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E-AIMS

Euro-Argo Improvements for the GMES Marine Service

Deep float experiment final evaluation
D2.222

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1. Introduction

1.1. General presentation

This document details the experiment and analysis carried out with the Argo Deep floats in the framework of the E-AIMS project

The IEO is leading task 2.2 Test of new deep float and testing one prototype of deep Argo floats designed by Ifremer that are capable of reaching depth greater than 4000 dBar. These prototypes are now commercialized by NKE who is in charge of performing the industrialization tasks. The float tested in the framework of task 2.2 was part of the first batch of prototypes and of the second generation of floats. The test were carried out in the Canary Basin.

1.2. Reminder of the objective of Task 2.2

As indicated in the description of the Work, “We proposed to test two of these new deep floats. Test will be carried out in an area where deep ocean waters properties have been reported to be very stable in the last thirty years, the Canary Basin. The float specification will be defined in close interaction with the float manufacturer. The energy budget, vertical sampling, repeated cycle and data transmission would be, in particular, carefully analyzed. Analysis of performance at sea will be focused on the stability of the sensors.”

This report is the deliverable D2.222 identified in the description of work DA-1, in the table WT 2, which was initially due by the end of June 2015 (T0+30), but which was postponed to October 2015 (T0+34) (see minutes of 5th Steering Committee meeting), T0 being the first of January 2013.

1.3. Applicable documents

DA-1: Annex 1 to the grant agreement N0 312642: “Description of work”, date 21 June 2012.

2. Extending Argo to the deep ocean

The Argo network is actually the most important component of the Global Ocean Observing system (GOOS) with 3500 floats that profiles every ten days the upper 2000 dBars of the ocean. Since the launch of the program, about ten years ago, the Argo network has collected more that one million profiles over the global ocean, which corresponds to about twice the number of profiles than had been collected by all the research vessels during the whole 20th century. These data have been crucial to contribute to understand the role of the ocean in the climate system. However, the concern that part of the budget of sea level rise may be due to the steric contribution from the deep ocean (>200 m) has increased the interested in the deep ocean. Data from the repeated hydrographic sections program have been used to estimate this contribution (Johnson *et al.*, 2008 and Purkey and Johnson, 2010). Nevertheless, the sparse geographical and temporal coverage of accurate measurements of deep water, with oceanographic sections covered, at most, every five years (Vélez-Belchí *et al.*, 2010), has raised concerns about the statistical significance of decadal trends in the deep ocean estimated from the spare hydrographic data (Aucan and Llovel, 2013).

In this context, monitoring the deep ocean below 2000 dBars is one of the main necessary evolutions of Argo.

3. Test for the deep Argo prototypes

The initial implementation plan for the upper ocean (<2000m) Argo array was designated based upon the experience of the XBT program, the TAO array and the Jason altimeter mission. Altogether these three different operational programs permitted to do the statistical analysis necessary to define the targeted 3x3 density and establish 1500m as the parking. This network configuration permits the sampling of global anomalies in temperature and heat storage and a cost-effective signal-to-error sampling of large-scale oceanic variability.

However, the case for the deep ocean is by far very different, since there are fewer deep ocean observations, and even fewer time series. Possibly, the Hawaii Ocean Time series (HOT) and the Bermuda Atlantic Time-series Study (BATS) are the only deep ocean time series.

In this context, the first test of the deep Argo floats pursue the objective of maximizing the amount and frequency of deep ocean data, but keeping it cost-effective, in the sense that the deep Argo floats should have a lifetime (three years) close to the upper ocean Argo floats.

Ifremer has designed a prototype of deep Argo floats (Deep Arvor) that is capable of reaching depth greater than 4000 dBar. These prototypes are now commercialized by NKE who is in charge of performing the industrialization tasks. Two of these deep Argo floats designed by Ifremer will be deployed in the Canary Basin during 2014. The Canary Basin has been chosen because of its relatively quiescent environment that will make possible to assess the long-term stability of the float sensors at depth. Additionally, the IEO is conducting periodic hydrographic surveys every two years since 2006, and extending back at different sampling rates to 1997. The 16-years times' series has permitted to establish a trend for the upper deep waters (2600-3600 dBar) of 0.001ºC and 0.002 in salinity per year. These values (per year) are smaller than the accuracy of the CT sensors in the present generation of Argo floats.

3.1. Final experiment design

In the DoW it was planned that the first deep Argo floats would be tested during October 2013, however the company commercializing the Ifremer design of Deep Argo had some delay in the production of the float due to problems in the coupling with the pump engine system. The deep Argo floats are second-generation prototypes and therefore it was unavoidable to find some problems during its production. The float was ready in October 2014, however, the new rules imposed to the Spanish research institutions, as consequence of the control of the national budgets in relation with the austerity measurements resulted in long delays in the processing of tenders and purchased orders. Once it was notified by the manufactures that the float was ready, it took several months to send them the final purchase order, and the float was not purchased until December 29th 2014. For the second float, and due to the same problems, at the time of writing this report (October 2015) the purchase order is still processing, in spite that the processes began in February 2015.

