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Accuracy and long-term stability assessment of inductive conductivity cell measurements on Argo floats

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Dear Editor-in-Chief of the “Journal of Atmospheric and Oceanic Technology”,

Thank you for considering our manuscript " Accuracy and long-term stability assessment of inductive conductivity cell measurements on Argo floats" to be published in the “Journal of Atmospheric and Oceanic Technology”. We feel that the subject material is suitable for the Journal. The scope of the paper corresponds to the issues listed among the journal’s focus, including “instrumentation and methods used in atmospheric and oceanic research” and “measurements, validation, and data analysis techniques”.

Our study was designed to evaluate accuracy and stability of Argo drifters equipped with inductive conductivity sensors, a promising energy-saving technology for salinity measurements at autonomous ocean-observing platforms.

On behalf of the authors,

Yours Sincerely

Dr. Nikolay P. Nezlin

Accuracy and long-term stability assessment of inductive conductivity cell measurements on Argo floats

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Abstract

This study demonstrates high levels of long-term stability of salinity measured by Argo floats with inductive conductivity cells, which have extended float lifetimes as compared to electrode-type cells. New Argo float sensor payloads must meet the demands of the Argo governance committees before they are implemented globally. Currently, the use of CTDs with inductive cells, designed and manufactured by RBR Ltd., have been approved as a Global Argo Pilot. One such requirement of new sensors is that they produce stable measurements over the lifetime of a float. To demonstrate this, data from four Argo floats in the western Pacific Ocean equipped with the RBR*argo* CTD sensor package, are analyzed using the same techniques (OWC method) and reference datasets as the Argo DMQC operators. Being a statistical tool, the OWC method cannot determine whether deviations in the salinity calibration are caused by oceanographic variability or sensor problems. This study demonstrates that anomalous salinity calibration values tend to occur in regions with a high degree of variability and can be explained by imperfect reference data rather than sensor drift. When run with default settings against the standard DMQC Argo and CTD databases, the OWC analysis reveals no drift in any of the four RBR*argo* datasets and an offset in one case, making the RBR inductive cell a qualified option for salinity measurements in the Argo Program.

1. Introduction

The Argo program consists of approximately 4000 autonomous profiling floats continuously operating in the world ocean (Jayne et al. 2017; Roemmich et al. 2019). Its implementation started in 1999 and it has been providing global coverage of the upper 2000 m of the open ocean since 2006. More recently, Argo coverage has grown to include seasonal ice zones and marginal seas. Argo is a part of the Global Ocean Observing System, providing basic oceanographic information for process studies, ocean model data assimilation, validation, reanalysis and forecasting (Legler et al. 2015).

Data quality is a key asset of the Argo program: target accuracies for measurements are set to 2.5 dbar for pressure, 0.005°C for temperature, and 0.01 for salinity (Riser et al. 2016). The main obstacle in achieving this goal is that autonomous floats cannot be recalibrated on a regular basis and, as such, indirect methods of data quality analysis and correction must be applied to achieve accurate results. For Argo data, quality control includes two steps following the Argo data collection and dissemination strategy. First, Real Time Quality Control (RTQC) procedures are applied to the data collected by the floats, focusing on the detection and elimination of outliers (Udaya Bhaskar et al. 2013; Wedd et al. 2015; Wong et al. 2020). This data is generally made freely available in Near-Real Time (NRT), that is within 24 h. Second, a Delayed-Mode Quality Controlled (DMQC) analysis is conducted to produce high quality datasets suitable for oceanographic research. Delayed-Mode (DM) analysis relies on Argo data experts to examine the data and apply corrections when necessary. DM products are available to users 6 to 12 months after collection.

While temperature and pressure are generally measured within the required accuracies throughout the life of a float, salinity (computed from conductivity measurements) is more problematic for two main reasons. First, biofilms can form on the conductivity cell, causing a change in the cell constant. Mitigation strategies, such as poisoning the water within the cell with tributyltinoxide (TBTO) may reduce biofouling, but TBTO is known to coat the electrodes inside the conductivity cell for the first few months of a deployment, before eventually washing off (Wong et al. 2020). Second, mechanical failures can seriously impact measured conductivity. Recently, for example, large batches of Conductivity-Temperature-Depth (CTD) instruments SBE41CP from Sea-Bird Scientific (SBE) have been found by DMQC operators and others to drifty salty, potentially arising from the failure of the encapsulant used in the cell construction (see Argo Steering Team 2018; Section 8). As a result, an essential part of DMQC process is the analysis and correction of salinity offset and drift using the standard 'Owens-Wong-Cabanes' (OWC) method (Cabanes et al. 2016; Owens and Wong 2009).

Salinity measurements in the ocean are commonly made using either electrode or inductive conductometry principles. While electrode cells measure electrical resistance between the electrodes in direct contact with seawater, inductive cells function according to Faraday's law of induction (Halverson et al. 2020). An electrical signal applied to the generating coil produces a magnetic flux, a resultant electric field, and finally an electromagnetic current induced in the seawater present in the center of the cell. This current flowing through the receiving coil is proportional to the resistance of the water, which is inversely proportional to conductivity. The measured conductivity is transformed to practical salinity using the seawater equation of state (Fofonoff 1985; McDougall and Barker 2011). Inductive conductivity cells possess key features that are particularly beneficial for autonomous observing systems (Halverson et al. 2020; Shkvorets and Johnson 2010). For example, water flushes freely through the inductive cell, significantly lowering power consumption compared to sensors using pumped electrode conductivity cells. Also, due to the absence of a direct coupling with seawater, inductive cells do not have problems with oil contamination or corrosion, both of which largely degrade the performance of metal electrodes.

Inductive conductivity sensors produced by Falmouth Scientific, Inc. (FSI) were installed on the first experimental Profiling Autonomous Lagrangian Circulation Explorers (PALACE) floats in 1990s and deployed mostly by the Woods Hole Oceanographic Institution (Bacon et al. 2001; Durand and Reverdin 2005). However, the performance of FSI CTD-equipped Argo floats was substandard, and the cells were subsequently phased out (the last FSI-equipped Argo float was deployed in December 2006) (Abraham et al. 2013). The poor performance of FSI CTDs was associated with biofouling mitigation techniques (ablative coatings) that changed the cell geometry and caused conductivity drift. The potential for mitigative measures resulted from the relatively long presence (sometimes longer than 24 h) of the float at the ocean surface, which was required for data transmission through the ARGOS satellite system. FSI CTDs also suffered from issues that are not inherent to inductive conductivity sensors. For example, a firmware fault in the data bin averaging algorithm resulted in a pressure bias that could not be corrected in post-processing (Barker et al. 2011). As a result of the problems plaguing the FSI CTD, and perhaps a lack of interest from competing manufacturers, an overwhelming majority of CTD instruments installed on Argo profilers use Sea-Bird's electrode-based CTDs.

A series of recent setbacks and technological improvements have motivated the development of a new sensor package for Core Argo floats. The switch to Iridium telemetry has reduced the time a float spends at the surface from 12–24 hours to 15–20 min. The shorter time spent at the surface means there is less of a need for biofouling mitigation, a problem that has historically plagued both electrode-based and inductive cells. Additionally, pump-free CTDs consume much less power, which directly translates into longer float lifetime. Finally, there has been a call to diversify the sensor packages on Argo floats so that the program is not susceptible to "single points of failure" (Roemmich et al. 2019).

The goal of this study is to assess the long-term accuracy and stability of salinity measurements collected by four Argo floats equipped with the RBR*argo* inductive CTD manufactured by RBR Ltd. (https://rbr-global.com/). All four floats were deployed in the western Pacific Ocean as either experimental or pilot-project Argo floats (Figure 1). For this analysis, we use the standard Argo community OWC MATLAB toolbox (https://github.com/ArgoDMQC/matlab_owc) combined with a custom MATLAB visualization toolbox designed to help Argo users to select appropriate settings for OWC processing and make defensible conclusions about accuracy and stability of conductivity sensors.

