission (Figure 6.) shows however, that in few profiles the surface data, down to 4-8 metres, is missing.

Based on the comparison with the SeaBird CTD Argo floats, the RBR measurements are in line: Figure 9 illustrates 8 best matches of the temperature and salinity profiles, and the distance of the measurements. All in all, when the measurements are near each other, they are very similar. When calculating average bias over the water column for the 15 closest matches, the bias between the RBR float and the others was -0.017 °C with standard deviation of 0.31 °C, and for salinity the bias was -0.002 PSU with standard deviation of 0.035 PSU. As both biases are over an order of magnitude smaller than the standard deviation between the sample, there can not be said to be any bias between the RBRargo[3] and SeaBird sensor based on these comparisons in the Bothnian Sea environment.

In general, based on this experiment, the RBR sensor performs well in the Bothnian Sea. There are few cases where the measurement data has stopped before the surface (Figure 8). In addition one profile (119) had near zero salinity (0.039) at the surface measurement. Some profiles (63, 74) have atypical jumps in salinity, which could be errors of measurement. These anomalies can be spotted on the salinity plot around 30m depth (Figure 7). On the other hand RBR sensor lacks the problem of incorrect surface layer salinity, which occasionally breaks the profile in SeaBird CTD. For this problem, see further details and examples in deliverable 2.7 (Klein et. al. 2022).

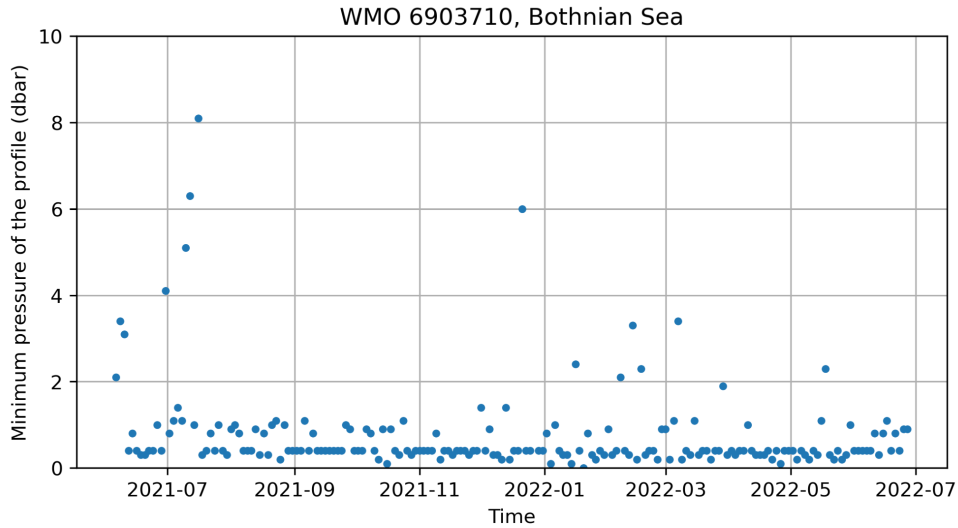

Figure 6: Minimum depth of each profile on the WMO 6903710, Bothnian Sea.

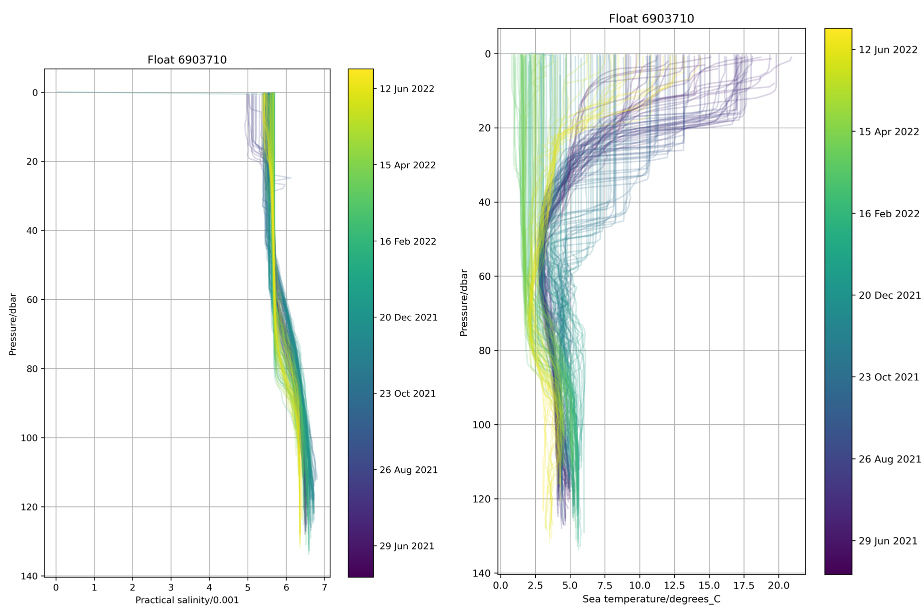

Figure 7: Salinity (left) and temperature (right) of each profile for the Bothnian Sea prototype.

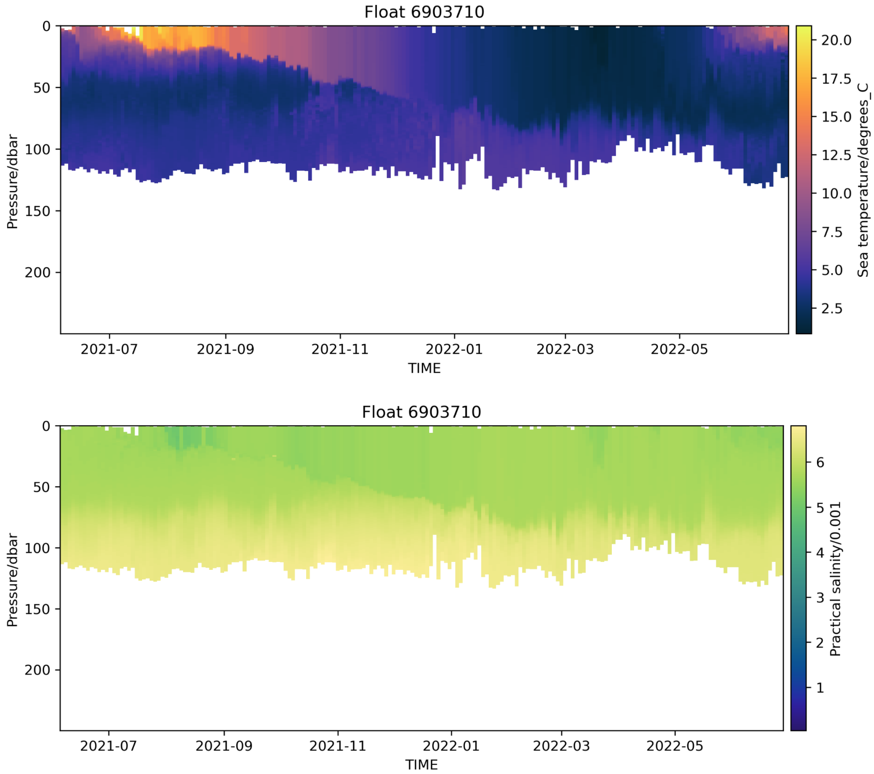

Figure 8: Temperature (up) and salinity (down) of each profile for the Bothnian Sea prototype on timeline. The development of the mixed layer can be well monitored from the dataset. White spots on the upper data show that even if the float measures to the surface in most of the cases, occasionally the data is missing from the last metres.

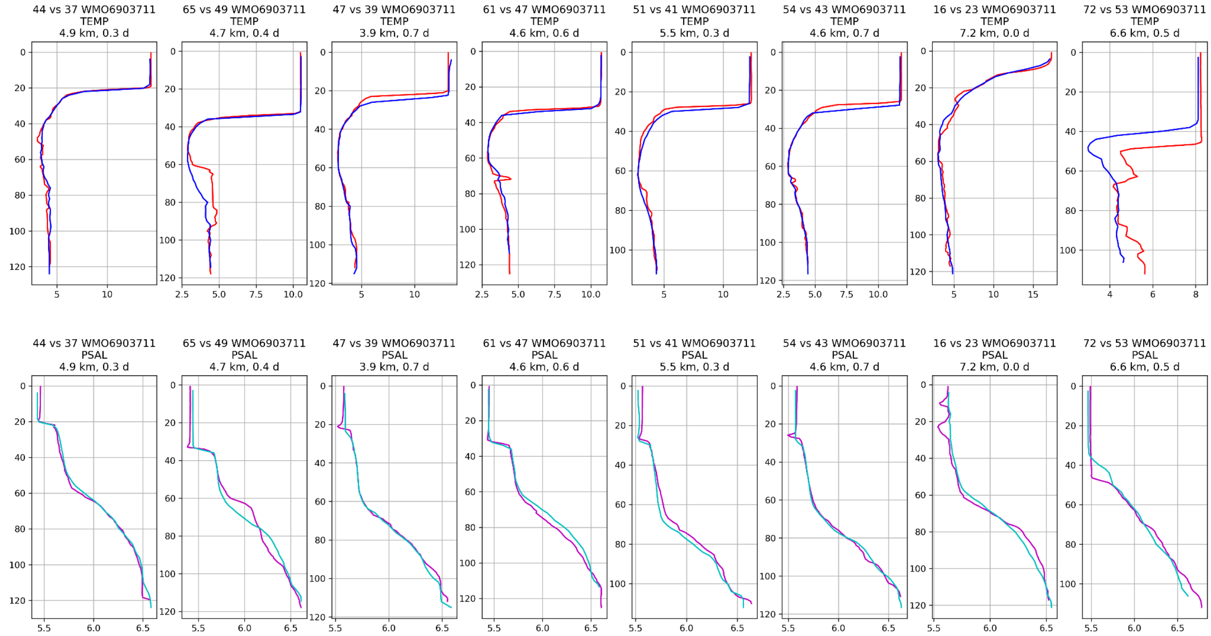

Figure 9: Eight closest matches for float WMO 6903710 from the other floats in the area. Ordered by match quality, the leftmost are the closest matches. Above the temperature, below salinity. Red/magenta profiles are from WMO 6903710, blue/cyan from the comparison floats. The comparison float, and distance in kilometres, and days is given above each profile figure.