The test to be carried out was described in D2.221 Deep float experiment design. In this deliverable, three tests were defined. In the first one, to be carried out during the first three months, the floats was planned to be parked at 1000 dBar, profiling to 4000 dBars every ten days, in the same way that the standard Argo floats sample the upper ocean. In the second test, and after the initial three months, the floats was planned to be parked at 1000 dBar, profiling to 2000 dBars every ten days, and to 4000 dBars every five profiles (once a month). In the third one, and after the initial six months, the float was planned to be parked at 1000 dBars profiling to 2000 dBars every ten days, and to 4000 dBars every five profiles (once a month). In this third test, the vertical sampling scheme was planned to be modified from the one used in the second experiment to adapt it to the results of the first test to minimize the power consumption of the prototype.

However, given the delays in the deployment of the first prototype, it was decide to begin with an accelerated version of the first test, with a sampling cycle of five days. Based on the observations of the first weeks, and the feedback with the manufactured, the configuration was not modified to better assets the local variability of the deep ocean in the Canary basin, and estimate the power consumption of the prototype, as it will be described in the following sections

3.2. First Deep Arvor Deployment

On March 3rd 2015 at 17:24 UTC, the Deep Arvor prototype with WMO 6901246 was deployed at 29.1670ºN, 18.4967ºN, in the Canary Basin (figure 1). The Deep Arvor was equipped with a SBE 41 CP sensors head, for the Conductivity, Temperature and pressure measurements. Salinity was compute internally based on the conductivity ratio and the UNESCO 1983 polynomial. (PSS 1978).

Initially, the Deep Arvor was configured to cycle every five days, doing the CTD measurement in the ascended profile and parking at 1000 dBars (Table I). During the first five cycles, the maximum profiling depth was established to 200 dBar, as recommend by the manufacturer to allow the adjustment to the higher pressure in the forthcoming profiles. The Deep Arvor was equipped with Iridium – SBD as the data transmission system (modem IMEI numbe: 300234061423370) that allowed to modified the maximum profiling depth to 4000 dBar. This maximum profiling depth is 500 dBars (15%) more than previously planned maximum depth (3500 dBar) in the DOW and D2.221 Deep float experiment design, and was established after feedback with the manufacturer.

The float was deployed right after a CTD cast was carried out north of the Canary islands. This CTD station (24 in figure 1) has been sampled since 1997.