The paper is organized as follows: The data and methods of data analysis are described in Section 2. Section 3 presents the results. First, the stability characteristics calculated by OWC method for four RBR*argo* floats are analyzed and compared to the initial accuracy assessments. Second, these statistics are compared to salinity drift and bias estimated during DMQC and applied to other floats operating in the same regions. Then, the methods helping to avoid misinterpretation of the results of OWC analysis are demonstrated. Finally, a discussion is presented in section 4.

2. Data and Method

2.1. Argo floats equipped with inductive conductivity sensors

Four Argo Teledyne Webb Research Autonomous Profiling Explorer (Apex) floats equipped with RBR*argo* CTDs with inductive conductivity cells were deployed in the western Pacific Ocean in 2015 and 2018 (Figure 1; Table 1).

The RBRargo CTD design changed in 2016, meaning the CTD on float 5904925 differs from the CTD on floats 2903005, 2903327, and 2902730 (Figure 2). The 2016 redesign was undertaken to improve the dynamic performance of the RBR*argo* CTD. Two modifications were made: 1) the thermistor was moved onto the conductivity cell itself, thereby eliminating the time lag from spatial mismatches of the sensors, and 2) the body of the cell was optimized to ensure the thermistor samples undisturbed water (Argo Steering Team 2018). Both CTD cell designs measure conductivity with induction.

All Argo floats operate on a nominal 10-day cycle. For most of that cycle, they drift at a "parking depth", typically 1000 m. Once in each cycle, the float dives to a 2000 m depth by changing its buoyancy and then performs an upcast profile measuring the Core Argo variables (pressure, temperature, and conductivity) up to the ocean surface. At the surface, the information is transmitted via satellite and the float descends back to its parking depth. The battery capacity of the float allows for at least 150 CTD profiles, which gives the float a theoretical four-year lifespan assuming a 10-day cycle.

Argo data telemetered via satellite are transmitted to one of the 11 Argo regional Data Assembly Centers (DAC) where they are checked for outliers by coarse semi-automatic RTQC tests (Wong et al. 2020). This data product, referred to as NRT, is then sent to Argo Global Data Assembly Centers (GDACs) and made publicly available within 24 h. DMQC analysis is then performed by DACs to produce a delayed-mode data product, available within 12 months after observation.

During the DMQC analysis, salinity observations are carefully checked by experts and, if necessary, corrected using the OWC method, a standard method for the Argo community (Wong et al. 2020).

2.2. Salinity bias and drift detection

The OWC analysis is the statistical method of salinity drift correction described in Owens and Wong (2009) and Cabanes et al. (2016). In this method, the salinity profiles observed by an Argo float are compared to reference data in the same region by using objective mapping (OM; Bretherton et al. 1976). In this study, we used separately two reference datasets approved and used by the Argo community and prepared by the Argo Data Management Team (ADMT) at the Coriolis Data Centre: 1) shipboard CTD casts (CTD_for_DMQC) and 2) DMQC-corrected Argo profiles collected during preceding years (Argo_for_DMQC). Both datasets are available for the members of the Argo program upon request to the *Institut Français de Recherche pour l'Exploitation de la Mer* (IFREMER).

Based on the fact that water-mass structures can be defined by the relations between potential temperature and salinity, the salinity measured by Argo float is compared to the reference along as many as 10 potential temperature isotherms, characterized by minimal salinity variations and 'calibrated' by the weighted least squares method to minimize its difference from the reference. The weights for the calculation are proportional to the inverse of the OM errors such that less variable deep-layer climatology influences the 'calibration' of float salinity more than those of the more variable surface and intermediate layers.

In the OM calculations, the selection of reference data for each profile and their respective weights depend on their distance from the observed profiles in space and time: highest weights are assigned to reference profiles most closely positioned and most contemporaneous to the float profile date, as well as those with measurements obtained on the same isobaths as the float profile (Böhme and Send 2005). OM is performed in two steps, by first fitting large-scale variability and then small-scale residuals. The parameters regulating these scales are referred to as decorrelation scales and are selected by the user on the basis of his/her knowledge of the effect of these factors on the objective mapping in the study region (Wong et al. 2003). The OWC method is based on the assumption that any conductivity offset changes slowly over time; as a result, a piecewise linear fit of the profile-based corrections over the float time series is applied. The OWC analysis returns a set of salinity correction factors, one for each completed profile. The decision whether or not the statistical trends represent sensor drift or ocean variability, and in turn whether or not conductivity corrections should be applied, is made by the user and involves some subjectivity.

The OWC MATLAB toolbox settings used in this study are listed in the Appendix.

2.3. Distinguishing between instrumental errors and oceanographic variability

The results of the OWC output strongly depend on the quality of reference data. Anomalies in salinity measured by the float CTD relative to water mass with different temperature-salinity characteristics can be easily misinterpreted as sensor drift, especially when reference data are sparse or inaccurate. The approach taken in this study relies on visualization methods designed to assist users to determine whether anomalies in measured salinity are caused by instrumental errors or oceanographic variability and, as such, avoid ambiguity in salinity drift detection. These methods include:

1. Plots showing 1) a time series of the profile fit coefficients (calculated by the OWC method as the vertically averaged reference salinities minus corrected float salinities at 10 selected reference potential temperature levels) and 2) a map showing the magnitude of the fit coefficients along the float trajectory. Such plots help to identify spatial coherency in discrepancies between the analyzed Argo measurements and the reference dataset, providing information on whether discrepancies should be attributed to errors in the reference data, or to sensor drift.
2. Diagrams comparing the objectively mapped reference salinity field calculated by the OWC method to a different reference data source. For this purpose, the nearest grid points of the World Ocean Atlas (2005-2017) monthly climatology of 1° resolution (WOA1) (Garcia et al. 2018) and/or other monthly gridded datasets were used. Discrepancies between different reference sources support the hypothesis that large salinity anomalies might be due to inappropriate reference data, rather than to sensor drift.
3. Simplified OWC analysis of nearby contemporary Argo floats provides yet another indication of whether the computed salinity error emanates from the reference dataset used.

3. Results

3.1. Salinity offsets and their dependence on reference data and time separation factors

The OWC analysis, when run with the settings specified in the Appendix against the two ADMT-CTD and ADMT-Argo reference databases, revealed no statistical trends in any of the four RBR*argo* float salinities. There were small differences between the salinities measured by the RBR*argo* and the reference data. When compared to the ADMT-Argo reference database, the salinity offsets were much smaller than the offsets based on the ADMT-CTD reference database (Table 2). We speculate that these differences result from different time periods when the reference data were collected (Figure 3). Most CTD casts were collected during 1980s-1990s (Figure 3-b3, c3); only in the Northwest Pacific a large number of CTD casts was taken after 2000 (Figure 3-a3). In contrast, most Argo profiles were collected after 2005 (Figure 3-a4, b4, c4). Comparing these data to RBR*argo* floats operating during the recent 2–4 yeas resulted in disagreement associated with long-term salinity variations in the Pacific Ocean documented in previous studies (e.g. Boyer et al. 2005; Durack and Wijffels 2010; Helm et al. 2010).

The salinity offset for Argo Australia float 5904925 in the Coral Sea demonstrated significant salinity bias: -0.0100 to -0.0132 when compared to ADMT-Argo reference data collected during the recent 15 years and -0.0152 to -0.0167 when compared to ADMT-CTD data collected mostly 20–35 years ago (Table 2). This offset exceeds the Argo accuracy limits (0.01) and may result from the fact that this float was equipped with old-design C-cell, although the conclusion about better accuracy of CT-cells have to be confirmed by additional data.

For three RBR*argo* floats equipped with CT-cells of new design (two Japan Argo floats in the Northwest Pacific and the China Argo float in the Philippine Sea), OWC comparison to ADMT-Argo reference dataset with a relatively small (1–3 years) time separation factor resulted in salinity offsets between -0.0009 and -0.0020, well below the Argo accuracy limits (Table 2).

