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Assessment of long-term stability of inductive conductivity sensors on Argo floats

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Abstract

This study analyses accuracy and stability of salinity measurements collected by four Argo autonomous drifters with RBR Ltd. inductive conductivity sensors operating in the Pacific Ocean during the recent 2-4 years. Inductive sensors have advantages over traditionally used electrode-type cells due to their better resistance to surface contamination and low power requirements, resulting in more robust and accurate measurements and extended float lifetimes. Proper assessment of the quality of the data collected by autonomous drifters is challenging due to lack of reference information. An important part of Argo program is the Delayed-Mode Quality Control process including salinity drift analysis and correction using the 'Owens-Wong Calibration' (OWC) method based on objective mapping of available reference data. This method, however, can misinterpret imperfect reference data as sensor drift. In this study, analyzing OWC output we introduce a combination of visualization methods focused on the locations where reference data can be treated as problematic. These methods include the analysis of spatial locations of the 'profile correction factor' along the float trajectory, comparing reference salinity fields calculated by the OWC method to additional reference sources (climatologies) and comparative analysis of different floats operating in the same area using the same reference datasets. The results demonstrate high level of stability of inductive conductivity cells on Argo floats, making them promising alternative for traditionally used Argo float CTDs equipped with electrode-type conductivity sensors.

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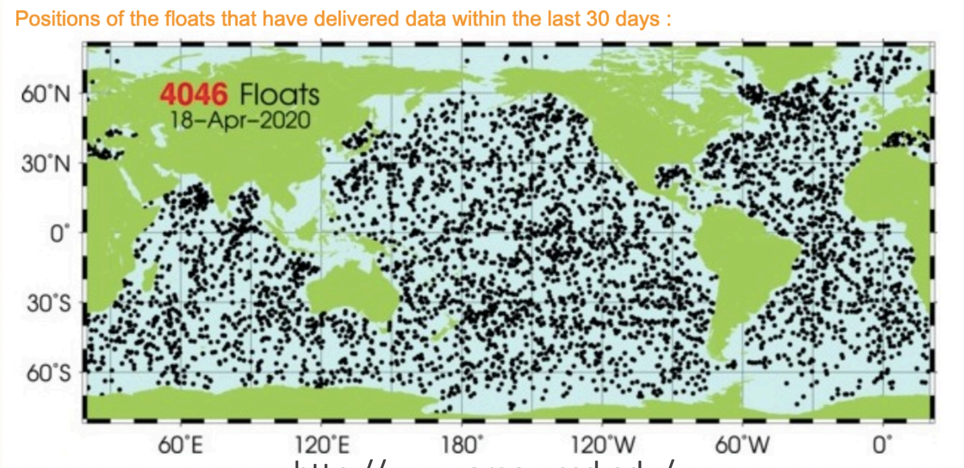
Argo program

Approximately 4000 autonomous profiling floats continuously operating in the world ocean

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.

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.



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Argo program

Data quality is a key asset of the Argo program

Target accuracies for measurements: 2.5 dbar for pressure, 0.005°C for temperature, and 0.01 for salinity.
The quality of salinity measurements (computed from conductivity) is most problematic due to:

- Biofilms on the conductivity cell cause a change in the cell constant
- Mechanical failures

The main obstacle in achieving high accuracy

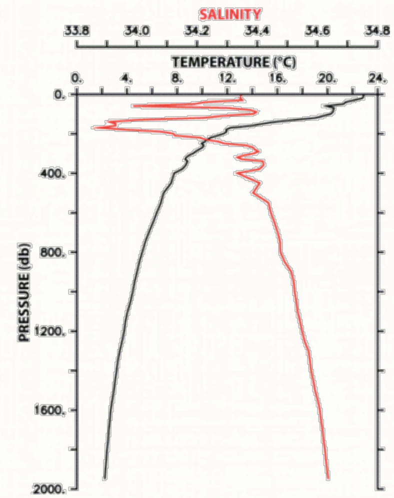
- Autonomous floats cannot be recalibrated on regular basis
- Indirect methods of data quality analysis and correction must be applied

Real Time Quality Control (RTQC)

- Detection and elimination of outliers
- Available in Near-Real Time (NRT) within 24 h

Delayed-Mode Quality Controlled (DMQC)