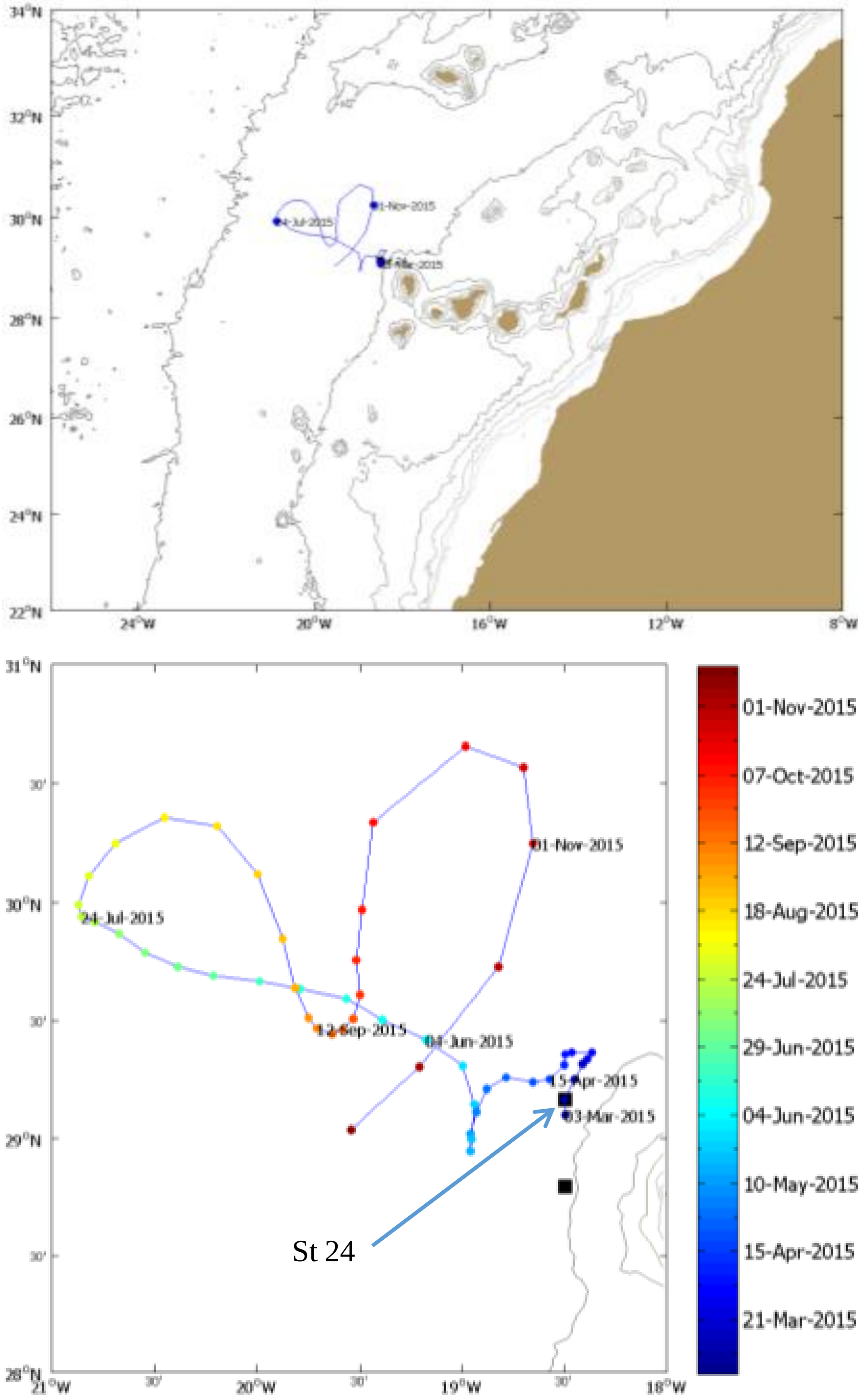

Figure 1: (a) Trajectory of the deep Arvor float WMO 6901246. (b) Zoomed in version of the Trajectory of the deep Arvor float, indicating the station 24, that has been sampled in the since 1997.

PM1	Cycle Period	5 of days
PM2	Reference Day	2 days
PM4	Delay Before Mission	0 Minutes
PM5	Descent Sampling Period	0 Seconds
PM6	Drift Sampling Period	12 Hours
PM7	Ascent Sampling Period	10 Seconds
PM8	Drift Depth	1000 dBar
PM9	Profile Depth	3000 dBar 4000 dBars (after 5 cycles)
PM10	Threshold surface/Intermediate Pressure	10 dBar
PM11	Threshold Intermediate /bottom Pressure	200 dBar
PM12	Thickness of the surface slices	1 dBar
PM13	Thickness of the intermediate slices	10 dBar
PM14	Thickness of the Bottom slices	25 dBar

Table I – Configuration of Deep Arvor 6901246, s/n OIN 14SP DP 01

3.3. Float reliability

By November 21st 2015, the float had done three cycles at 3500dBars and 49 cycles at 4000 dBars. There is a good reproducibility of the float behavior. The regularity of the cycles along time, the stability of the float at parking depth and the quality of data transmission are very satisfying. The parking depth and the starting profile depth was reached with very few overshoots, indicating a good control of the descent phase. The drift at the parking depth interval (+/- 50m) i stable. The ascendant profiles are done at a steady speed of 9 cm/s. The the float spends less than five minutes to transmit a low resolution profile (~200 CTD samples). The total time spent at surface, including buoyancy management, is approximatively 30 minutes. The bidirectional communication with the float was also satisfying, since in was reprogramed to a second configuration.

3.4. Sensor stability

From the first profile, an evident fresh bias in salinity (-0.25 PSS78, figure 2) was observed. Temperature differences with respect the CTD cast at the deployment site, where with the precision of the temperature sensors (table 2). The bias in salinity was also observed (not show in figure 2) in the descend profile carried out by the float right after its deployment. It has to be noted that the float was configured to do all the measurements in the ascend profile, except the first one that was carried out in the first descend profile. During the profiles 1-4 there was also a strong and irregular drift in salinity, that modified the initial bias to 0.22 PSS78 (figure 2). Probably this behavior during the first five profiles was due to TBNO that was washed off. After the fifth profile, the observed drift in salinity was constant in time (0.0003/day). According to the manufacturer, this bias could be due to technological issues on the conductivity sensor: a degradation of the coating of the cell could lead to such a bias. IEO has a planned cruise in February 2016, when the float could be recovered. Although the recovery would be after the end time of the project, it would be a valuable information in order to improve the performance of the floats

	Accuracy	**Stability**
Conductivity	0.002 S/m (equivalent salinity)	0.001 S/m per year (equivalent salinity)
Temperature	0,002 °C	0.0002 °C per year
Pressure	7 dBars	3.5 dBars per year

Table II. Accuracy and stability of the Deep Arvor SBE-41CP sensors.