Larger time separation factors resulted in larger offsets, especially for both Japan Argo floats. We attribute this fact to recent salinity changes in that area. When compared to ADMT-CTD data, the largest disagreement (>0.01) was observed with small (1–3 years) time separation factors. Small time separation factors mean that RBR*argo* measurements are compared with most recent measurements, but for the ADMT-CTD database this is a comparatively short time period 10-15 years ago when the majority of recent ADMT-CTD data was collected (Figure 3-a3, b3, c3). We may suggest that during that short period salinity was different from the recent period when the analyzed RBR*argo* data were collected. When the short-scale and large-scale time separation factors were set to 10 and 30 years, respectively, the resulting offsets decreased below the Argo accuracy limits (Table 2).

The dependence of the OWC results on other settings (see Appendix) was small. Based on these results, we chose the ADMT-Argo 2019v01 database as a source of reference data and the following time separation factor values (small/large): 3/10 years for Argo Australia 5904925 and China Argo 2902730, and 1/3 years for Japan Argo floats 2903005 and 2903317 (Table 2). The resulting OWC output showed no significant statistical trends for all four floats, which we interpret to mean that salinity, as measured by the RBR*argo* CTD, does not drift. We concluded that only salinity measured by one float (Argo Australia 5904925) required a correction in the form of a constant offset of -0.01; the other three floats did not need a salinity correction whatsoever.

3.2. Initial accuracy of floats

The assessments of the initial accuracies of RBR*argo* salinity measurements indicated that they were close to the salinity offsets calculated by the OWC method. Assessments were made by comparing the salinity measured in the first few cycles to CTD casts collected shortly after the float deployments (Figure 4). The differences in salinity along isopycnals (potential density levels) were computed and averaged over the range of potential temperature below 5°C (Table 3). Only the Argo Australia float deployed in the Coral Sea demonstrated salinity bias exceeding the Argo accuracy limits (>0.01). For the three other floats, the initial accuracy was within the Argo requirements (Table 3). Comparing the first Argo profiles to the WOA1 climatology demonstrated larger differences than when compared to the CTD casts. In the Northwest Pacific and the Philippine Sea, the salinity measured by Argo floats varied mostly within the WOA1 climatology standard deviation limits (Figure 4b, c). In contrast, salinity in the Coral Sea measured by the starting profile of the Argo float 5904925 exceeded both the CTD and WOA1 salinity variation limits within the entire deep (θ<5°C) layer (Figure 4a).

3.3. RBRargo in situ drift and bias correction comparison to the electrode-based CTDs

To put the RBR*argo* salinity drift analysis in context, we assessed the long-term stability of other Argo floats equipped with electrode-based SBE41/41CP. To compare the CTDs directly, Argo datafiles were downloaded from a GDAC for all floats that (1) operated starting 2011 in the same areas (the 20°x20° rectangles around the float trajectories in Figure 1a) and (2) contained a sufficient number of DM data (at least 25 profiles). A total of 360 floats met these criteria; the median time of operation was about 4 years, and the median number of DM profiles was 175 (minimum 27 profiles, maximum 438 profiles). For each float, the salinity offsets used for DM correction were computed from the mean difference between the raw salinity (PSAL) and the adjusted salinity (PSAL_ADJUSTED) in all DM profiles. In about 16% of the Argo floats with electrode conductivity sensors (57/360), the applied salinity offsets exceeded 0.01. For 31% of floats (111/360), the salinity drift exceeded 0.0025 yr^{-1}.

Only one float with an RBR*argo* CTD (Argo Australia float 5904925) demonstrated a significant offset (-0.010) relative to ADMT-Argo reference salinity (Figure 5a), which is also the first float with RBR-equipped conductivity cell deployed in 2015. Since then, the design of the RBR conductivity cell was improved, with the thermistor located next to the conductivity cell (see Figure 2b). The three RBR*argo* CTDs with new conductivity cell design (i.e., floats 2902730, 2903005, and 2903327) did not need salinity correction. Their calibration offsets were significantly lower than the calibration accuracy of ocean salinity measurements claimed by RBR (~ ±0.003, or ±0.003 mS/cm at 15°C) (Halverson et al. 2020). All four RBR*argo* CTDs demonstrated no salinity drift, although in many floats equipped with electrode conductivity cells salinity drift was detected and corrected during the DMQC analysis (Figure 5b).

3.4. Detecting problematic reference data in salinity drift assessment

The OWC calibration method, when applied to data from four RBR*argo*, indicated that the CTDs are very stable over a two or more years. However, there remain anomalies in the calibration salinity that warrant further investigation because, as a statistical method, OWC cannot determine whether variations in the calibration salinity are related to sensor problems or oceanographic variability. In this section, we describe in detail the results from the OWC output of four RBR*argo* floats and demonstrate the methods helping us to avoid this kind of ambiguity. The approach we use includes (1) identifying spatial coherency in discrepancies between the analyzed Argo measurements and the reference dataset, (2) comparing the reference salinity fields calculated by the OWC to a different reference data source, and (3) applying the OWC analysis to other nearby contemporary Argo floats.

3.4.1. Argo Australia float 5904925 in the Coral Sea

For the Argo Australia float 5904925 deployed in the Coral Sea, the computed fit coefficients were comparable in the beginning (July 2015–April 2016) and the end (March 2018–August 2019) of the dataset, demonstrating a high level of the sensor stability (Figure 6a). The computed salinity offset, however, was significantly different in-between those two time periods. A more detailed analysis demonstrated that the deviations from the average offset were spatially coherent, suggesting that the discrepancy might be due a specific oceanographic feature that was measured by the float, but not captured by the reference dataset. In fact, for Argo Australia float 5904925, the geographical location of these deviations clearly demonstrates that all profiles with salinity offsets anomalously larger than -0.010 were concentrated in the area to the south-southeast from the Solomon Islands, between 11°S–13°S and 161°E–165°E (Figure 6b). Additional evidence of shortcomings of the reference dataset arises from the comparison between the reference salinity calculated by the OWC OM algorithm on the basis of the ADMT-Argo dataset to the World Ocean Atlas 1° resolution 2005-2017 climatology (WOA1, Figure 6c). A large discrepancy is observed during the same time period when the reference Argo dataset yielded larger salinity. Comparison between the ADMT-Argo reference data and other climatologies and gridded monthly products (World Ocean Atlas 1955-2017 of 0.25° resolution WOA4 (Garcia et al. 2018)*;* Monthly Isopycnal & Mixed-layer Ocean Climatology MIMOC (Schmidtko et al. 2013)*;* CSIRO Atlas of Regional Seas CARS2009 (Ridgway et al. 2002); Roemmich-Gilson Argo Climatology RG (Roemmich and Gilson 2009)) demonstrated similar results. We concluded that the variations in the salinity profile fit coefficients calculated by the OWC method from the ADMT-Argo reference dataset was likely be attributed to shortcomings in the reference data rather than to sensor drift.

3.4.2. Japan Argo floats 2903005 and 2903327 in the Northwest Pacific

The OWC output for of the two Japan Argo floats in the Northwest Pacific did not show a statistically significant trend in salinity, and it returned salinity offsets well below salinity measurement accuracy (+0.0009 for float 2903005 and +0.0017 for float 2903327; see Table 2 and Figures 7a and 8a). These results, however, strongly depend on the time separation factors (see Table 2). The salinity offsets closest to zero were obtained when the small/large factors were set to 1/3 years, the values recommended for highly variable regions like the North Atlantic (Cabanes et al. 2016).

Although the OWC output did not show a statistical trend in both Japan Argo floats, the differences between the salinity measured by the float 2903005 and reference salinity demonstrated substantial changes over time: a maximum in September 2018 followed by a gradual decrease until May 2019 (Figure 7a). Spatial analysis of these variations once again shows spatial coherency (Figure 7b). Comparing the OWC OM output to the WOA1 climatology demonstrates that the variations in the profile fit coefficients are correlated with the differences between the reference data and WOA1 (Figure 7c). Profile fit coefficients were positive between February 2018 and November 2018, and negative over the period ranging from February 2019 and September 2019. During the first half of the times series, float 2903005 was located in the water with salinity significantly higher than captured by WOA1, which may be explained by recent changed in salinity in the Pacific Ocean (Figure 5c) (Li et al. 2019; Liu et al. 2019; Wang et al. 2017). During the latter half of the time series, the float moved to the northwest before being advected by strong currents and transported to west-southwest, covering about 240 km in less than a month (March 16, 2019–April 12, 2019), resulting in a mean trajectory velocity greater than 10 cm s^{-1}. This relocation of the float to a different region affected by the Kuroshio extension was associated with water characterized by lower salinity, which is evident from the large positive anomaly observed between the reference dataset and WOA1 (Figure 7c) before relocation and no significant difference after. Once again, these results are independent of the climatology considered.