- Produce high quality datasets for oceanographic research
- Argo data experts examine the data and apply correction when necessary
- Takes 6 to 12 months
- An essential part of DMQC process is the analysis and correction of **salinity** offset and drift



http://www.argo.ucsd.edu/

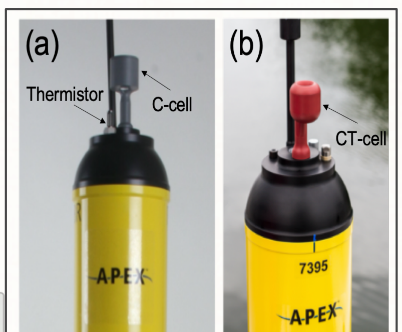
Salinity measurements in the ocean

Salinity measurements in seawater are commonly made using either electrode or inductive conductometry principles

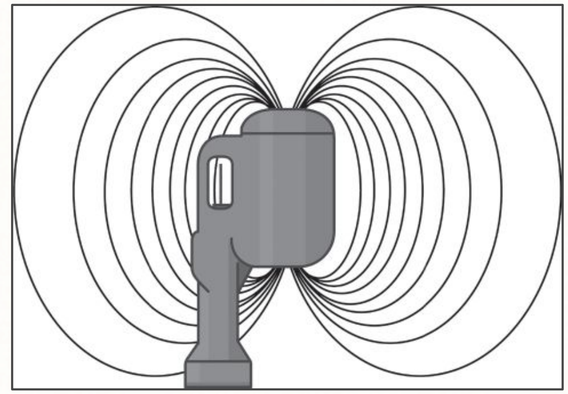
- Electrode cells measure electrical resistance between the electrodes directly contacting with seawater
- Inductive cells function according to Faraday’s law of induction

Inductive cells are particularly beneficial for autonomous observing systems

- Water flushes freely through the inductive cell, significantly lowering power consumption compared to sensors using pumped electrode conductivity cells
- In the absence of a direct coupling with seawater, inductive cells do not have problems with oil contamination or corrosion



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 but is on the far side of the cell and therefore not visible in the photo. Photos courtesy of Teledyne Marine.



Schematic of the RBR **inductive conductivity** cell. The curved lines represent conceptual invisible lines of magnetic and electric fields surrounding the cell. The temperature sensor is co-located with the conductivity sensor to measure the same water parcel (from Halverson et al., 2020).

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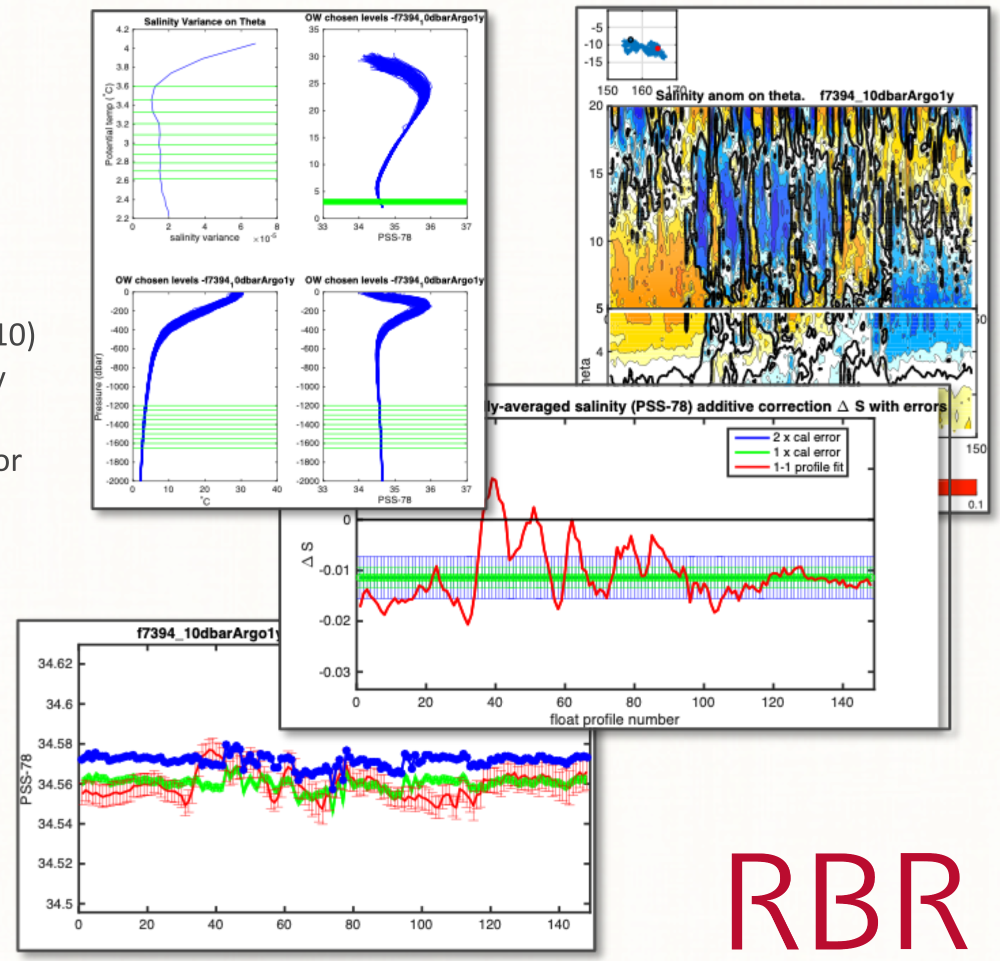
Salinity bias and drift detection