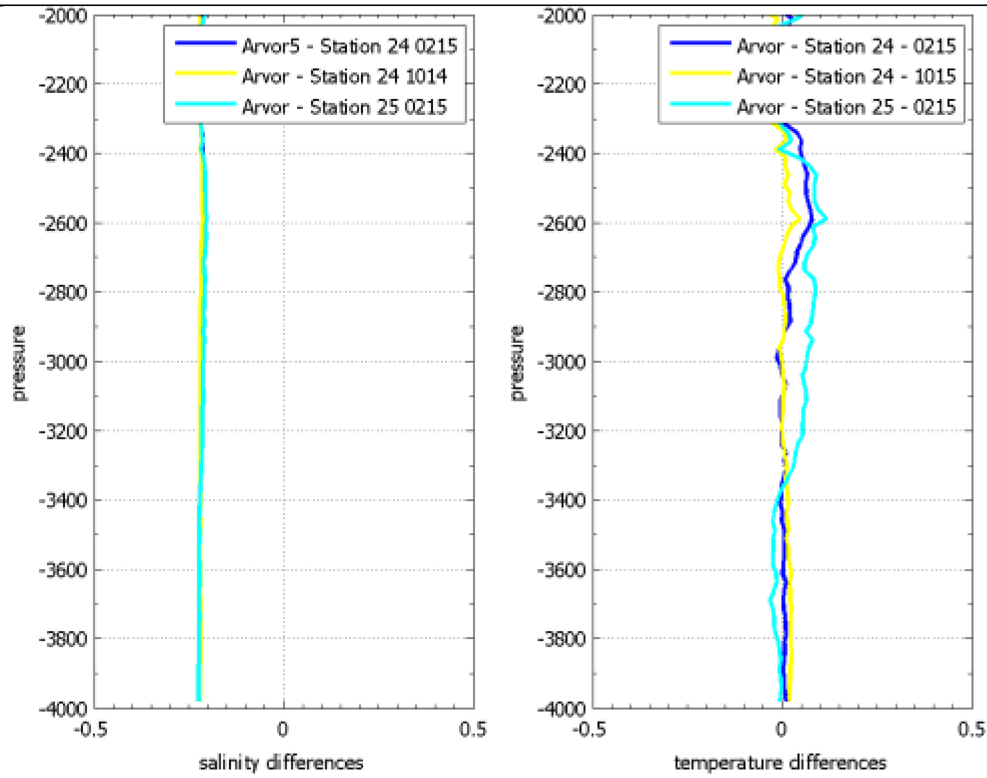

Figure 2: (a) Salinity differences between the first 4000 dbr Deep Arvor profile and the CTD station 24, carried out at the deployment site a few hours before the deployment, station 25 carried out 2 hours after deployment and 20 miles south, and CTD station 24, carried out at the deployment site in October 2015 (b) Same as (a) but for temperature. All the CTD stations were done using a SBE911+, with redundant TC sensors and autosal calibrations.