The salinity measured by the Japan Argo float 2903327 was on the average within 0.0017 of the salinity in the reference dataset (Figure 8a). As with float 2903005, the comparison between the reference salinity in the ADMT-Argo dataset and the WOA1 climatology demonstrated strong disagreement (Figure 8c), except during the first few months, when the float was located to the south of 30°N (Figure 8b). Float 2903327 also moved to the region where float 2903005 was taken by strong current and transported to water with different temperature-salinity properties (32°N; 160°E). However, it arrived to that region about two months later, which might explain why the salinity variations observed in the data collected by float 2903005 were not observed by float 2903327.

3.4.3. China Argo float 2902730 in the Philippine Sea

The results of OWC analysis of the China Argo float 2902730 in the Philippine Sea demonstrate close correspondence between the measured and reference salinity, except during the last 4 months of the time series, when the profile fit coefficients are negative and reach -0.0112 (Figure 9a). During that period, the float drifted to the north of 14°N and remained in this region until the end of the time series (green rectangle in Figure 9b). Comparison between the reference data and all five climatologies did not reveal significant disagreement during that period, in contrast to other floats analyzed in this study (Figure 9c). Instead, the negative offset observed after July 2019 is attributed to a large decrease in the number of simultaneously collected reference data, as DM Argo data would only be available minimum 6 months after collection. To confirm this hypothesis, this trend observed in OWC results is further analyzed.

To verify that the disagreement in salinity in this area was not related to sensor drift, we extracted from the GDAC all data from floats profiling in the same area (14°N–17°N; 126°E–129°E; green rectangles in Figures 9b and 10b) during the same period (starting July 2019), which is comprised of NRT data exclusively. Six floats with more than 10 profiles were selected for comparison (2902703, 2902708, 2902688, 2902683, 2902707 and 2901545). All six floats demonstrated similar decrease of the OWC profile fit coefficients in that small area. Results for float 2902683 are shown in Figure 10; other floats are not shown for clarity. It is interesting that the large negative ΔS starting January 2019 is not seen in the OWC vs WOA1 comparison (Figure 10c); we attribute this fact to recent salinity changes in the Pacific Ocean (Li et al. 2019; Liu et al. 2019; Wang et al. 2017).

4. Discussion

This study demonstrates the high level of accuracy and stability of salinity data collected by the RBR*argo* CTDs. When analyzed by the standard OWC method with default settings, all four RBR*argo* floats operating in the Pacific Ocean revealed no drift and only one of them deployed more than four years ago and equipped with C-cell of old design demonstrated a calibration offset of -0.010, right at the limit of Argo guidelines. All three RBR*argo* equipped with CT-cells of new design collected data which do not require correction. These characteristics look promising, taking into account that many Argo floats with electrode conductivity sensors produce measurements that require a salinity offset and/or drift correction. Of 360 Argo floats operating in the same areas, >30% demonstrated significant drift (>0.01 in 4 years) corrected during DMQC processing. Statistics for previous years reveal similar figures: for example, about 75% of Argo profiles in the COriolis dataset for Re-Analysis (CORA3) (1999-2010), had to be adjusted for pressure and/or salinity offset (Cabanes et al. 2013).

The OWC analysis of salinity stability of data collected by Argo floats demonstrated some caveats, which can result in subjectivity in the application of a salinity drift correction. These caveats are associated with limitations of reference data, which can naively be misinterpreted as sensor drift. The likelihood of a float encountering salinities different from the reference data is expected to be higher in the areas characterized by high gradients and increased variability of salinity in deep layers selected by the OWC analysis. This is illustrated by the patterns of geographical distribution of WOA1 salinity mean and standard deviation averaged over the 1000–1200 dbar layer (Figure 11). In the Coral Sea, the most problematic area (in terms of reference salinity) was the region between the Solomon Islands and Vanuatu (Figures 6b, 11a, d). The intermediate waters (>700 dbar) in that area are dominated by the low-salinity Antarctic Intermediate Water (AAIW) transported from the south (Gasparin et al. 2014; Qu and Lindstrom 2004). The northern extension of the AAIW terminates in a strong salinity front (Sokolov and Rintoul 2000) (Figure 11a). We speculate that during the objective mapping, high salinity measured to the north from this sharp gradient added positive bias to the reference data to the south resulting in the observed disagreement (Figure 6b).

The disagreement between the salinity measured by the Japan Argo float and the reference data (Figure 7a, b) increased when the float drifted northwest to the area affected by the Kuroshio extension characterized by high salinity variations (Qiu 2001) (Figure 11e). A similar pattern was observed in the Philippine Sea where the China Argo float was drifting northward to the area where the main part of the Pacific North Equatorial Current bifurcates and feeds the northward flowing Kuroshio and the southward flowing Mindanao Current (Qiu and Lukas 1996; Wang et al. 2015). Salinity in the northern part of the Philippine Sea is lower and more variable as compared to the area to the south (Figure 11c, f) (Zhou et al. 2018), and the northward trajectory of the Argo float resulted in gradual increase of the disagreement between the measurements and the references (Figure 9a, b).

The importance of reference data for salinity drift assessment was evident from the beginning of the Argo program (Gaillard et al. 2009; Kobayashi and Minato 2005). Previous studies demonstrated an increase in the number of Argo profiles erroneously attributed as suspicious in dynamic and weakly stratified regions like the North Atlantic (Böhme and Send 2005; Cabanes et al. 2016), high eddy kinetic energy regions such as Western Boundary Currents (Jia et al. 2016; Wang et al. 2013), or during anomalous events such as the El Niño–Southern Oscillation (ENSO) (Cabanes et al. 2013). This study also demonstrates the importance of long-term trends in salinity which must be taken into account in OWC analysis. We see that increasing the OWC time separation factor causes the Argo DMQC reference databases to approach climatology, while current conditions are different from climatological values. Although a sufficient number of high-quality reference data and proper selection of parameter settings for OWC calculations are a primary requirement for proper assessment of Argo sensor stability, visualization approaches like the ones demonstrated here can provide significant help. We recommend these methods for Argo users and believe that they can help Argo community in its mission – collecting high-quality oceanographic observations.

Data Availability Statement

The Argo data is freely available from the Argo program website (http://www.argo.ucsd.edu/Argo_data_and.html**).**

Acknowledgments

The data from the Argo Australia, China Argo and Japan Argo floats used here were collected and are made freely available by the International Argo program and the national programs that contribute to it. G. Maze was supported by the EARISE project, a European Union's Horizon 2020 research and innovation program under grant agreement no 824131, call INFRADEV-03-2018-2019: Individual support to ESFRI and other world-class research infrastructures. We acknowledge Susan Wijffels, who provided advice on reference climatologies, coordinated access to the data from Argo Australia float 5904925, and provided ship CTD data to evaluate the initial accuracy of the float. Toshio Suga and Shigeki Hosoda provided ship CTD data for assessing the initial accuracy of Japan Argo floats 2903005 and 2903327. We would like to thank Zenghong Liu for coordinating access to ship CTD data and continued discussion regarding RBR*argo* CTD accuracy and stability. We thank Annie P. S. Wong for critical comments and recommendations in data analysis. We thank Mathieu Dever for critical reading and comments for the manuscript. Finally, we wish to thank the Argo Steering Team for encouraging Argo member nations to take part in the RBR CTD Argo Global Pilot Project.

Appendix

The OM interpolation of reference data by OWC MATLAB toolbox was performed with the settings listed in Table A1. The parameters regulating linear fit of the profile-based corrections were set to default values, i.e., the number of breakpoints was selected automatically.

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Tables

Table 1. Four Argo floats with RBR*argo* CTDs operating in the Pacific Ocean.