The OWC (Owens-Wong-Cabanes) analysis is the statistical method of salinity drift correction[1,2,3] approved and used by Argo community

- The salinity profiles observed by an Argo float are compared to reference data in the same region by using objective mapping.
- Argo salinity is compared to the reference along several (typically 10) potential temperature isotherms, characterized by minimal salinity variations.
- The OWC analysis returns a set of salinity correction factors, one for each completed profile.
- The decision whether or not conductivity corrections should be applied, is made by the user and involves some subjectivity.

OWC analysis output:



[1] Owens and Wong, 2009. Deep-Sea Research I, 56(3), 450-457, https://doi.org/10.1016/j.dsr.2008.09.008.
[2] Cabanes et al., 2016. Deep-Sea Research I, 114, 128-136, https://doi.org/10.1016/j.dsr.2016.05.007.
[3] MATLAB toolbox (https://github.com/ArgoDMQC/matlab_owc)

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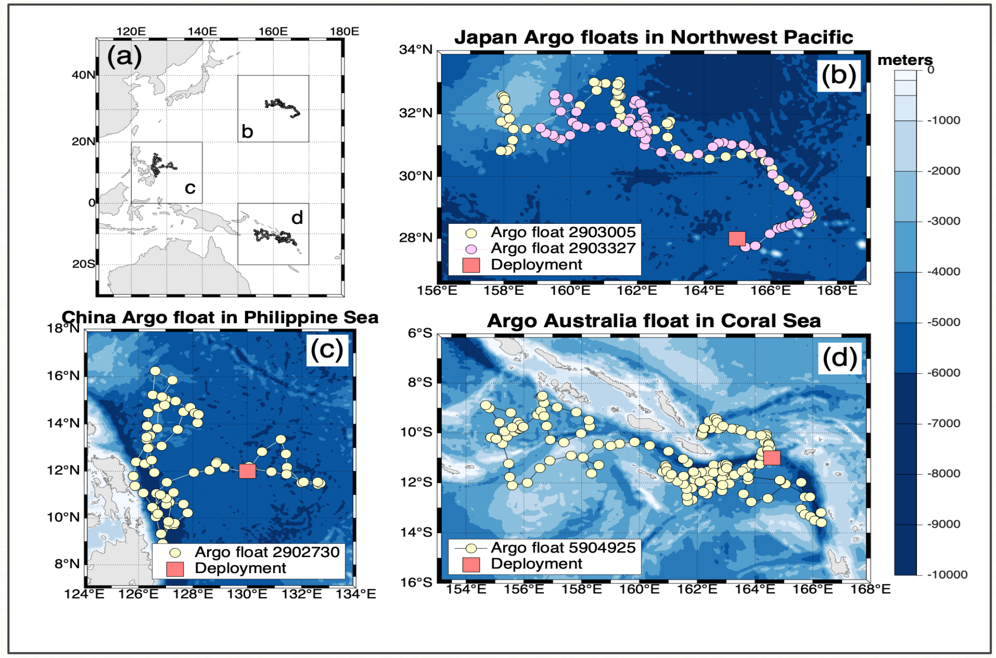
Argo floats equipped with inductive conductivity sensors

Four Argo floats equipped with RBR*argo* CTDs with inductive conductivity cells were deployed in the western Pacific Ocean in 2015 and 2018

Float WMOID	Deployment date	Deployment coordinates	Operator
5904925	24 July 2015	10.98°S; 164.57°E	CSIRO, Australia
2903005 2903327	3 February 2018	27.999°N; 165.003°E	JAMSTEC, Japan
2902730	11 January 2018	11.98°N; 129.998°E	CSIO, China



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.