2.2.2 Baltic Proper

First year of the float WMO 6903709 profiles are shown on Figure 11, and in Figure 12 as a timeline. As with the Bothnian Sea float, after the initial adjustment of the mission, the float managed to perform its mission without the need for further adjustments, and stayed on the designated area. Similarly as with the Bothnian Sea float, RBRargo[3] CTD manages to measure the surface layer, although in few profiles the data on the top layer is missing here as well (Figure 12)

Similar comparison to the SeaBird CTD floats was made as in the Bothnian Sea: Figure 13 illustrates 8 best matches of the temperature and salinity profiles, and the distance of the measurements.

The average bias over the water column for the 15 closest matches was -0.04 °C with standard deviation of 0.122 °C, and for salinity the bias was 0.0045 PSU with standard deviation of 0.05 PSU. As with the Bothnian Sea, here too, both biases are over an order of magnitude smaller than the standard deviation between the samples, so no relevant bias can be said to exist based on these comparisons.

Based on these results, the RBR sensor performs well in the Baltic Proper. In some profiles the measurement data has stopped before the surface (Figure 10 and 12). In the datafiles this does not show as missing values, but rather with the first depths being 2-10 metres as compared to near 0. Figure 10 shows the minimum depths on each profile. Typically the depth is less than one metre, but occasionally, it has stopped after 4 to 9 metres (See Figure 10).

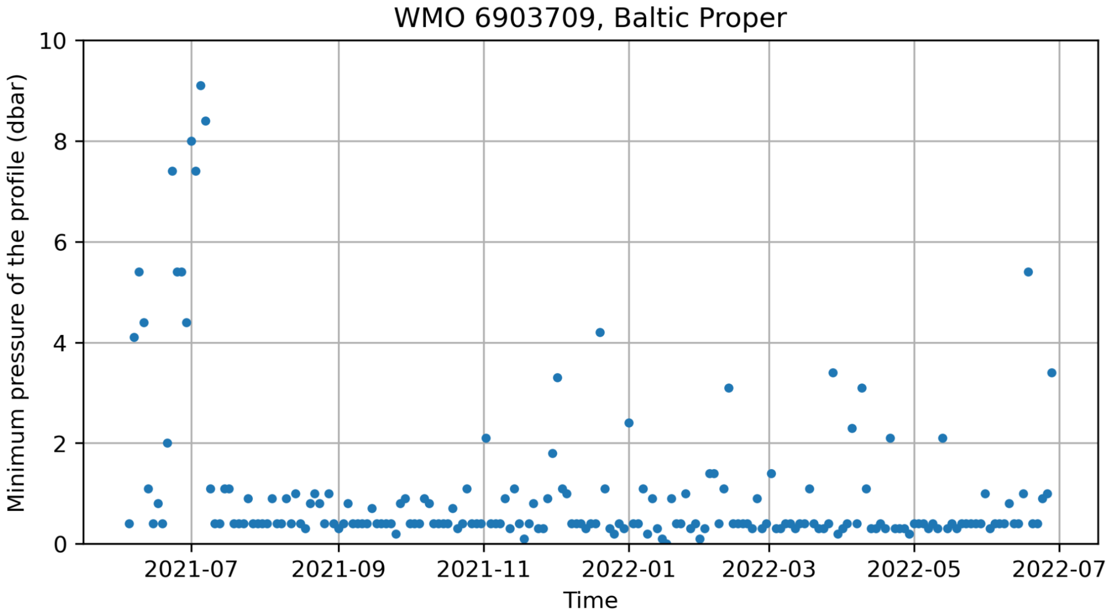

Figure 10: Minimum depth of each profile on the WMO 6903709, Baltic Proper.

In six profiles (46, 53 ,58, 74, 75 and 201) the float has recorded two consequent missing data points near the thermocline.

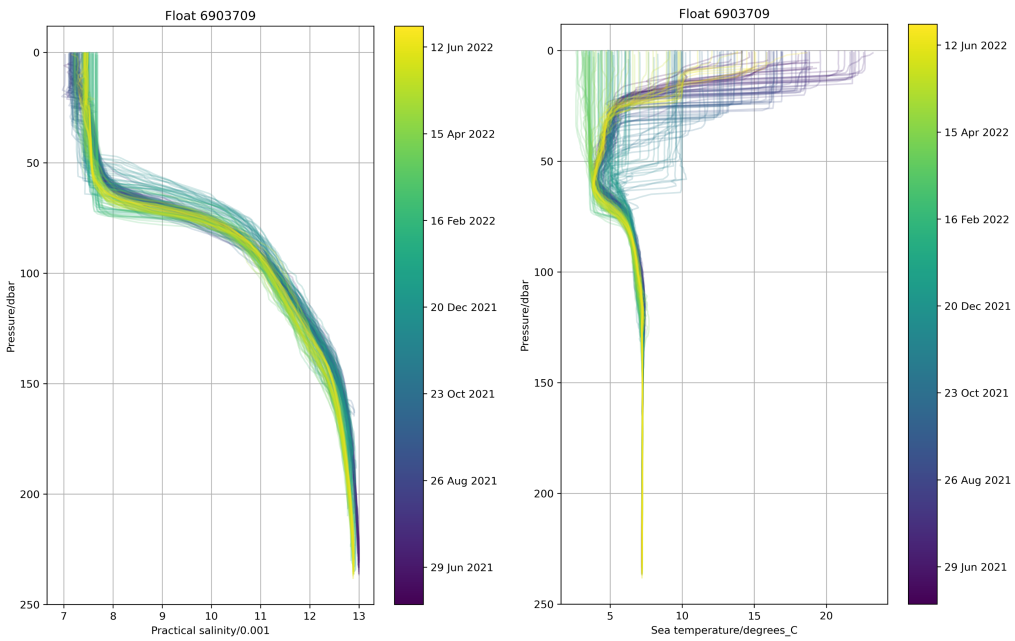

Figure 11: Salinity (left) and temperature (right) of each profile for the Baltic Proper prototype.

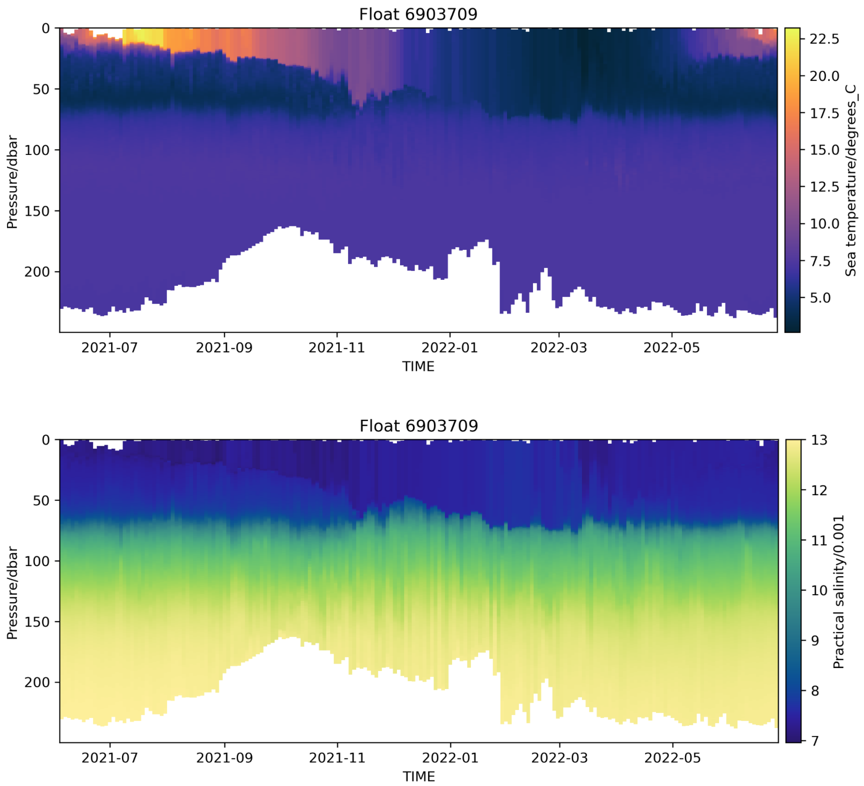

Figure 12: Temperature (up) and salinity (down) of each profile for the Baltic Proper prototype on timeline. The development of the mixed layer can be well monitored from the dataset. White spots on the upper data show that even if the float measures to the surface in most of the cases, sometimes the data is missing from the last metres.

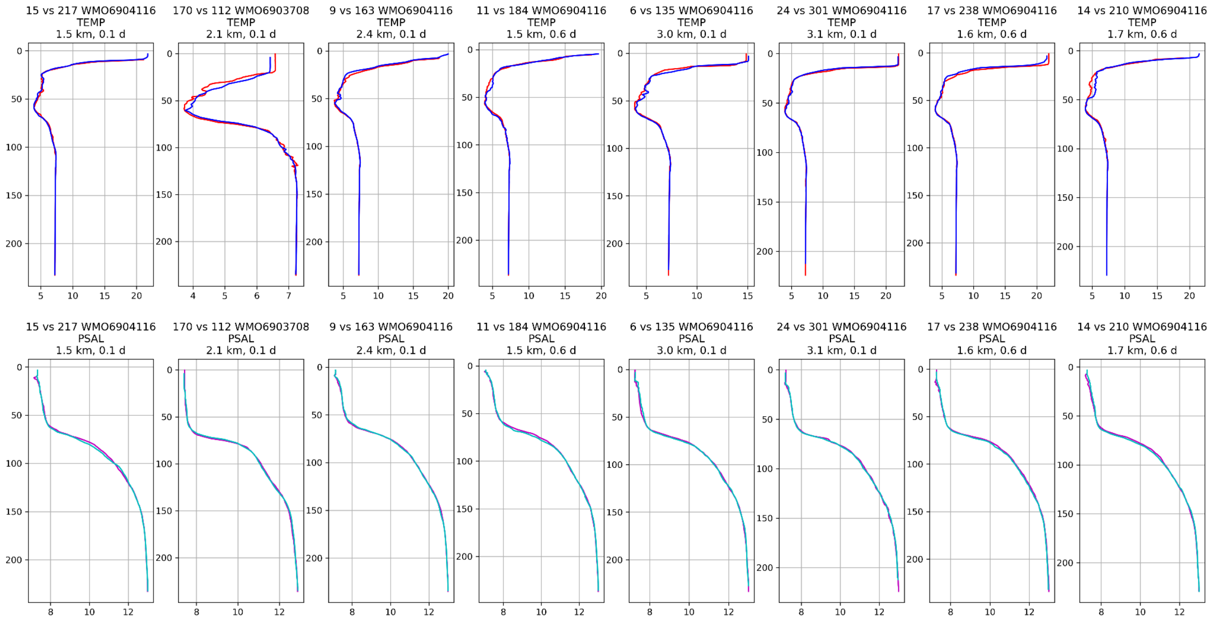

Figure 13: Eight closest matches for float WMO 6903709 from the other floats in the area. Ordered by match quality, the leftmost are the closest matches. Above the temperature, below salinity. Red/magenta profiles are from WMO 6903709, blue/cyan from the comparison floats. The comparison float, and distance in kilometres, and days is given above each profile figure.