Float WMOID	Region	Deployment date	Deployment coordinates	Vessel	Operator	No of cycles analyzed
5904925	Coral Sea	24 July 2015	10.98°S; 164.57°E	*R/V Cassiopee*	Australian Commonwealth Scientific and Industrial Research Organization (CSIRO)	148
2903005 2903327	Northwest Pacific	3 February 2018	27.999°N; 165.003°E	*R/V Keifumaru*	Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	61* 61*

2902730	Philippine Sea	11 January 2018	11.98°N; 129.998°E	*R/V Ke Xue San Hao*	China Second Institute of Oceanography (CSIO)	69

[*]During the starting two-month period, both Japan Argo floats operated at 1-day cycles and starting March 28, 2018 switched to 10-day cycles. To avoid overweighting of the starting period in the drift assessment, one of every 10 consecutive profiles was selected for both floats before March 28, 2018.

Table 2. Salinity offsets calculated by the OWC method at different reference datasets and time separation factors. Numbers in bold indicate the reference dataset and time separation factors selected for analysis.

IFREMER DMQC reference dataset	Small/large time separation factors (years)	Argo Australia 5904925	Japan Argo 2903005	Japan Argo 2903317	China Argo 2902730
CTD 2019v01	1/3	-0.0152	-0.0116	-0.0139	-0.0139
	3/10	-0.0167	-0.0088	-0.0107	-0.0144
	10/30	-0.0152	-0.0077	-0.0075	-0.0076
Argo 2019v01	1/3	-0.0114	**-0.0009**	**-0.0020**	0.0017
	3/10	**-0.0100**	-0.0065	-0.0037	**-0.0016**
	10/30	-0.0132	-0.0149	-0.0163	-0.0068

Table 3. Assessment of the initial accuracy of the four Argo floats with RBR*argo* CTDs in the Pacific Ocean compared to the CTD and Rosette profiles collected in parallel with the float deployment, and the World Ocean Atlas data in the deployment locations. Numbers in bold exceed the Argo accuracy requirements.

Float	Distance (km)	Difference in time (h)	Salinity offset in the layer with potential temperature 2–5°C; averaged difference (Reference - Argo), calculated along potential density levels		
			bottle	SBE911	World Ocean Atlas (WOA1)
Argo Australia 5904925	2.5	25.2	**-0.0114**	-0.0081	**-0.0124**
Japan Argo 2903005	0.38	23.1	-0.0044	-0.0034	-0.0024
Japan Argo 2903317	0.30	23.7	-0.0090	-0.0081	-0.0066
China Argo 2902730	0.38	19.2	no data	-0.0044	-0.0006

Table A1. Parameters values used for OM interpolation (the file "ow_config.txt") in OWC analysis

	Parameter	OWC variable	Value
1	Maximum number of historical casts used in objective mapping	CONFIG_MAX_CASTS	300 (default)
2	Use/not use PV constraint	MAP_USE_PV	0
3	Use SAF separation criteria	MAP_USE_SAF	0
4	Spatial decorrelation scales (degrees)	MAPSCALE_LONGITUDE_LARGE	4
		MAPSCALE_LONGITUDE_SMALL	2
		MAPSCALE_LATITUDE_LARGE	4
		MAPSCALE_LATITUDE_SMALL	2
5	Cross-isobath scales	MAPSCALE_PHI_LARGE	0.5 (default)
		MAPSCALE_PHI_SMALL	0.1 (default)

6	Temporal decorrelation scale (years)	MAPSCALE_AGE MAPSCALE_AGE_LARGE	1-10 3-30 see Section 3.1
7	Exclude the top xxx dbar of the water column	MAP_P_EXCLUDE	1000
8	Only use historical data that are within +/- yyy dbar from float data	MAP_P_DELTA	250 (default)

Figures

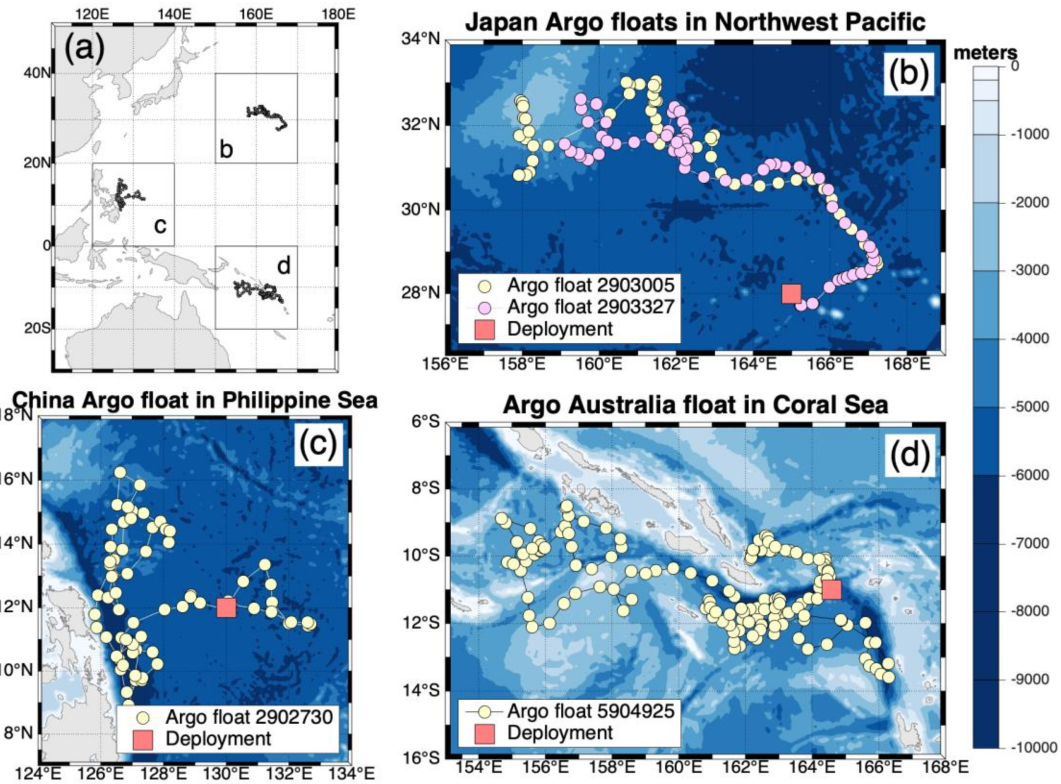

Figure 1. Four Argo floats equipped with RBR*argo* CTDs operating in the western Pacific Ocean. Rectangles around each float in (a) indicate the regions where other Argo floats (deployed starting January 2011) were selected for comparison (Section 3.3). Red squares in (b)–(d) indicate the deployment locations where the CTD profiles used for assessment of the initial accuracy of Argo salinity measurements (Section 3.2) were collected. The color shading in (b)–(d) indicates bathymetry.