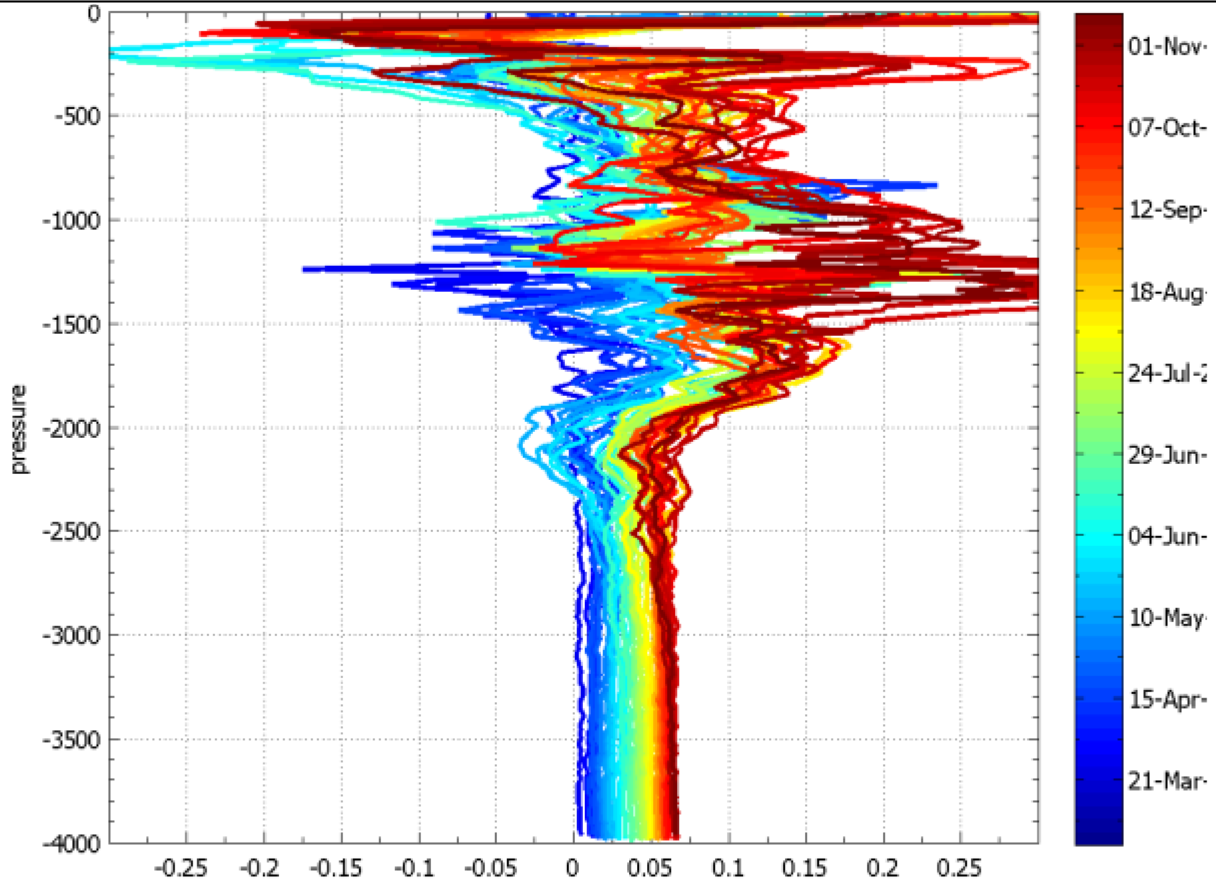

Figure 3: Salinity differences between the 5th Deep Arvor profile (the first one to 4000 dBar) and the reminder 52 Deep Arvor profiles until November 21st. The color scale reflects the time of the measurements.

Sine the deployment area has been monitored since 1997, it was possible to use two very stable water masses in the area, the North Atlantic Central Waters and North Atlantic Deep Waters. For two isotherms characteristics s of both water masses, 12ºC for the NACW and 2.25ºfor the NADW (figure 4), the drift in salinity was the same, 0.0003/day, indicating that it was mostly an actual drift in the sensor rather than natural variability, and that drift was not pressure dependent.

In the TS diagram of figure 4 can be appreciated the constant drift and the stable character of the NACW and NADW water masses. The 12ºC isotherm is roughly at 540 dBars, while the 2.25ºC isotherm is roughly at 3480 dBars.

The salinity drift for the whole waters column in the Deep Arvor measurements was corrected using the drift observed in the Salinity over the 2.25ºC isotherm. As it will be described in the next section, this correction was satisfying and permitted to afford the objective of estimating an optimum deep ocean sampling rate.