2.2.3 North Atlantic

The RBR equipped floats have been operating well since deployment (last check: Sep. 12th, 2022). The floats monitoring webpage can be accessed here:

https://fleetmonitoring.euro-argo.eu/float/6903075

https://fleetmonitoring.euro-argo.eu/float/6903076

They have performed 63 profiles, one every 10 days, so far. Figure 15 shows all temperature and salinity data for the 2 RBR floats and Figure 14-top shows trajectories. Deployment was done on December 11st, 2020, and after 63 cycles, floats have nearly completed 2 seasonal cycles. Temperature ranges from about 4 to 24 °Cand salinity from 35 to 37.7. Except for a few salinity spikes observed near 1000m on 6903075 cycle 39 (see here), and easily flagged by Argo real-time QC procedures, all sensors behaved appropriately.

To assess the quality of RBR sensor measurements, we first compared floats data with the reference shipboard CTD profile from a SBE911. Results are shown Figure 16 on pressure levels, and Figure 17 on theta levels. On pressure levels, all floats seem to report a small cold and fresh bias with regard to the CTD reference station 25. On theta levels, the RBR float 6903075 is biassed salty, while the RBR float 6903076 and SBE float 6903010 are biassed fresh. However, the amplitude of these biases remain small compared to the ocean variability that could make the comparison hazardous, since the shipboard CTD cast and the floats first ascent profile used here are 35 hours and 2.6 km away from each other.

Therefore, we can further try to inter-compare floats measurements. From trajectories, we can compute the distance between each pair of floats, this is shown in Figure 14-bottom. We see that the 3 floats have been very close to each other during the first 17 cycles, less than 50km, i.e. about 1

Rossby radius in the area (LaCasce and Groeskmap, 2020). After that, the Arvor-SBE41CP float has drifted eastward while the two Arvor-I RBR have drifted westward. So the 3 floats have remained in a reasonable 1 Rossby radius from each other during the first 17. We follow on to compare data during the first 17 cycles. Figure 18 shows the T/S diagram for the deep part, below 1500m, of the floats profiles 1 to 17. We see that the RBR 6903075 float is slightly fresher than the SBE float 6903010, while the RBR 6903076 float looks too salty. This comparison relies on the assumption that the SBE float could be a reference to compare the 2 RBR floats. However, we've seen in the comparison with the shipboard CTD cast performed during deployment of the 3 floats (Figure 17) that all floats look biassed, even the SBE one. So again, this evaluation result may not be reliable.

Therefore, on a second hand we performed a standard OWC salinity calibration analysis. The OWC method consists in objectively interpolating all historical salinity data on the theta surfaces of one Argo float. The goal is to determine the best salinity reference possible. Results for the 2 RBR floats are shown in Figure 19 and Figure 20 and for the SBE float on Figure 21. The RBR float 6903075 has no detectable salinity biais (the additive correction is not significantly different from 0). On the other hand the RBR float 6903076 shows a fresh biais that requires a 0.01 additive correction. This biais is fairly constant throughout the 63 cycles. For the SBE float 6903010, no significant biais is found. However, a fresh biais could be found in the early life of the float (up to cycle 21) and then a drift seems to take place. A longer term examination (more cycle) for this SBE float is required in order to determine whether this is a long term drift or only the local ocean variability that is biassing the reference salinity values.

To summarise:

- The RBR float 6903075 has no detectable salinity biais and appears to report measures within Argo standards.
- The RBR float 6903076 has a fresh salinity biais that requires a correction of about 0.01 psu.
- The SBE float 6903010, which was expected to be used as a reference, reports an initial fresh biais of about 0.01 and then appears to drift salty. This can explain the initial results of the comparison with the shipboard CTD cast. A longer term monitoring of this float is required.

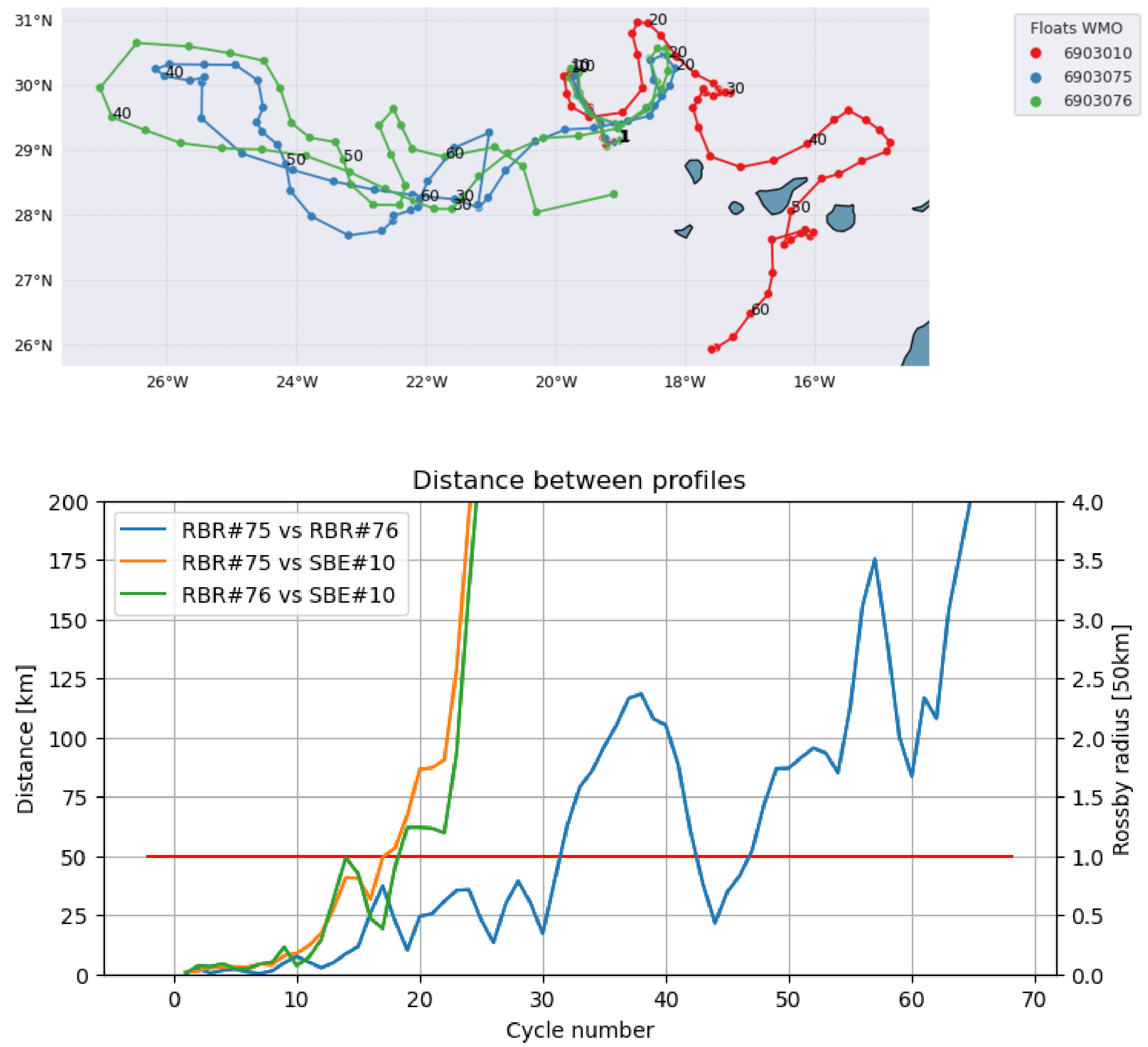

Figure 14. Top: Trajectories and profile positions of the two Arvor-I RBR3 equipped floats (blue and green curves) and the Arvor-SBE41CP standard float (red curve) deployed at the same time during this experiment. Bottom: Distance, in km (left axis) or local Rossby radius (right axis), between the successive pairs of float profiles.

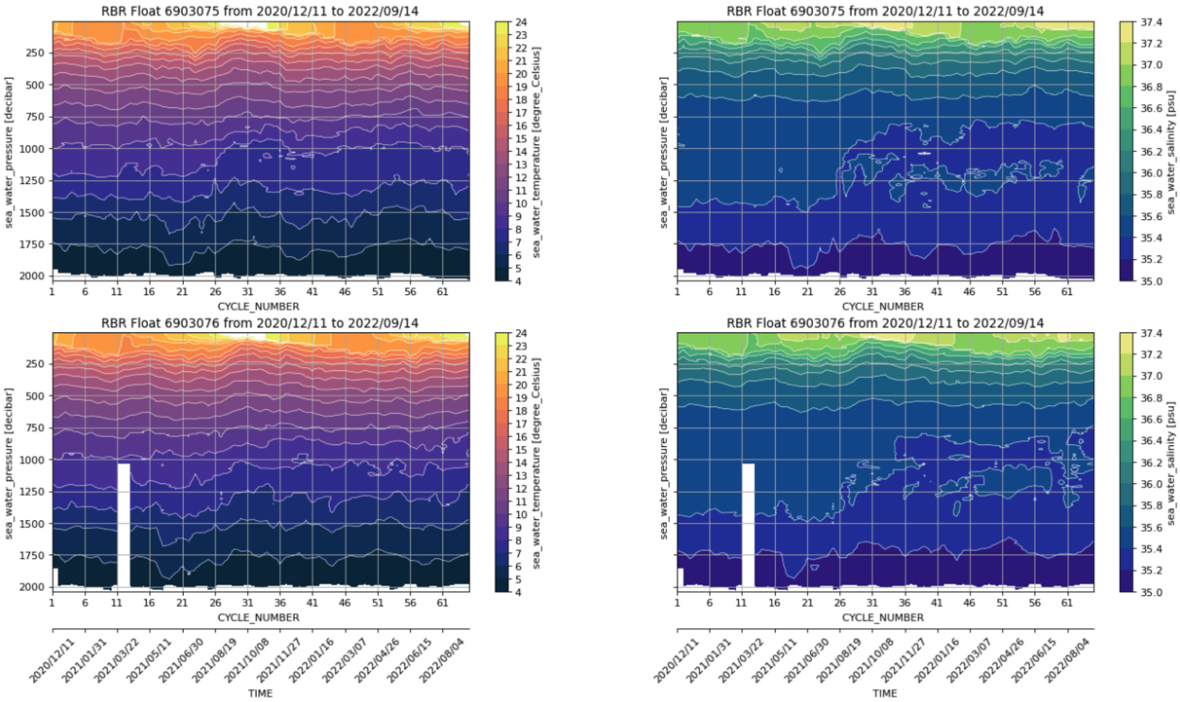

Figure 15. Temperature (left) and Salinity (right) data for the 2 RBR floats 6903075 (top) and 6903076 (bottom).