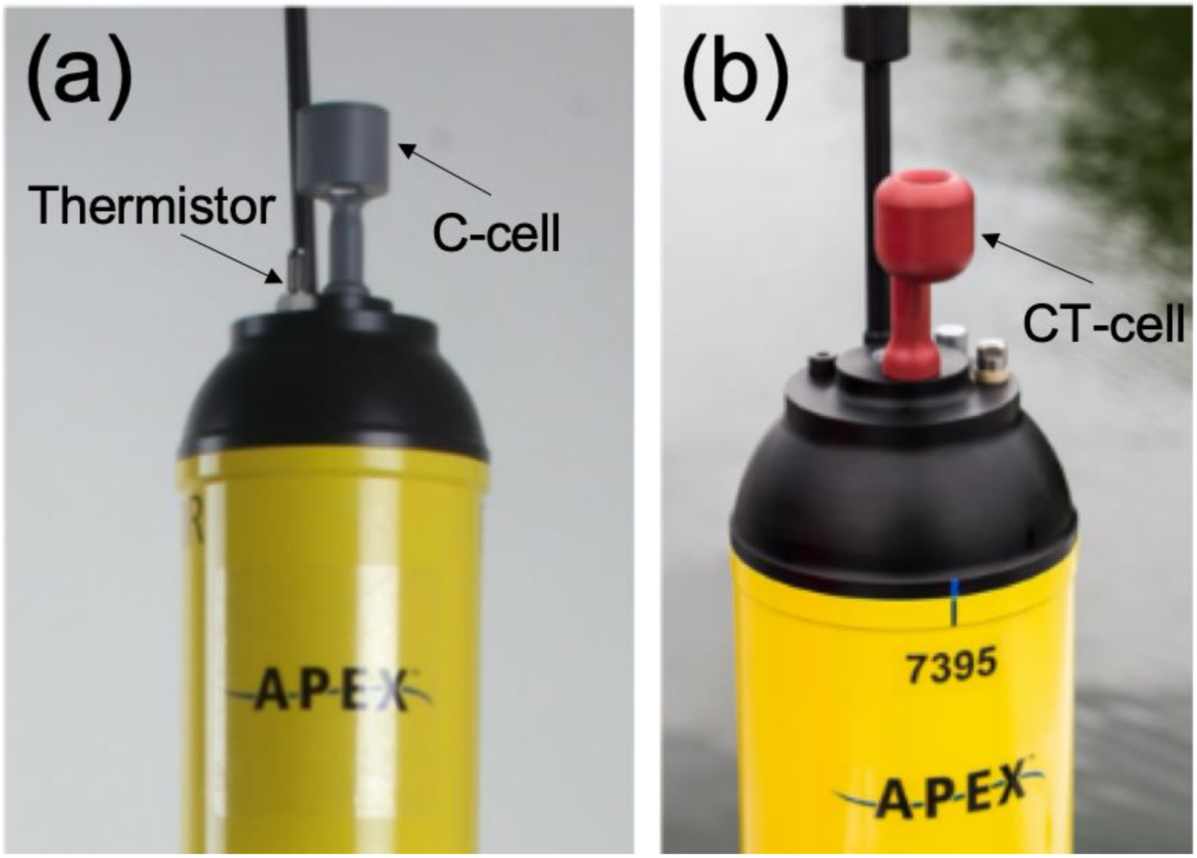

Figure 2. Photographs of (a) the RBR***argo*** CTD with inductive conductivity cell ("C-cell") (previous to 2016) and (b) the current inductive cell ("CT-cell"). The thermistor on the CT cell is collocated with the conductivity cell, however in the photo it is on the far side of the cell and therefore not visible. Photos courtesy of Teledyne Marine.

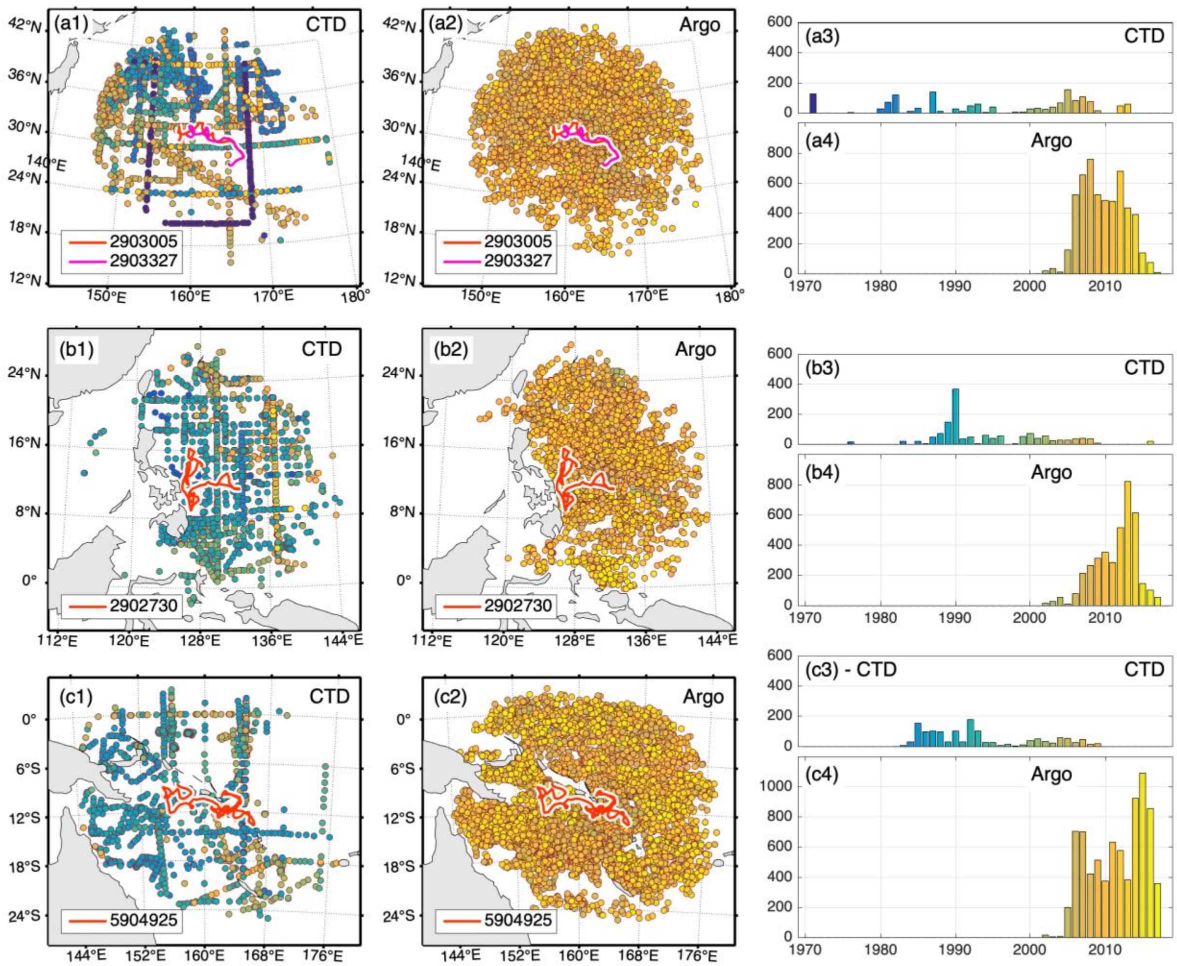

Figure 3. Availability of reference data for OWC analysis of RBR*argo* floats: Japan Argo (a1–a4); China Argo (b1–b4) and Argo Australia (c1–c4); CTD casts (a1, a3, b1, b3, c1, c3) and DMQC-corrected Argo profiles (a2, a4, b2, b4, c2, c4). Maps (a1, a2, b1, b2, c1, c2) demonstrate the locations of reference data; histograms (a3, a4, b3, b4, c3, c4) demonstrate the numbers of profiles collected during different years. The color scale in maps and histograms indicate the years when reference data were collected.

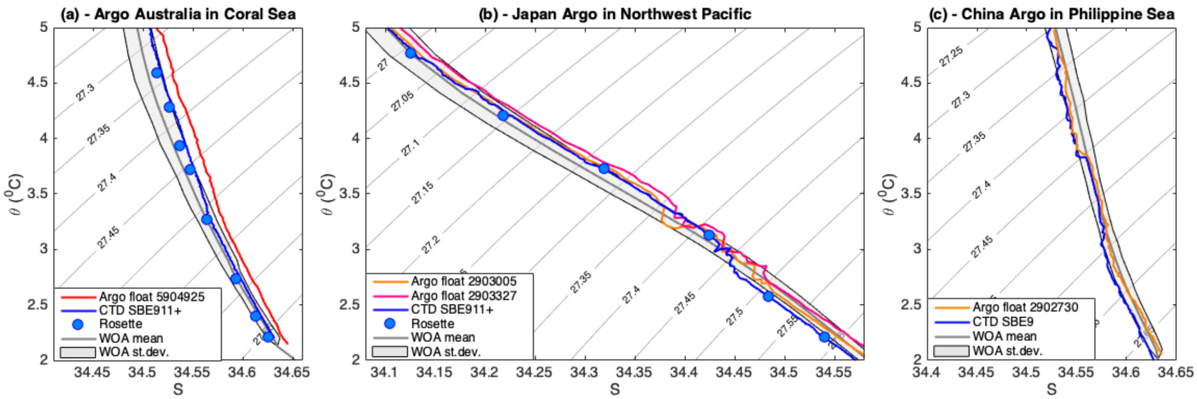

Figure 4. Comparison between the starting profiles of the four Argo floats equipped with RBR*argo* CTDs, CTD casts collected when the float was deployed, and the World Ocean Atlas (WOA1) climatological data at the deployment locations. X-axes are practical salinity; Y-axes are potential temperature (°C).

