

Recalibration of temperature and conductivity sensors affixed on Argo floats

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Abstract Temperature and conductivity sensors manufactured by Sea Bird Electronics, Inc. (SBE) are affixed to APEX-type Argo floats manufactured by Webb Research Co. Before shipping to users, calibration of the sensors is carefully carried out at SBE. However, the sensors are recalibrated at Japan Marine-Earth Science and Technology Agency (JAMSTEC) to reconfirm sensor accuracy considering a long transportation from SBE and quite a long storage time at JAMSTEC before deployment. In this paper, we describe and analyze these recalibration results. We used the same calibration technique as used by SBE, comparing outputs of temperature and conductivity sensors with those of highly quality-controlled standard temperature and conductivity sensors. We set thresholds of good or bad temperature and conductivity (salinity) sensors to be ± 0.0050 °C and ± 0.010 psu, respectively. The thresholds are selected to meet the target of the Argo project. Between 2001 and 2005, 228 sensors which are about 60 % of all were recalibrated at JAMSTEC. All the temperature sensors fall within the threshold. Of the conductivity sensors, 175 (77%) passed at the first measurement of recalibration series, while 30 (13%) passed after two or more measurements. The latter sensors were carefully cleaned to remove contaminations by dust or chemical pollutants. However, nine sensors (4%) did not pass recalibration test and were returned to SBE for further checking and repairs.

Keywords: Argo float, CTD sensor, Recalibration, Salinity error

1. Introduction

The Argo project, which began in 2000 in Japan, is an international project that observes temperature and salinity variations in the world ocean in quasi-real time. The project goal is to have 3000 operational floats observing vertical profiles of ocean temperature and salinity down to 2000 dbar. When the float array is completed, it is expected that the data obtained will clarify the mechanisms of ocean variations associated with climate change and contribute to forecasts of long-term climate change (Argo Science Team, 1998)¹. Temperature and salinity sensors of the Argo project are required to maintain accuracies of ± 0.0050 °C for temperature, ± 0.010 psu for salinity, and ± 5.0 dbar for pressure throughout the float mission.

According to the method of salinity definition in UNESCO (1981)², salinity is calculated from three parameters: conductivity, temperature, and pressure (JMA, 1999; see the appendix)³. Seawater conductivity and temperature data are crucial for high quality calculations of salinity. It is more difficult to obtain conductivity

measurements that satisfy the given salinity accuracy because conductivity sensors have a greater age deterioration than temperature sensors do. However, unlike a ship-board conductivity-temperature-depth (CTD) profiler, even if sensor quality of working floats is in question, it is difficult to confirm the sensor accuracy by recovering floats.

SBE41 CTD sensors (manufactured by Sea Bird Inc., [SBE]) are affixed on APEX-type Argo floats (manufactured by Webb Research Corporation.). According to the SBE manual, the sensor accuracies are specified as ± 0.0020 °C for temperature, ± 0.0050 psu for salinity, and ± 2.4 dbar for pressure. To maintain these accuracies, SBE carefully calibrates the sensors before shipping. However, a long transportation from SBE to JAMSTEC and quite a long storage time at JAMSTEC before deployment may affect the sensors; in other words, the accuracy specified in the manual is not necessarily guaranteed.

Recalibration (hereinafter we call it as “calibration”) is performed at JAMSTEC using the same calibration sys-

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tem as SBE's. No other institution or agency in the world conducts such calibration of the sensors after shipping by SBE. Therefore, we think we should inform the Argo community on our results.

We describe our calibration method in section 2, provide statistics of the calibration in section 3, give a more detailed analysis and classify sensors with insufficient quality in section 4, discusses the correlation of calibration values with the elapsed time after calibration at SBE, and summarize and conclude our results in section 6.

2. Calibration method at JAMSTEC

We use the same calibration system as SBE's. This system consists of a constant temperature water bath (hereinafter we call it as "bath"), a bath temperature control system, a telecommunication system, and standard sensors (Figure. 1). We use the same calibration method as SBE's, and maintain and update our technical level by sending technicians to SBE when we need. For example, we now use NaCl solution instead of artificial seawater because SBE informed us that artificial seawater includes strontium which may affect the calibration result. For the calibration, we use NaCl solution of 35 ± 0.1 psu.

As conductivity depends on temperature change, we can calibrate temperature and conductivity sensors at the same time by selecting several different temperature conditions (Matsumoto et al., 2001)⁴. Thus, we calibrate the sensors at seven temperature conditions (32.5, 29.0, 24.0, 18.5, 15.0, 4.5, and 1.0 °C), and control the bath temperature within ± 0.0020 °C of selected temperatures. To maintain stable environment in the bath, we keep the room temperature at 22 ± 3 °C. We have confirmed that the accuracy of the bath temperature is maintained in the bath system (Inoue et al., 2001)⁵.