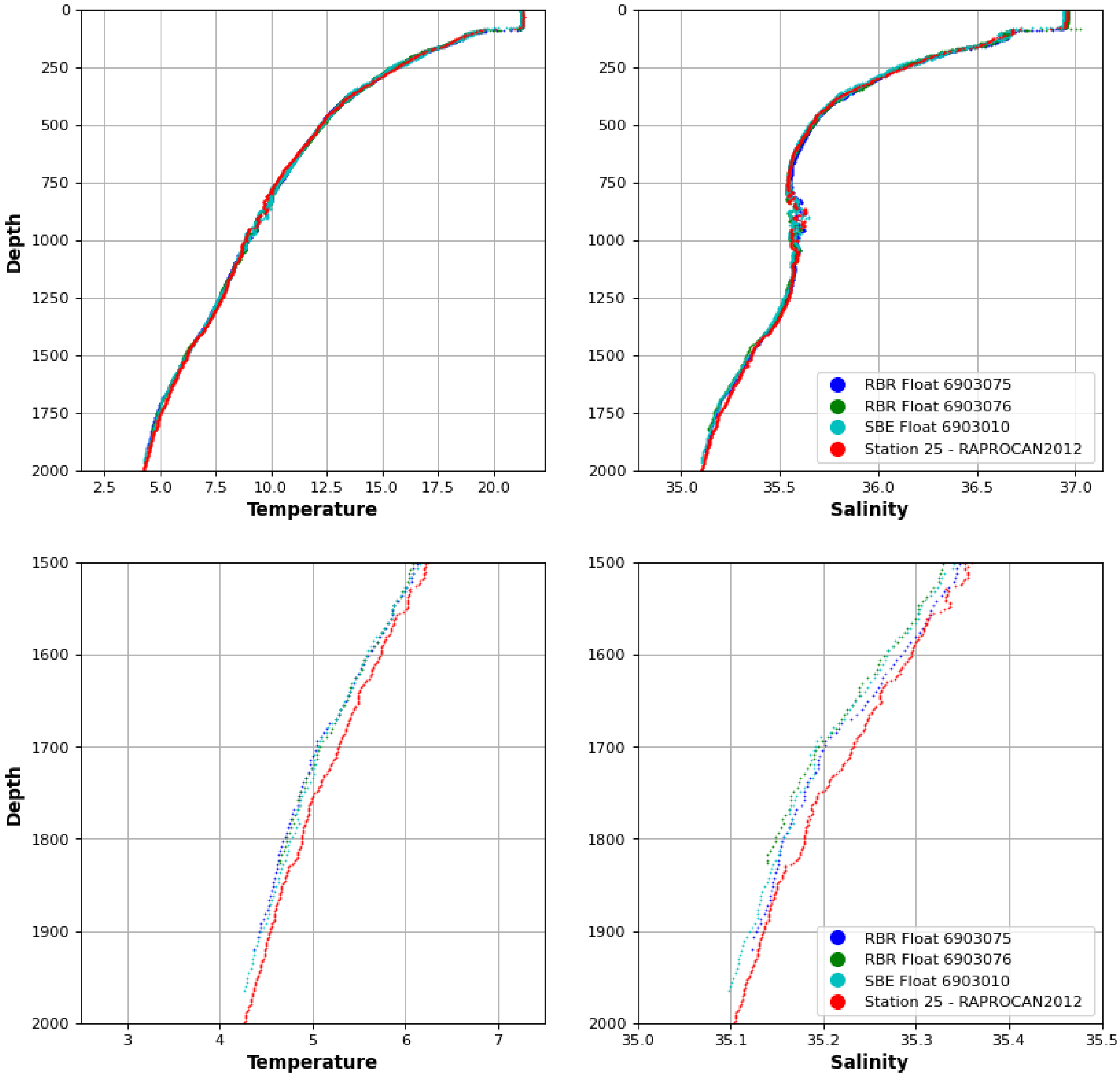

Figure 16. Comparison of the first 2 profiles from the 2 RBR and 1 SBE floats and the reference shipboard CTD station 25 conducted at deployment time. Upper plots show the full 2000m profiles, lower plots the 1500-2000m bottom layer. Left for temperature, right for salinity.

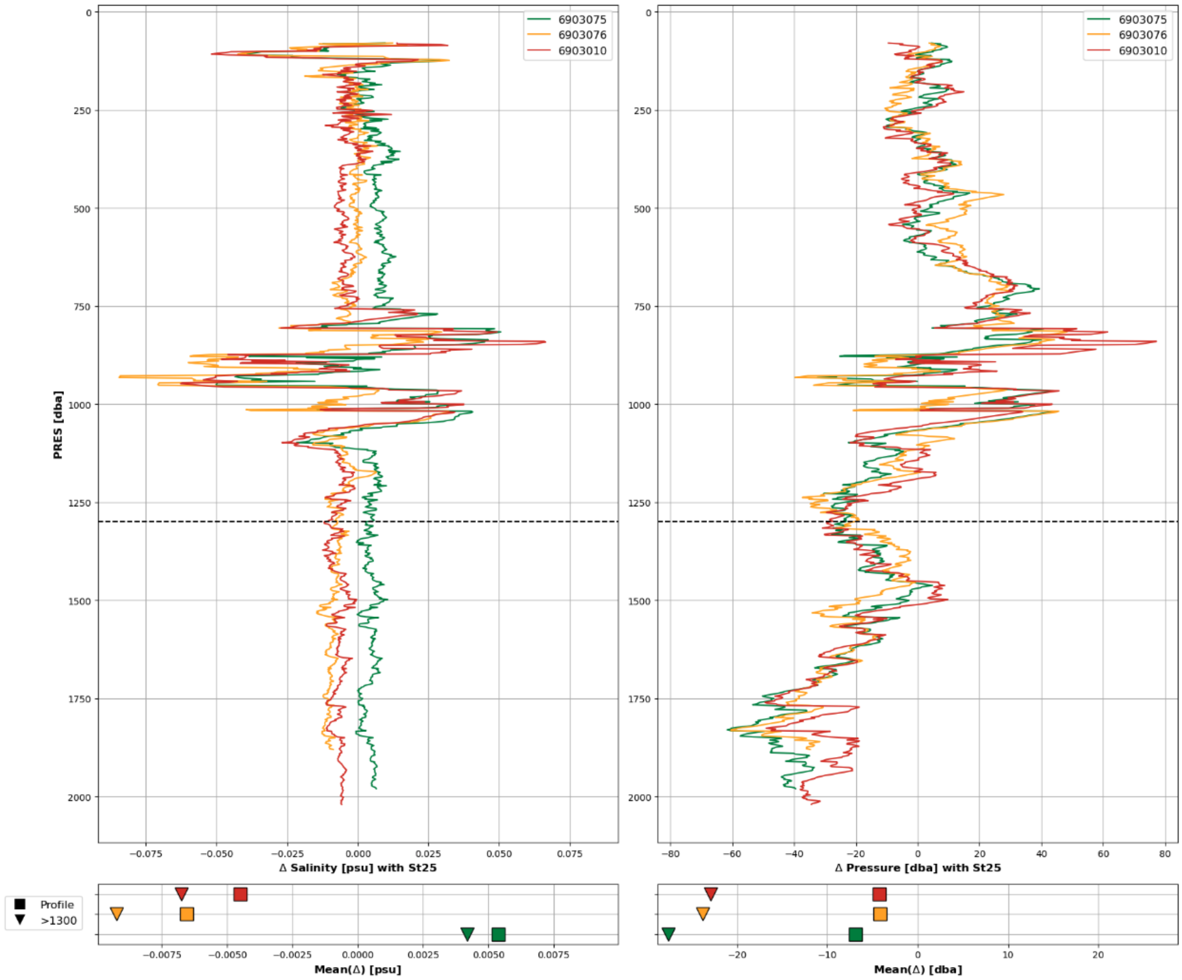

Figure 17. Comparisons of the first ascent floats profile with the reference station 25. Data were interpolated on reference theta levels. Left for salinity, right for pressure. Lower plots are the layer averaged differences (not the different abscise limits).