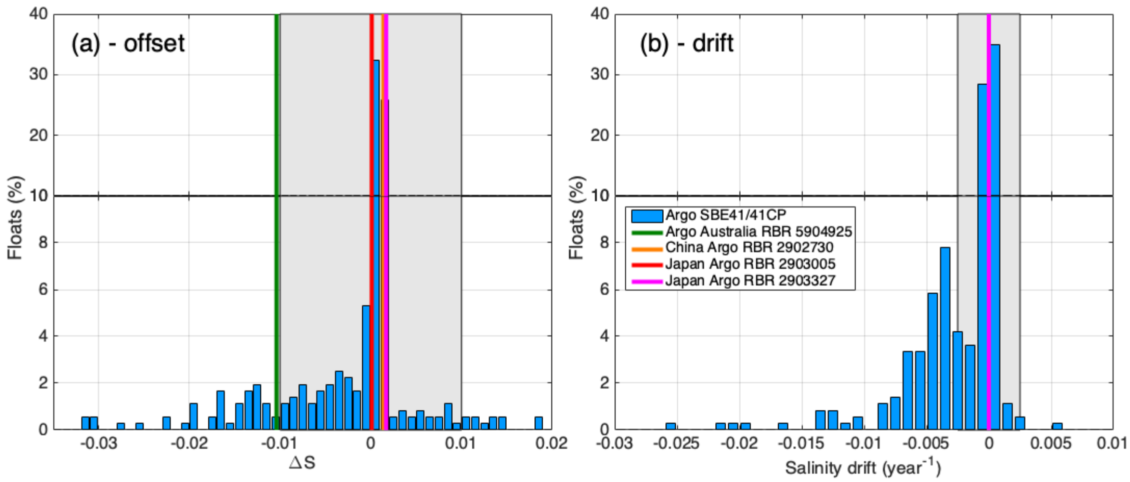

Figure 5. The averaged salinity (a) correction bias and (b) drift (the slope of the linear change of the correction offset between the beginning and the end of the float lifetime) in four Argo floats with RBR*argo* CTDs and 360 Argo floats with electrode conductivity sensors operating in the same areas since 2011 (blue bars). Shaded areas show: (a) the target accuracy of Argo salinity measurements (0.01) and (b) the stability limits of Argo salinity measurements (0.01 in 4 years = 0.0025 year^{-1}). Note that in (b) the drift estimates for all four RBR*argo* CTDs indicated in the legend are zero.

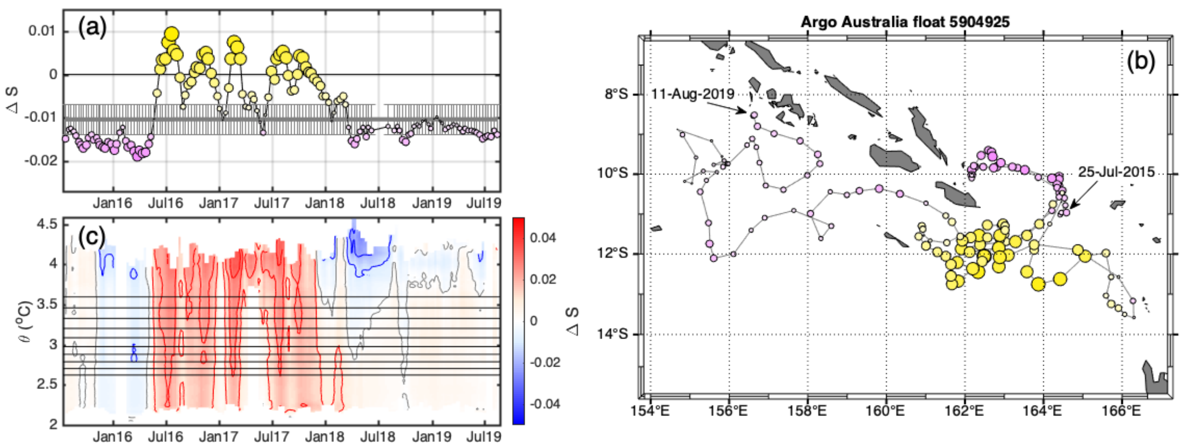

Figure 6. (a) OWC profile fit coefficients for Argo Australia float 5904925, (b) geographical location of the profiles with different OWC fit coefficients. The size and color of the circles indicate the deviations of the profile fit coefficients from the constant offset. Arrows with dates indicate the start and end float positions. (c) The differences between the reference salinity calculated by the OWC method using the Argo reference database and the World Ocean Atlas (2005-2017) climatology (Y-scale is potential temperature). Horizontal lines in (c) show the 10 potential temperature levels with minimum salinity variations used for the OWC analysis.

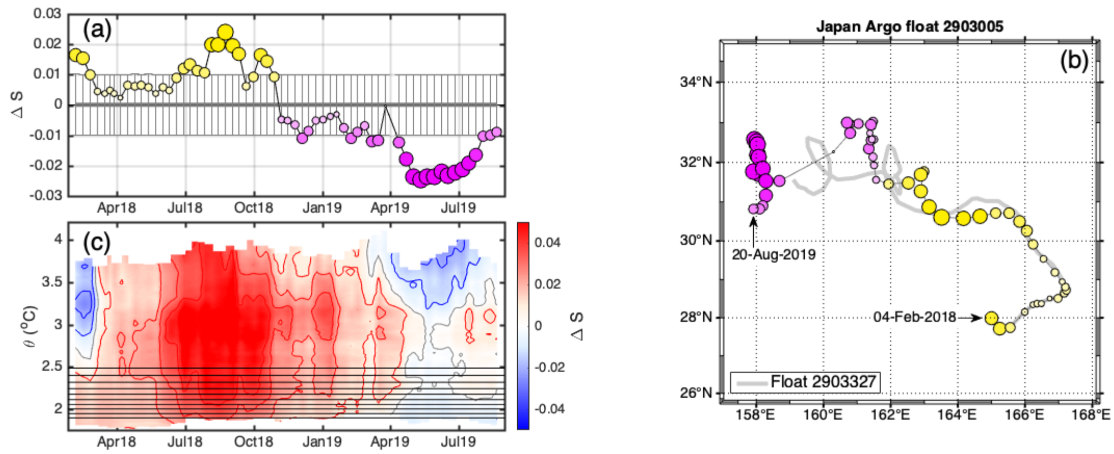

Figure 7. Similar to Figure 6, for Japan Argo float 2903005. Gray line in (b) shows the trajectory of the Japan Argo float 2903327 deployed in parallel with the float 2903005.

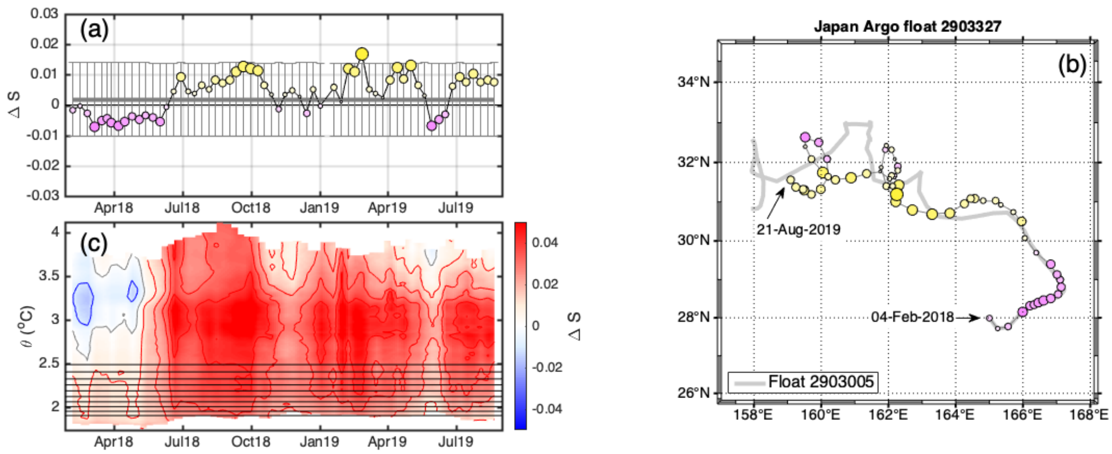

Figure 8. Similar to Figures 6–7, for Japan Argo float 2903327. Gray line in (b) shows the trajectory of Japan Argo float 2903005 deployed in parallel with the float 2903327.