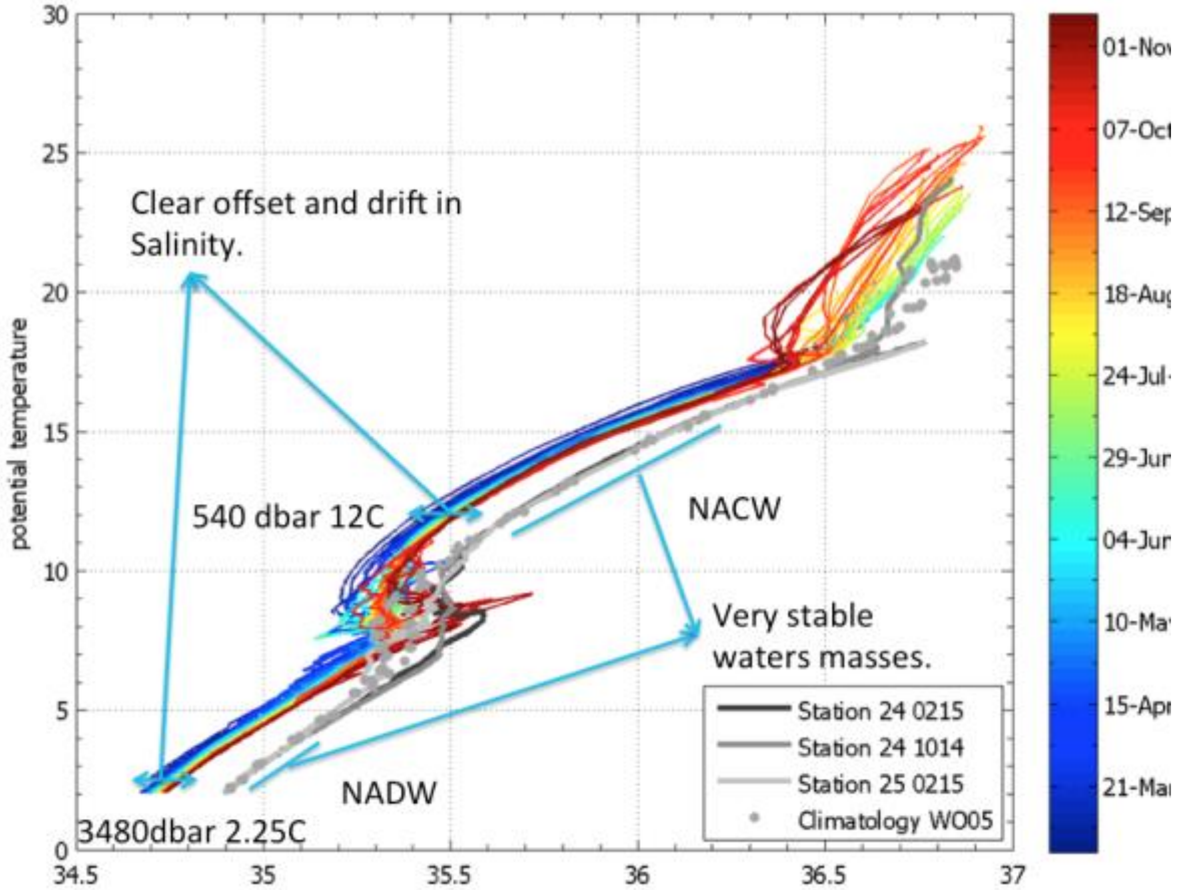

Figure 4: (a) Potential Temperature/Salinity diagram with the CTD profiles from the Deep Arvor (color scale), the CTD profiles carried out with SBE911 on board the vessel Alngeles Alvariñi (grey lines) and the World Ocean Atlas 2005 climatology (grey dots)

3.4. Deep ocean variability

Since temperature observations were from the first profile within the specification of the sensors, we are going to focus in salinity. After correcting the drift in the salinity, as described in the previous section, salinity over the 2.25ºC isotherm differences with the SBE911 CTD observations carried out in the area in April and October 2015 were within the uncertainty of the SBE41 CP sensor (figure 5b). The differences with respect the SBE911 CTD measurements in July 2015, were slightly higher that precision of the sensors (0.00318), but at this time, the float was at is further point (250 miles) from station 24. Altogether we can assume that was possible to correct the salinity drift and that the de-trended time series of Deep Arvor salinities reflect, with the sensor accuracy, the natural viability.

Since the NADW has been found to be very stable in the area, the isotherm of 2.25ºC, characteristic of this water masse will be used to assets the annual vs inter-annual variability of this water mass.

During the ten month of data from the Deep Arvor, on the 2.25ºC isotherm, it was found a range salinity variation of 0.0074 PSS78. This annual variability is similar to the 0.0084

PSS78 variability found during the 20 years of measurement in the area, or the 0.068 PSS78/decade trend in the area (figure 5a). Therefore, in order to avoid aliasing, the annual variability should be sampled at an optimum sampling scheme.

During the test, the Deep Arvor float was observing the deep Canary basin every five days, characterizing completely the annual cycle, however this sampling scheme could be reduced to one profile every 50 days (one deep profile every five standard 2000 dBars Argo profiles) and the annual cycle would be also resolved. In Figure 5b, the time series of the Deep Arvor salinity over the 2.25ºC isotherm is displayed together with a subsampling every five profiles, this is a deep observation every 50 days, of the original time series, to indicate that a deep observation every five standard 2000 dBar Argo profiles would be enough to resolve the annual variability.