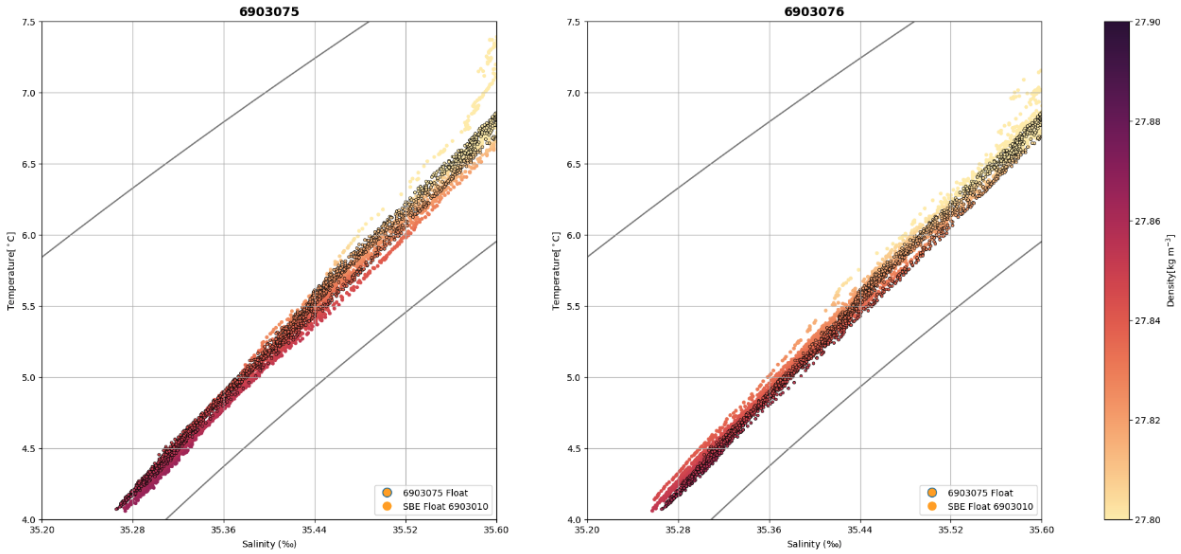

Figure 18. T/S diagram with data from the first 17 cycles of all floats. Left compares the RBR 6903075 with the SBE 6903010, right compares the RBR 6903076 with the SBE 6903010.

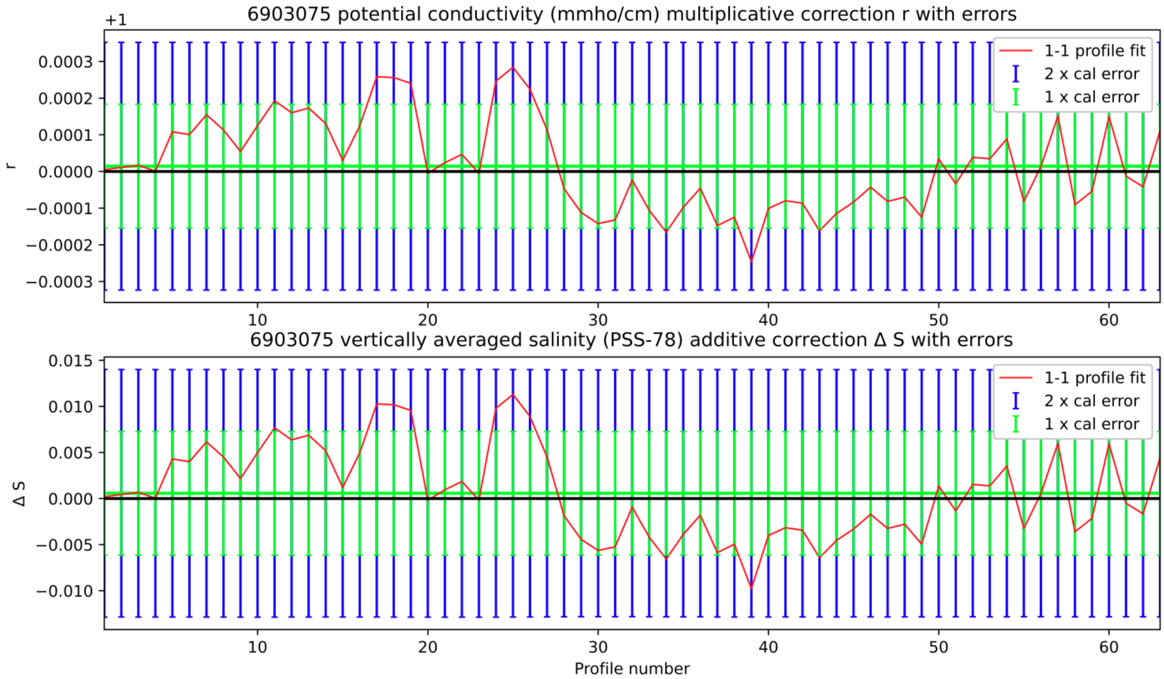

Figure 19. Salinity correction computed using the OWC method on RBR float 6903075. The correction is not statistically significant, meaning that this float data cannot be distinguished from relevant historical measurements. **No corrections required for 6903075.**

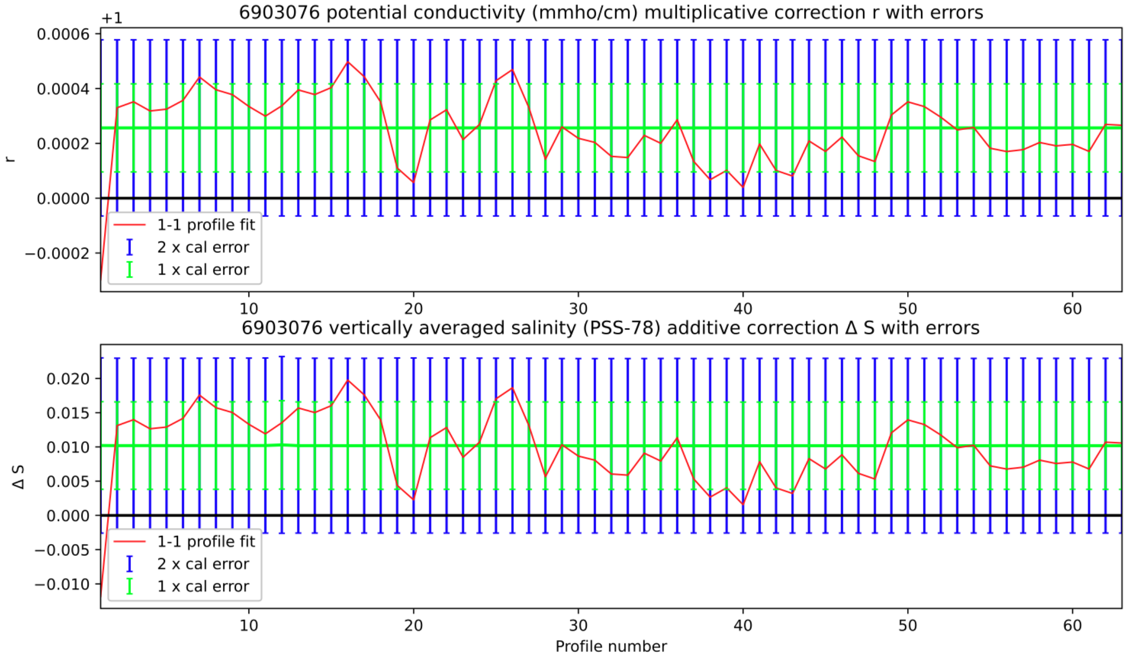

Figure 20. Salinity correction computed using the OWC method on RBR float 6903076. A fresh biais requiring **a positive correction** for 6903076 is found.

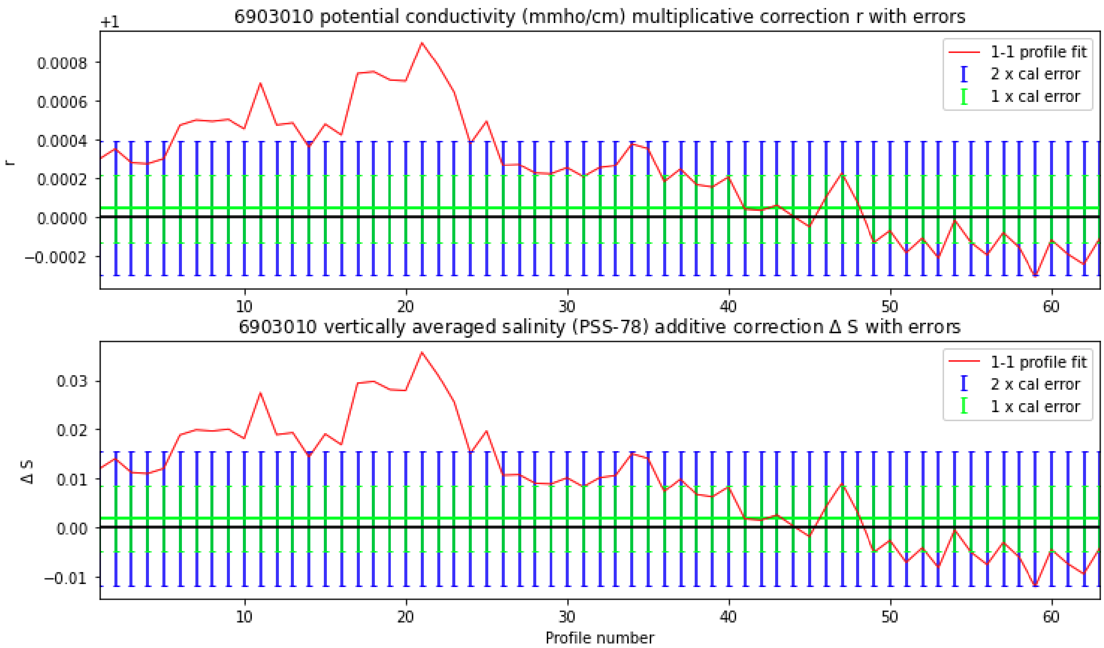

Figure 21. Salinity correction computed using the OWC method on SBE float 6903010. Over the 63 cycles, no correction is found. But a fresh biais could be found in the early life of the float (up to cycle 21) and then a drift seems to take place. A longer term examination for this float is required.

3 National Experiments

3.1 Experiment description

3.1.1 Northwest Atlantic (Germany)

The German national project DArgo 2025 funded by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) focused on pilot studies for the extended Argo monitoring network in Germany. A "swarm" of Argo floats equipped with RBR and Sea-Bird CTD was deployed in the Northwest Atlantic (Table 2) as part of this project. A total of 10 floats, 5 equipped with RBR CTDs and 5 with SBE CTDs, were deployed from the RV Sonne in January of 2021. All RBR floats were funded by the DArgo2025 project and all the SBE floats were from the annual contribution of BSH - Argo Germany to the global Argo programme. Within the swarm the floats were deployed in pairs (1 RBR + 1 SBE) with a few minutes difference while navigating at 1-2 knots at 45.50N, 21W. To minimise the dispersion of the floats, they were deployed inside an anticyclonic eddy.