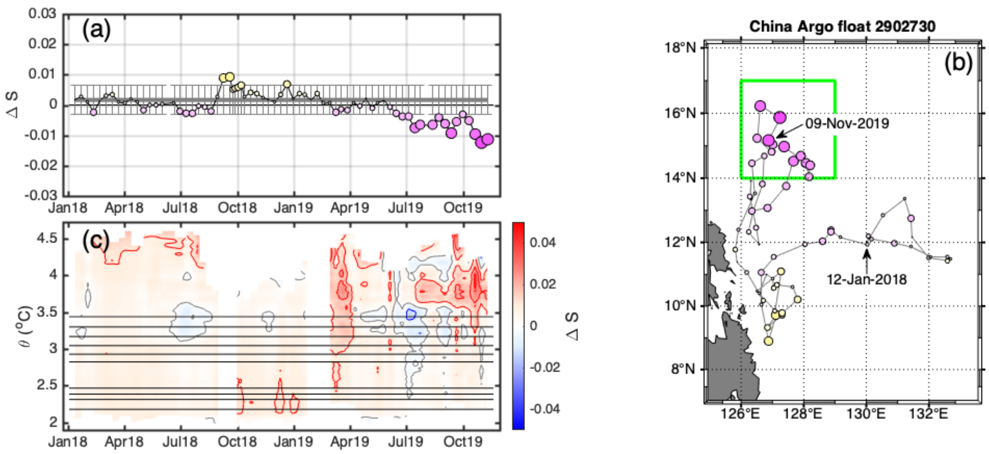

Figure 9. Similar to Figures 6–8, for China Argo float 2902730.

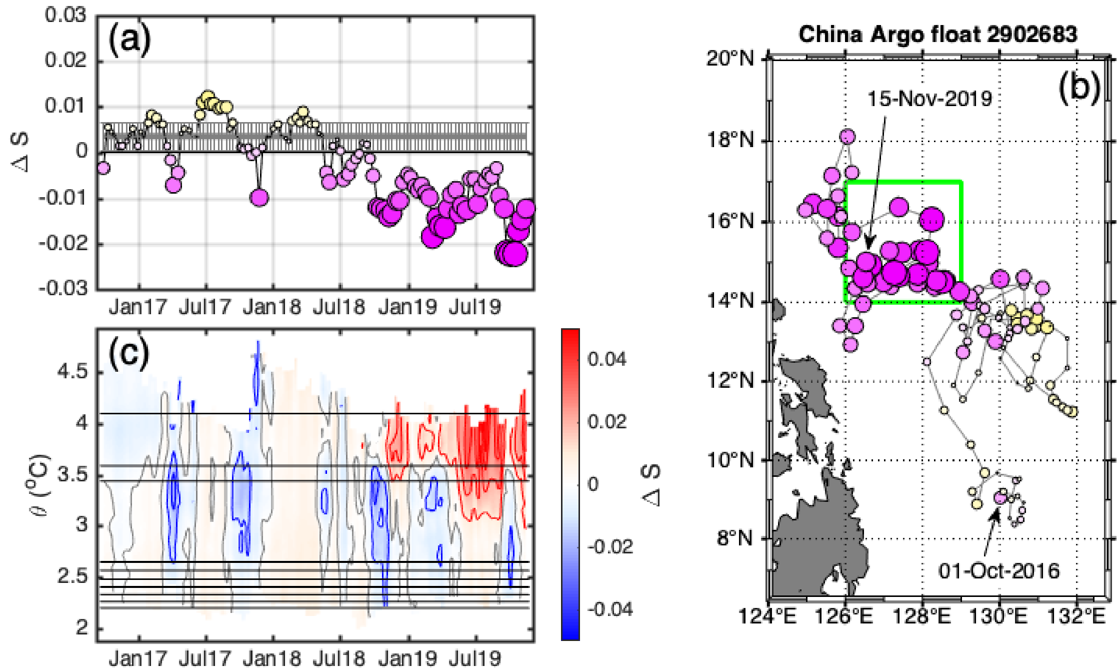

Figure 10. Similar to Figures 6–9, for China Argo float 2902683 with SBE41 CTD operating in the same area and the same time with the China Argo float 2902730 (Figure 9).

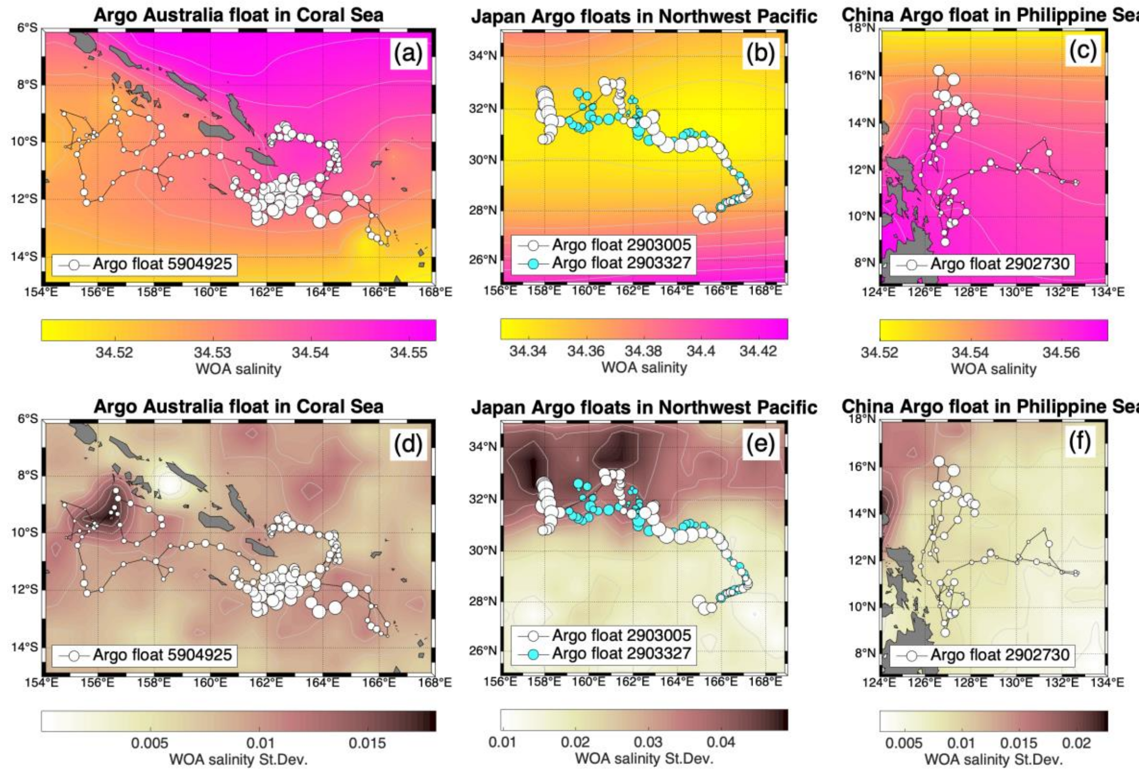

Figure 11. World Ocean Atlas *[Garcia et al., 2018]* salinity means (a-c) and standard deviations (d-f) averaged in the 1000–1200 dbar layer in (a, d) the Coral Sea, (b, e) the Northwest Pacific and (c, f) the Philippine Sea, where the Argo floats with RBR*argo* CTDs operated. The size of circles along the float trajectories is proportional to the differences between the profile fit coefficients and the mean offsets calculated by the OWC method (similar to Figures 6b-9b).