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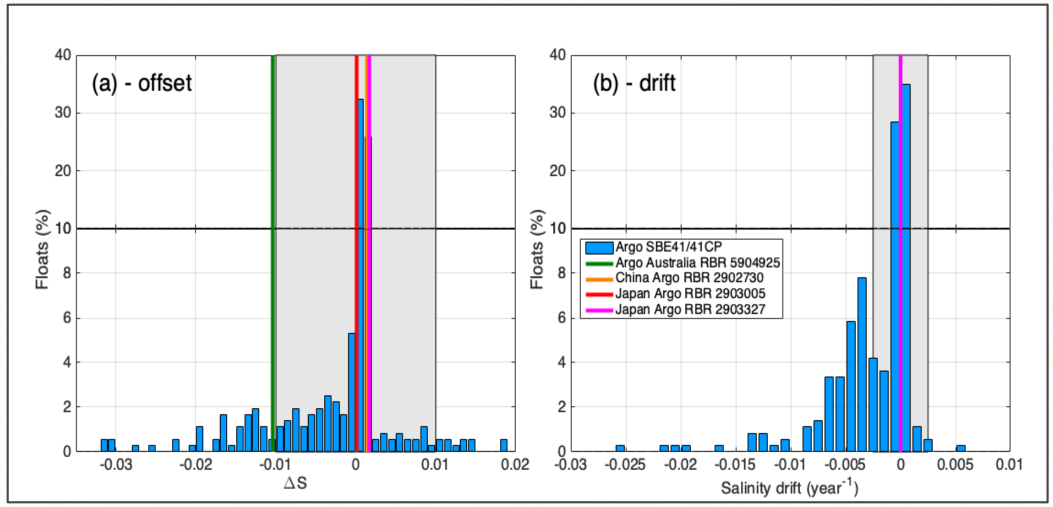
RBR*argo* in situ drift and bias correction compared to the electrode-based CTDs

Only one of four RBR*argo* float demonstrated significant offset (-0.010) from reference salinity

- Argo Australia float 5904925 was the first float with RBR-equipped conductivity cell deployed in 2015.
- The three RBRargo CTDs with new conductivity cell design (2902730, 2903005, and 2903327) did not need salinity correction.
- For comparison, in about 16% of the Argo floats with electrode conductivity sensors (57/360), the applied salinity offsets exceeded 0.01 (a).

All four RBRargo CTDs demonstrated no salinity drift

- In many Argo floats equipped with electrode conductivity cells salinity drift was detected and corrected during the DMQC analysis.
- For 31% of Argo floats (111/360), the salinity drift exceeded 0.0025 yr^{-1} (b).



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 RBRargo 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 $year^{-1}$).

OWC analysis: Detecting problematic reference data

Distinguishing between instrumental errors and oceanographic variability

- Drift of Argo float to water mass with different temperature-salinity characteristics can be easily misinterpreted as sensor drift.
- The designed visualization methods assist OWC users in determining whether anomalies in measured salinity are caused by instrumental errors or oceanographic variability:
    1. Plots combining the variations of the OWC profile fit coefficients (the vertically averaged reference salinities minus corrected float salinities at 10 selected reference potential temperature levels) with their location along the float trajectory
    2. Diagrams comparing the objectively mapped reference salinity field calculated by the OWC method to a different reference data sources:
        - World Ocean Atlas (WOA)[1]
        - Monthly Isopycnal & Mixed-layer Ocean Climatology (MIMOC)[2]
        - CSIRO Atlas of Regional Seas (CARS2009)[3]
        - Roemmich-Gilson Argo Climatology (RG)[4]
    3. Simplified OWC analysis of nearby contemporary Argo floats using the same reference dataset

[1]Garcia, H. E., and Coauthors, 2018. World Ocean Atlas 2018 (pre-release): Product Documentation, https://www.nodc.noaa.gov/OC5/woa18/
[2]Schmidtko et al., 2013. Journal of Geophysical Research: Oceans, 118(4), 1658–1672, https://doi.org/10.1002/jgrc.20122.
[3]Ridgway et al., 2002. Journal of Atmospheric and Oceanic Technology, 19(9), 1357-1375, https://doi.org/10.1175/1520-0426(2002)019<1357:OIBFDW>2.0.CO;2
[4]Roemmich and Gilson, 2009. Progress in Oceanography, 82(2Oceanography), 81-100, https://doi.org/10.1016/j.pocean.2009.03.004