Table 2. Swarm floats list. All floats were deployed on 12.01.2021 at 45.50N, 21.00W. The ΔS (reference - float) corresponds to the mean over the first 40 cycles (CTD reference database 2021v01 or 02)

WMO number	**CTD sensor**	**Conductivity correction coefficients**			**OWC ΔS in DMQC**
		x2 new	X3new	X4 new	
6904101	RBR	-	-	-	-
6904102	RBR	1.47E-06	-4.7E-10	7.48E-14	+0.0192
6904103	RBR	1.45E-06	-4.6E-10	7.39E-14	+0.0206
6904104	RBR	1.58E-06	-5E-10	8.06E-14	+0.0226
6904105	RBR	1.41E-06	-4.5E-10	7.22E-14	+0.0120
6904096	SBE41CP	-	-	-	+0.0262
6904097	SBE41CP	-	-	-	+0.0270
6904098	SBE41CP	-	-	-	+0.0221
6904099	SBE41CP	-	-	-	+0.0182
6904100	SBE41CP	-	-	-	+0.0258

The RV Sonne is equipped with a rosette and a SBE911 CTD which was used to collect reference data. A Datalogger RBR concerto, whose CTD sensor has the same design as the sensors in the Argo floats, was also mounted in the rosette to obtain an extra source of comparison between the sensors (Figure 22).

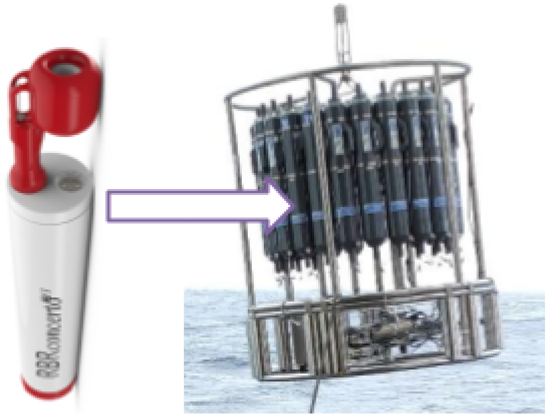

Figure 22: "RBRconcerto" data logger mounting position on the CTD rosette

The deployment of the floats was preceded by a reference profile and followed by 4 reference profiles with both sensors until 2000m (due to the RBR data logger depth restriction) and 4 with only the SBE sensor until the bottom. The same positions were revisited in about 24h (see Figure 23). During these casts water samples at different depths were collected and used afterwards for the calibration of the ship-born sensors after the cruise using a Guildline Autosal. The deployment and reference profiles positions are shown in Figure 23.

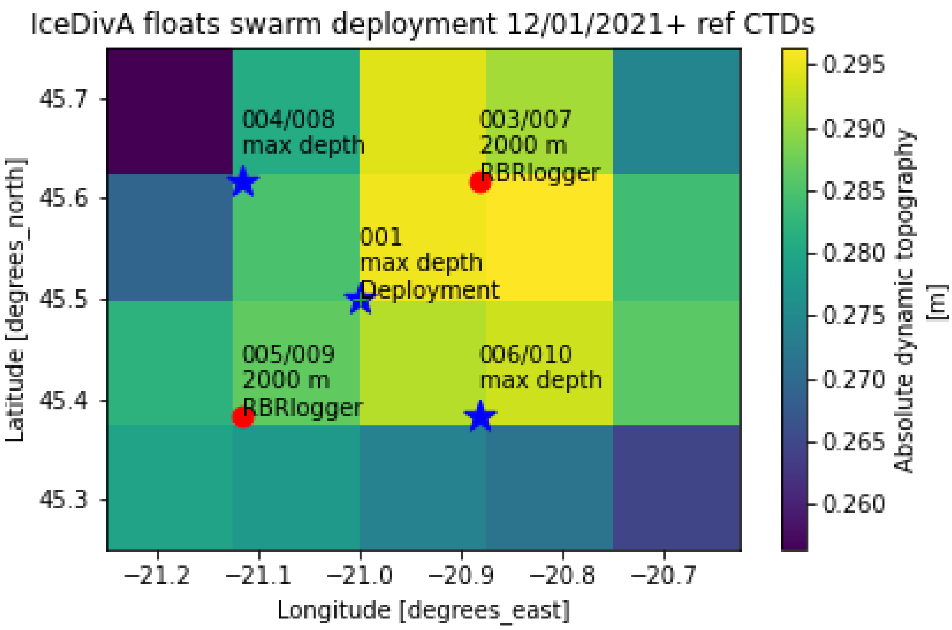

Figure 23. Map with the positions of the ship-born reference profiles. Profiles marked with a star go down to the bottom and include only measurements with the SBE CTD. Profiles marked with a red dot also include RBR data logger measurements and go down to 2000 m depth. The dynamic topography in metres is also shown in colour scale.

3.1.2 UK experiment with APEX/RBR – eastern North Atlantic (UK)

The question concerns the rate at which the RBR inductive conductivity cell responds to changes in the temperature of the surrounding water. The cell has a significant thermal mass, so if there is an abrupt change in the water temperature, and the response of the conductivity cell lags, there can be a resulting bias in the reported salinity. This is a known part of the cell response. The challenge is to devise algorithms that compensate for the effect so that reported data are free from bias after adjustment.

In February 2022, the UK deployed two APEX-RBR floats in the eastern North Atlantic. They were deployed in international waters, near 24°56' N, 21° 16'W. Each float was deployed after a shipboard CTD cast to 2000 dbar, and each float was deployed with a buddy float which was a BGC PROVOR float equipped with a SBE41 CTD. The serial numbers of the APEX-RBR floats were 9188 and 9189. The floats were deployed from UK Discovery Cruise 146.

The region is influenced by the Mediterranean water outflow, and the influence can be observed at least down to 1650 dbar.

Inspection of the initial profiles from the floats showed that we had been fortunate to deploy the floats into a region where they found the phenomenon of 'thermohaline staircases'. These oceanographic phenomena are created by diffusive processes, which result in regions of rather uniform density, bounded by regions of sharp density change. They are a very good test of CTD sensors. In order to measure the phenomenon correctly, a CTD sensor must be able to respond rapidly and accurately when passing through regions of strong vertical gradient of density, and in particular a sensor must measure the strong vertical salinity gradient associated with the strong density gradient. If a sensor does not measure the salinity correctly the error is usually because the sensor response is too slow relative to the rate of change of water properties as the float rises. This creates artificial and unrealistic inversions in density calculated from temperature and salinity.

Before the February 2022 float deployments, it was known that the RBR sensor for floats had an imperfect response when passing through strong vertical gradients. Considerable effort by RBR and the Argo community had already been expended on investigating the actual sensor response, and creating algorithms to correct for the imperfect response, to enable the user to recover an accurate vertical profile, free from artificial density inversions. Algorithms had been developed by inspecting data from (a) test RBR sensors deployed on floats, (b) from test RBR sensors deployed on ship-tethered CTD packages, and (c) from laboratory tank/flow tests, in which a sensor was plunged from air into a tank of flowing water, to produce a thermal shock. A decision had just been taken by the Argo community to advertise the algorithms devised so far as providing acceptable corrections to raw CTD data from RBR-equipped floats.

The data from these two floats would provide a good test of the present state-of-the-art algorithms for shore-based correction of raw float data.

3.2 Results

3.2.1 Northwest Atlantic (Germany)

Shipborne measurements

Comparison of the CTD sensors needed correction for pressure (0.5 dbar) due to the different positions of the sensors in the rosette, and for time (seconds). For the RBR Datalogger an extra time correction of 0.35 s between conductivity and temperature was necessary (according to the processing of the ship CTD data). The coefficients (Table 2) for the corrected conductivity formula (Equation 1) were calculated by comparing the measurements (water samples) with the salinity of the CTD sensors.

$$Conductivity_{corrected} = Offset + a_t * t + a_{conductivity} * conductivity + a_{pressure} * pressure + a_{temperature} * Temperature$$

Equation 1. Ship-born CTD calibration. Coefficients in Table 2.

Table 3. Calibration coefficients for the correction of the shipborne CTD measurements

Sensor	Offset	a_{time}	$a_{conductivity}$	$a_{pressure}$	$a_{temperature}$
SBE	-0.059600718743	0.000087959130	0.002044627039	-0.000001342261	-0.002472669106
RBR	0.799547183281	/	-0.027781785477	0.000011930696	0.027423669298

The main findings of this comparison (Figure 24) are:

- Before calibration: the RBR sensor has a pressure dependency, showing higher salinity in the upper layers and lower salinity in the lower layers.
- After calibration: the deviations of both sensors are around 0. The RBR sensor shows a variability range ±0.004 psu in each depth due to its slower response time. This is slightly larger than the accuracy of ±0.003 reported by the manufacturer. In comparison, the SBE sensor had a smaller variability range of ±0.002.
- No other important differences between the sensors were identified.

Float data

The floats were programmed to do a first complete profile from the 2000 m profile depth to the surface after 24h, and afterwards switch to a 48h cycle parking at 1000m. Therefore the floats were cycling in the same rhythm and collecting the profiles simultaneously, which helped to lower the dispersion at the surface. Float 6904101 malfunctioned after the first profile, which could not be solved after several restarts from the manufacturer. Float 6904097 sent data at irregular times, but this problem was solved after restarting it. Although this technical problem put the float at a different sampling rhythm as the other 8 floats, it still had a similar trajectory (Figure 25). All floats were deployed in the northern edge of the eddy and dispersed anti cyclonically around the eddy centre. All floats did a complete spin at least once (after 30 cycles). Then the mission configuration was changed to the standard 10 day cycle.