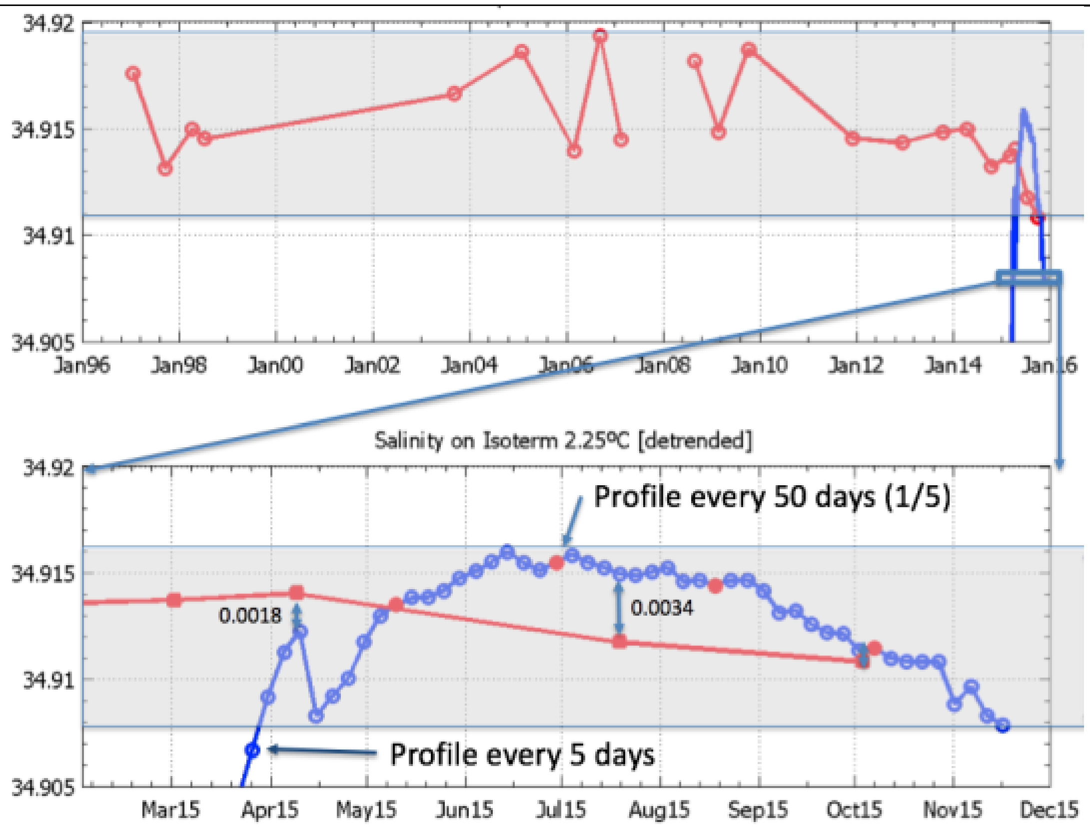

Figure 5: (a) Salinity on the isotherm 2.25ºC during the complete time series of SBE911 CTD observations in the canary basis in station 24 (red), the blue line denotes the observations carried out by the Deep Arvor float. (b) as (a) but just for the period with observations with the Deep Arvor. Blue dots are observations of the Deep Arvor every 5 days, and red dots are observations of the Deep Arvor subsampled every 50 days, this is one every 5 profiles. The red squares are the SBE911 CTD observations, and the number below it, the differences with respect the Deep Arvor observation.

3.5. Power consumption

In term of power consumption, an analysis using all the Deep Arvor public available data and eight standard 2000 dBars Arvor floats was carried out. For all these floats, the voltage value given during the first pump action at deepest pressure (approximate 2000 dBars for standard Arvor floats, and 4000 dBars for *Deep Arvor* floats) was used as a proxy for the health of the battery, and therefore to estimate the accumulated power consumption.

All the standard 2000 dBars Arvor floats showed a similar voltage drop (Figure 6), from ≈9.75v to ≈7.0v at the end of the working live. It has to be noted that the nominally voltage was 10.8 v, as produced by three battery packs of 3.6v. A mean value of the actual voltage drop is a good representation of the power consumption for all the eight standard Arvor floats. Assuming that the most of the power is consumed by the pump during the ascend and that the nominally voltage for a Deep Arvor was 14.4 v, as produced by four battery packs of 3.6v, the mean voltage drop could be used to model del voltage drop for the Deep Arvor. If the pump consumes most of the power, the vertically profiled distance can be used, rather than the number of cycles, since standard Arvor and deep Arvor have different profiling depth. In figure 6, the thick red line between 13v and 12.0v corresponds to this modeled voltage drop for the Deep Arvor. It shows a very good agreement with the actual measurements of voltage drop, and the difference would be explained if the model would have taken into account the minor contributions to power consumptions due to transmission and CTD measurements.

The agreement between the voltage drop for the Deep Arvor and the model based on the voltage drop for the standard Arvor 2000 dBars floats demonstrates that the life of the Deep Arvor is proportional to the vertically climbed km (figure 6).

Using this model, it is possible to estimate the decrease in lifetime expectancy for a deep Arvor based on the number of deep (4000 dBars) profiles. For a sampling scheme of one deep 4000 dBars profile every five standard 2000 dBars profiles, the reduction in the lifetime expectancy of the float, if compared with the standard 2000 dBars Argo floats, and using the same battery configuration that during this test, is of 17%.