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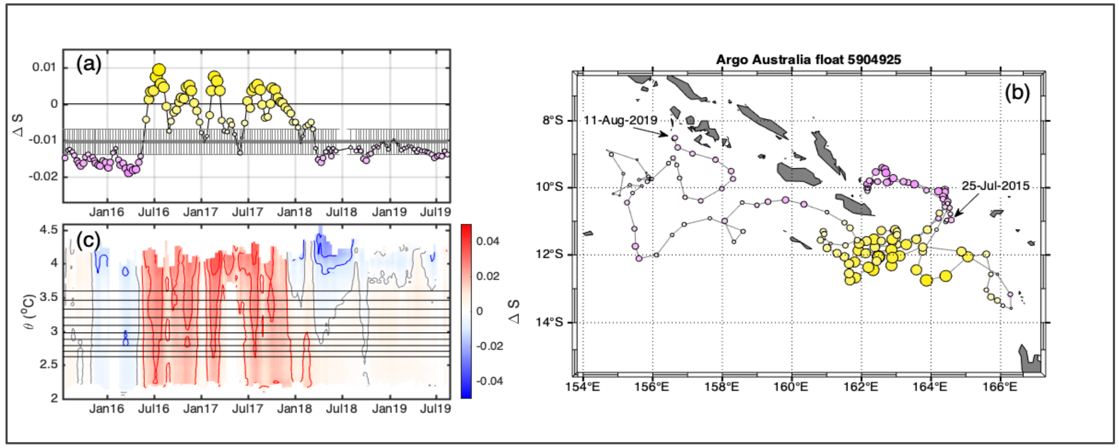
OWC analysis: Argo Australia float 5904925 in the Coral Sea



Average salinity offset -0.010

High level of the sensor stability

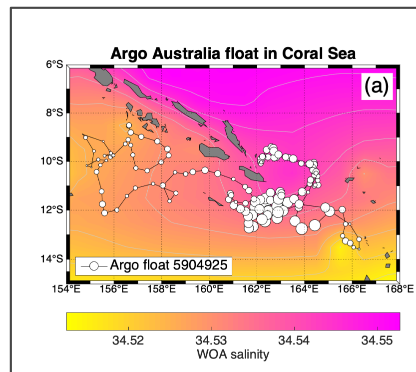
- OWC fit coefficients comparable in the beginning and the end of the operation period (a)

Disagreement between measured and reference salinity can be explained by problematic reference data

- Different salinity offset during 2016-2018 (a)
- The deviations from the average offset were spatially coherent (b)
- Disagreement between reference salinity calculated by OWC method and climatology (c)

Problems with reference data happen in the areas characterized by high gradients

- Strong salinity front at the northern extension of the the low-salinity Antarctic Intermediate Water (AAIW)



World Ocean Atlas salinity averaged in the 1000–1200 dbar layer in the Coral Sea

OWC analysis: Japan Argo floats 2903005 and 2903327 in the Northwest Pacific

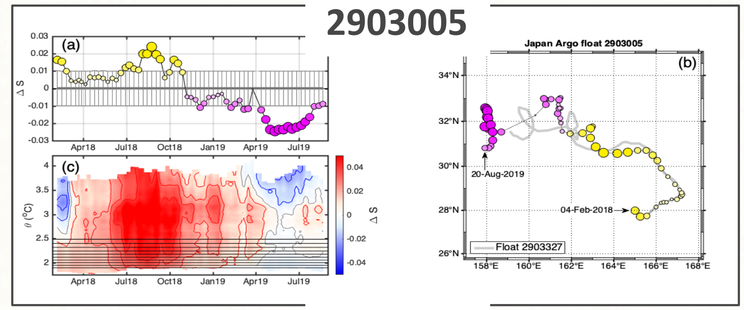
Salinity offsets well below salinity measurement accuracy