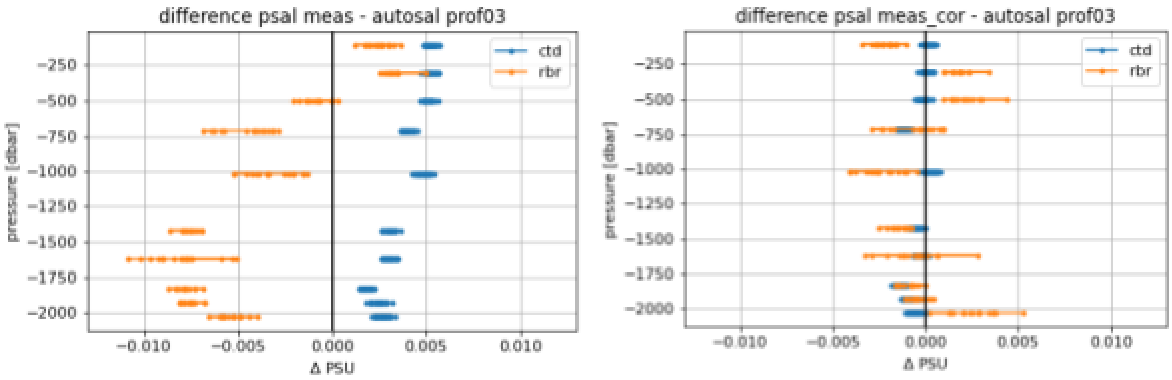

Figure 24. Vertical profiles of the differences between the uncalibrated (left) and calibrated (right) shipborne salinity profiles and the salinity samples. The colours represent the SBE (blue) and RBR (orange) CTD salinity differences. The data shown are from profile 03 (station NE1) which is representative of all profiles that show similar patterns.

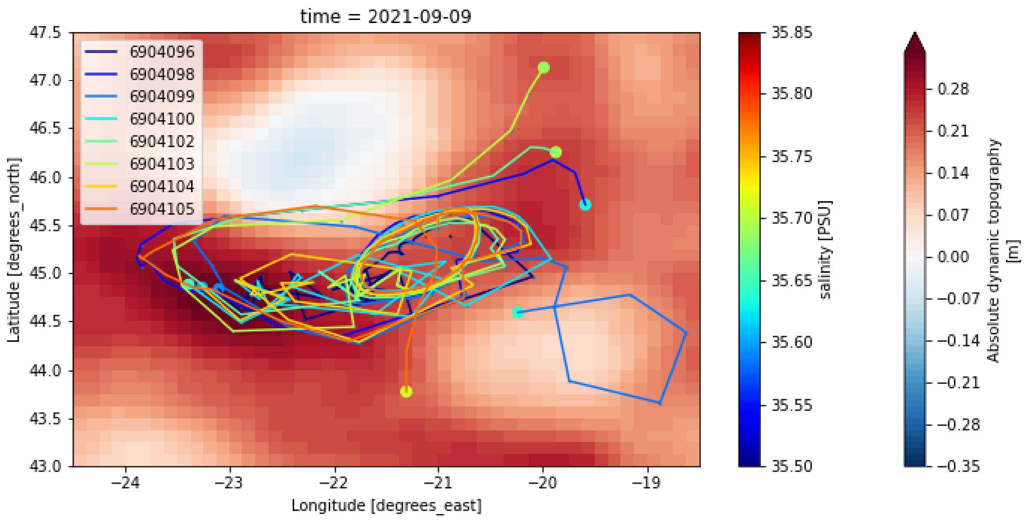

Figure 25. Swarm floats' trajectories from deployment (12.01.2021) to 09.09.2021. The last point of each trajectory is colour-coded with the last surface salinity value measured by the float. Trajectories are overlaid on the absolute dynamic topography in metres for 09.09.2021 (Dataset: CMEMS-SEALEVEL_EUR_PHY_L4_NRT_OBSERVATIONS_008_060).

All the first profiles, which are less affected by the spatial variability in the water columns because the floats were still close to each other, show in general a similar vertical structure (Figure 26). But even in the reference profiles that only have a time difference of 1 day between them, there is larger variability in the lower layers.

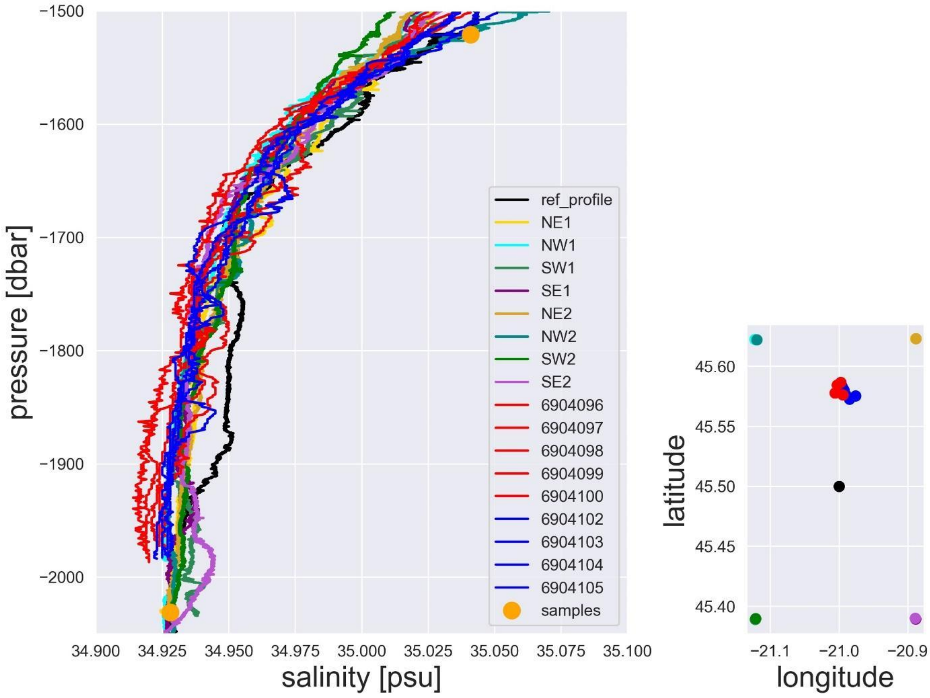

Figure 26: Left: Comparison of the uncorrected salinity data from the swarm floats with the shipborne calibrated reference salinity (SBE CTD). RBR floats are shown in blue and SBE floats are shown in red. Salinometer water sample values are also shown (circles). Right: Positions of the reference profiles during deployment. In black the profile at the deployment position while the other reference profiles around the deployment position (distance of about 6 nautical) and the float positions are colour-coded according to the legend.

As observed in the shipborne measurements, the RBR floats measured higher salinity in the upper layers and lower salinity in the upper layers (Figure 27). This dependence was also identified in other RBR experiments conducted by different partners of the global Argo programme.

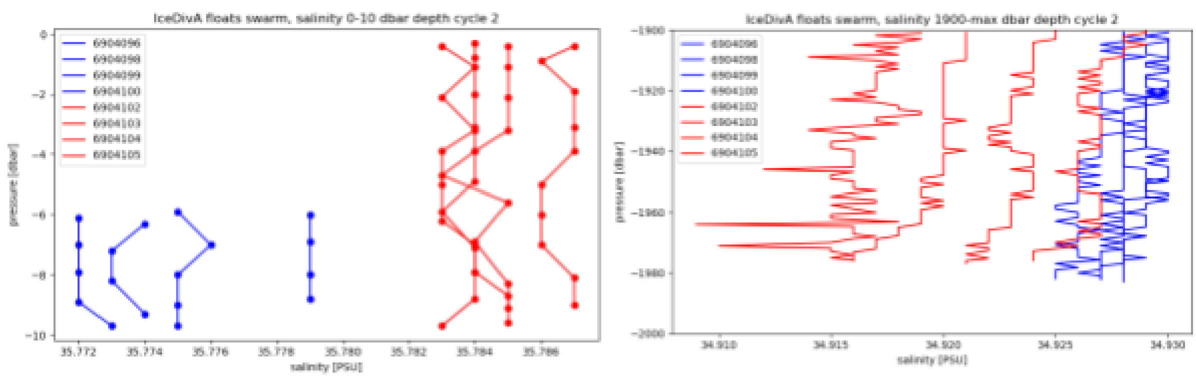

Figure 27. Uncorrected salinity profiles of the swarm floats in the uppermost 10 m (left) and lowermost 100 m (right). The SBE floats are marked in blue and the RBR floats in red.

These results of the swarm experiment were shared with RBR and they sent back sensor specific correction coefficients to correct the pressure dependence (Equation 2). After 2021 April, RBR provides the individual calibrations based on data collected in a pressure tank. For floats manufactured before that date, sensor specific coefficients can be calculated if reference CTD profiles are available during deployment.

$$C_{corr} = C_{meas} * \frac{1 + x2_{old} * P_{meas} + x3_{old} * P_{meas}^{\ 2} + x4_{old} * P_{meas}^{\ 3}}{1 + x2_{new} * P_{meas} + x3_{new} * P_{meas}^{\ 2} + x4_{new} * P_{meas}^{\ 3}}$$

Equation 2. Corrected Conductivity (C_{corr}) from measured conductivity (C_{meas}) for the RBR Argo Sensors. Where $x2_{old}$ = 1.8732E-06, $X3_{old}$ = -7.7689E-10, $X4_{old}$ = 1.489E-13. The sensor specific coefficients for $x2_{new}$, $x3_{new}$, $x4_{new}$ are in Table 1.

The final corrected data (Figure 28) showed better consistency with the water samples. The differences at 2030 dbar were of +- 0.001 g/kg.

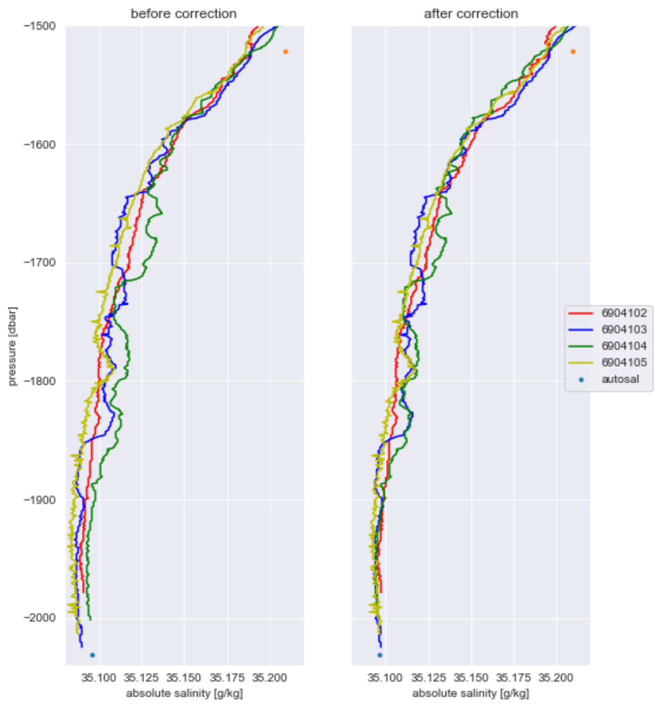

Figure 28. First salinity profiles measured by the RBR floats before (left) and after (right) correction using Equation 2 and the sensor specific coefficients (Table 1). The salinometer water sample values are shown as circles. Only the lower 500 m are shown.