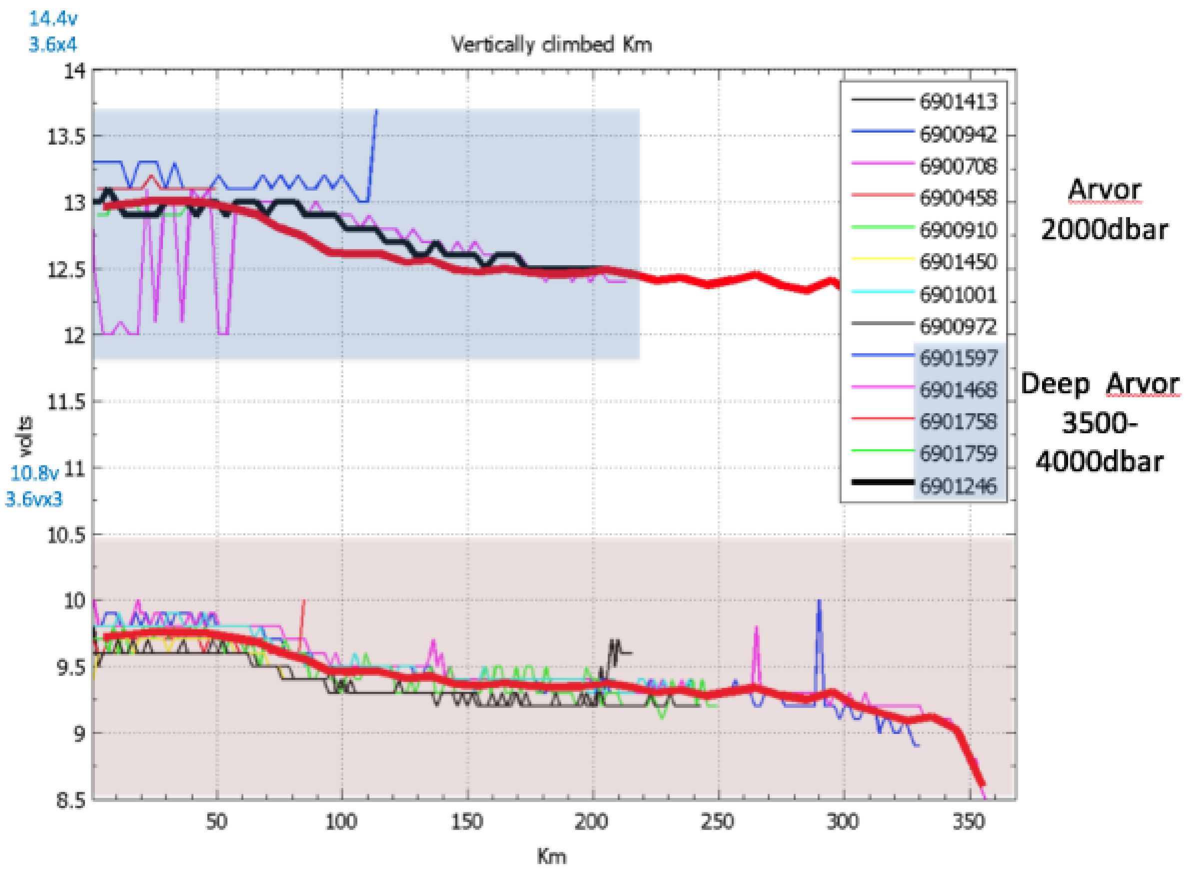

Figure 6: Time series of the voltage value given in technical message, measured during the first pump action at deepest pressure (approximately 2000 dBar for standard Arvor floats, and 4000 dBar for Deep Arvor floats). As needed current is most important, voltage drot is maximum during this first pump action at the deepest depth. The thick red line between 10 v and 8.5 v corresponds to the mean value of the voltage drop computed using the 8 standard 2000 dBars Arvor floats. The thick red line between 13v and 12.0v corresponds to the model of voltage drop for the Deep Arvor, computed as indicated in the text.

4. Summary

Regarding **float reliability**, the Deep Arvor NKE has shown a good behavior, making it a relievable platform. It was easy for the end-user to program and test for deployment and also to reprogram via the iridium transmission system.

Regarding sensor **stability**; the salinity sensor showed and strong fresh water bias and a constant drift. Other prototypes have also showed fresh bias, which were, also, not pressure dependent. Moreover, other deep Argo floats from different manufactures, but fitting the same SBE41 CTD, have reported similar bias and drift in salinity. This drift and bias do not meet the needs of the deep Argo observations.

Regarding the **sampling recommendations**; in order to sample properly the scales in the deep ocean and avoid aliasing, it would be necessary to perform, at least 1 deep 4000 dBars profile every five standards 2000 dBars profiles. This sampling scheme would imply a reduction in the lifetime expectancy of the Deep Arvor float, if compared with the standard 2000 dBars Arvor floats, of 17%.

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