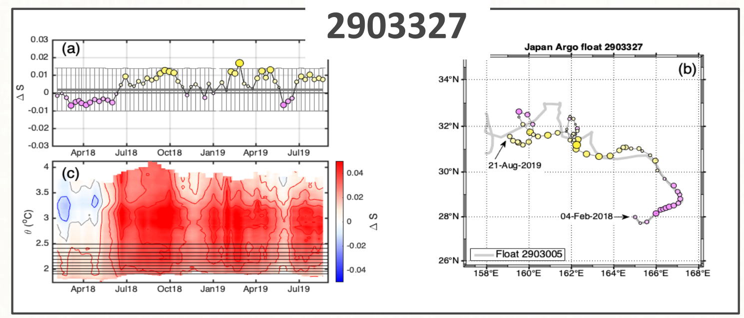
-0.0009 for Argo float 2903005

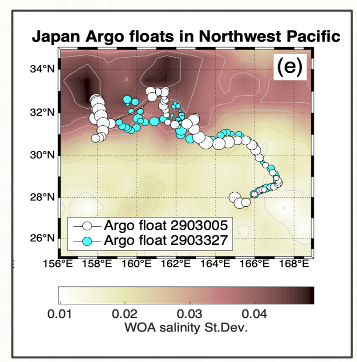
-0.0020 for Argo float 2903327

No statistically significant salinity drift in both floats

Disagreement between measured and reference salinity was observed when the float 2903005 moved northwest to the Kuroshio extension area characterized by high salinity variations







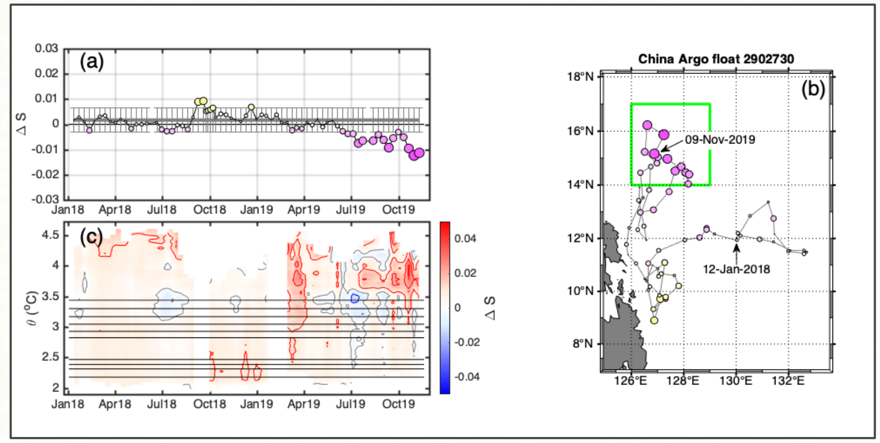
World Ocean Atlas salinity standard deviation averaged in the 1000–1200dbar layer

OWC analysis: China Argo float 2902730 in the Philippine Sea

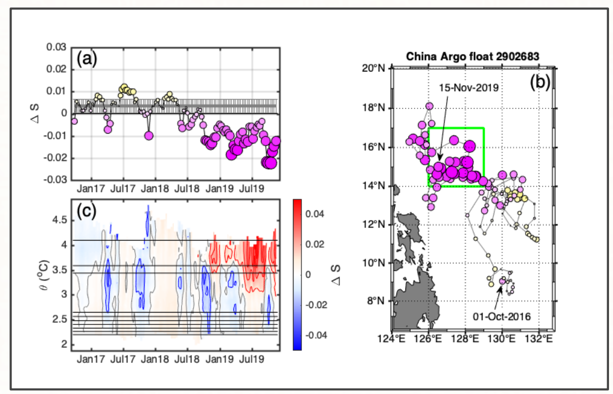
Close correspondence between the measured and reference salinity

- Salinity offset close to zero
- No salinity drift

Negative OWC profile fit coefficients during the last 4 months (a) are explained by problematic reference data (small number of DMQC Argo profiles)



Similar disagreement with the same reference dataset is demonstrated by all (6) Argo floats profiling at the same time in the same area



Argo float 2902683 with SBE41 CTD operating in the same area and the same time with the float 2902730. Other 5 floats are not shown for clarity

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Conclusions

- 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, making the RBR inductive cell a qualified option for salinity measurements in the Argo Program.
- The OWC method of salinity drift detection cannot determine whether deviations in the salinity calibration are caused by oceanographic variability or sensor problems
- The developed methods of visualization of OWC output demonstrate that anomalous salinity calibration values can be explained by imperfect reference data rather than sensor drift

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.
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Thank You

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