OWC Analysis

The OWC analysis was run for the first 40 cycles of the swarm floats. Compared with the objectively mapped climatology, the float data has lower salinity and would need a correction of +0.02 to match the climatological values. This offset is however due to eddy variability, since the floats were deployed in an anticyclonic low salinity eddy. No salinity drift was present. Figure 29 shows the time series of interpolated salinity for the first 40 cycles. The values were interpolated to the same theta

level (4 degrees), because this theta level is found below the Mediterranean outflow in the deeper layers (between 1600 and 1800 dbar) and therefore shows small spatial and temporal variability.
At the beginning of the time series, the dispersion range is ±0.005 and increases with time. No systematic differences are observed between the different CTD sensors. After cycle 30, when the floats started to cycle every 10 days, the dispersion increased further. Again, no drift can be identified in the sensors.

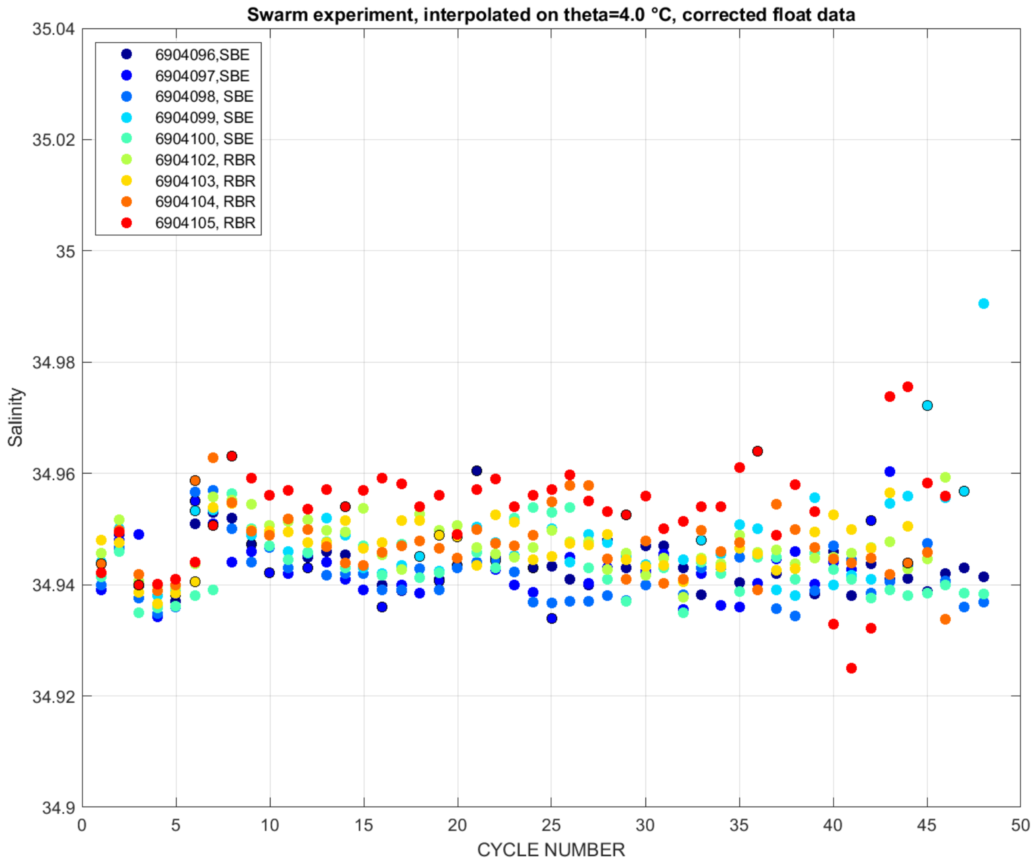

Figure 29. Time series of interpolated salinities for the first 46 cycles of the swarm floats salinities (RBR after pressure-correction). interpolated on the 4°C potential temperature level.

3.2.2 UK experiment with APEX/RBR – eastern North Atlantic (UK)

Figure 30 shows two vertical profiles of density for part of the water column. The black trace is from Discovery Cruise 146 station 25, the associated shipboard CTD profile. This is from a well-calibrated SeaBird-911 CTD, with data averaged to 2-dbar bins. The red profile is from profile 1 of APEX-RBR float s/n 9188. The quantity plotted is sigma-1000. Potential density referenced to 1000 dbar, with 1000 kg/m^3 subtracted for the display. The plus symbols denote the 2-dbar ship CTD averages, and the raw bin averages reported by the float.

The ship CTD trace shows no density inversions, and shows regions with small density gradient, bounded by regions of strong density gradient. For example from 1500 to 1480 dbar, there is a layer of near-uniform density, and again from 1470 to 1450, with a density gradient in between.

The red float/RBR trace shows the artificial density inversions due to the imperfect RBR sensor response, for example at 1480 dbar. As the float rises through a density gradient, the density spikes to the left, due to the thermal lag of the conductivity cell resulting in salinity bias. The density recovers back to higher values as the sensor is dragged through the water of what should be uniform density. Recall that the float profile was collected approximately 18 hours after the ship CTD profile, so that while the general character of the water column shows similar features, those features can shift by a few dbar in the vertical between the profiles.

The RBR trace in Figure 30 was raw data from the float, and before the adjustment algorithms were applied. The raw data were passed to RBR for evaluation. Mat Dever at RBR cooperated in the analysis and interpretation, and it became apparent that the algorithm that had been agreed to adjust the data to compensate for the known sensor response was not sufficient to remove all the artefacts visible in this example.

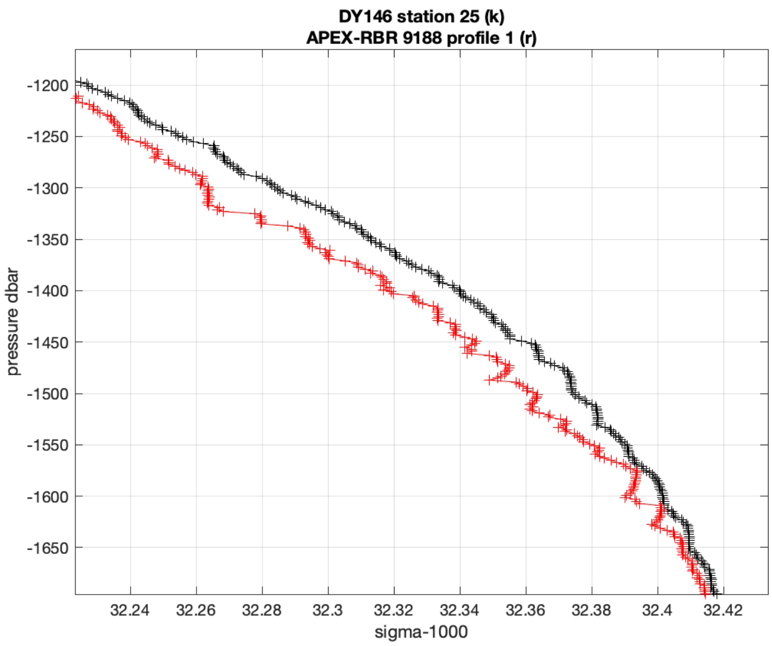

Figure 30. Two vertical profiles of density for part of the water column at DY146, station 25. Black line is from the ship CTD, the red one from Apex/RBR 9188.

The data from these test floats illustrated the importance of the rate at which water flowed round the sensor. The magnitude of the imperfect sensor response depends on this flow rate. This was already known before these float deployments, but it had been hoped that a single algorithm would be sufficient to adjust all Argo float data. These profiles, in a region of severe test for the algorithm, illustrated that the algorithm was incomplete and would not be sufficient for all floats in all ocean regions. The algorithm would have to be made more complex, and allow for float rise rate through the water column.

In response to these results, RBR undertook more laboratory tank testing, plunging a cell into a tank with different flow rates, discussing the results with the Argo community. This tank testing allowed RBR to further characterise the sensor response and its dependence on flow rate, resulting in a new algorithm that will produce data with smaller bias in ocean regions with unusually strong gradients.

4 Conclusions

Based on the experiments in the Baltic Sea, the RBRargo^3 CTD performance seems acceptable for use in the area. Comparison with the data with other Argo floats in the area show no detectable bias on the measurements, and the possibility to measure up to the surface is a valuable asset. The accuracy of RBRargo^3 sensors seems to be within requirements for the Baltic Sea (Klein 2022).

There are still some possibilities of problems in some profiles, such as the lack of upper layer, or some possibly faulty measurement points, as seen in some profiles in the Bothnian Sea float. However the complete missing of the faults where surface salinity shows values from deeper layers enhances the reliability of RBRargo^3 sensors. A discussion on these findings has been started with RBR.

Based on the experiments in the North Atlantic, the RBRargo^3 CTD performance can be acceptable for use in the open ocean. Even if 1 out of the 2 floats appeared biassed, salinity can be corrected using standard DMQC method.

The German experiment in the Northwest Atlantic shows that the pressure dependance of the RBRargo^3 sensors can be properly corrected with sensor specific correction coefficients, and that its accuracy is appropriate for the Argo accuracy standards. Since sensor specific coefficients will be delivered with new RBRargo^3 CTD sensors (April 2021 onwards), their use does not require additional corrections. These results were presented in the 23th Argo Steering Team meeting 23-25.3.2022 and RBRargo^3 was endorsed by the community as one of the sensors to be used in the Argo Core mission.

The feedback from UK experiments will likely lead to modifications in float hardware. The flow rate past the sensor is determined by the float ascent rate through the water column, often around 8 to 10 cm/s. It is likely that modifications to the float platforms will be required, preferably to control this rise rate as a steady rise, and certainly to make enough pressure measurements to enable the users to know the rise rate at all times in the ascent.

In general, the RBRargo^3 CTD demonstrated a performance within requirements in all tests, the continuing communication with RBR is recommended for further improving both sensor performance and post processing practices.

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