All the temperature and conductivity sensors that we calibrated are model SBE41 affixed on Apex-type floats (Figure. 2). We use SBE3 and SBE4 as the standard sensors (Figure. 3). Figure 4 shows the arrangement of SBE3, SBE4 and SBE41s in the bath. For SBE3 and SBE4, calibration at SBE is conducted every year to guarantee the specified accuracy (Table 1). According to SBE, a linear drift of SBE4 is ± 0.00030 S m⁻¹ (± 0.0039 psu) per month (Sea Bird Electronics, 2005)⁶. To remove the effect of the linear drift, we check concentration of the NaCl solution in the bath with an accuracy ± 0.0020 psu using an AUTOSAL salinometer (Guildline Instruments Ltd., Model 8400B).

We consider a sensor to be "good" when temperature and conductivity measurements fall within the thresholds; the difference between the standard sensors and SBE41 are smaller than ± 0.0050 °C for temperature, and \pm

Table 1: Standard sensor accuracy of SBE3 (temperature) and SBE4 (conductivity).

	Accuracy
SBE3(Temperature)	± 0.0010 °C
SBE4(Conductivity)	± 0.00030 S m ⁻¹ (± 0.0039 psu)

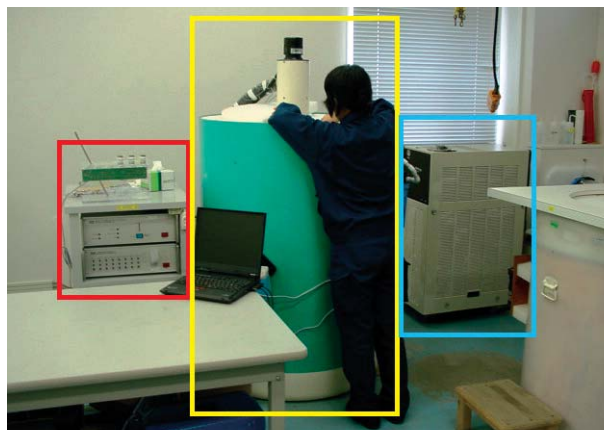


Figure 1: Calibration system (produced by Sea Bird, Inc.) used at JAMSTEC. Red frame: telecommunication system; Yellow frame: constant temperature water bath for calibration; Blue frame: bath temperature control system.



Figure 2: Preparing SBE41s of Apex floats to set them on the calibration system.



Figure 3: Standard sensor unit of temperature (SBE3; T sensor) and conductivity (SBE4; C sensor). A water pump (SBE5) is attached to SBE4 to circulate seawater in C sensor cell.

0.00050 S m⁻¹ and ± 0.00100 S m⁻¹ for conductivity at 3.0 S m⁻¹ and 6.0 S m⁻¹ (equivalent to ± 0.0065 psu for salinity), respectively (see red dashed lines in Figure 9). Here, we use a stricter threshold for the conductivity sensor than that of the Argo project target, because the standard conductivity sensor suffers from the linear drift as stated before (Matsumoto, 2001)⁴.

If a conductivity sensor does not pass at the first measurement of calibration series, it is cleaned and calibrated repeatedly until it passes. Note that repeated measurement itself leads to cleaning the conductivity sensor cell. If a sensor does not pass even after repeated measurements, we judge the sensor to be bad.

3. Statistics of calibration

We calibrated 228 sensors from 2001 to 2005; this number corresponds to about 60 % of all delivered floats (390 floats). Figure 5 shows the number of calibrated floats each fiscal year which is increasing year by year.



Figure 4: Bath with a reference sensor unit and five SBE41s.

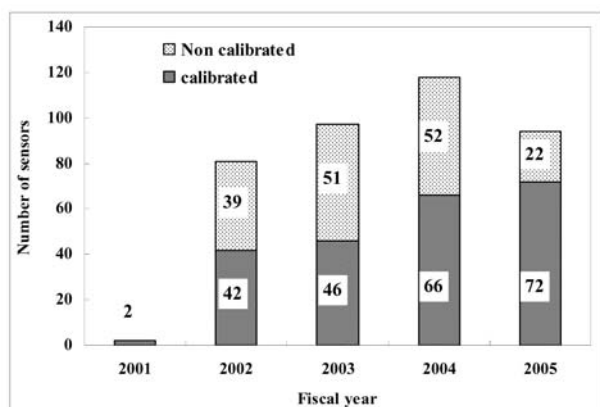


Figure 5: Number of calibrated sensors and non-calibrated sensors at JAMSTEC from FY 2001 to FY 2005.

3. 1 Temperature sensor (T sensor)

Deviations of T sensor temperature from SBE3's at (a) 1.0 °C, (b) 18.5 °C, and (c) 32.5 °C are shown in Figure 6. In this calculation, we use only first of each calibration series. In Figure 6 (a), (b), and (c), the deviations are distributed as normal distributions around zero; all the T sensors fall within the threshold (±0.0050 °C). Here, the distributions (standard deviations) at 1.0 °C and 32.5 °C are broader than that at 18.5 °C. This seems to be caused by the larger difference of bath temperature from air temperature of the laboratory (22 °C).

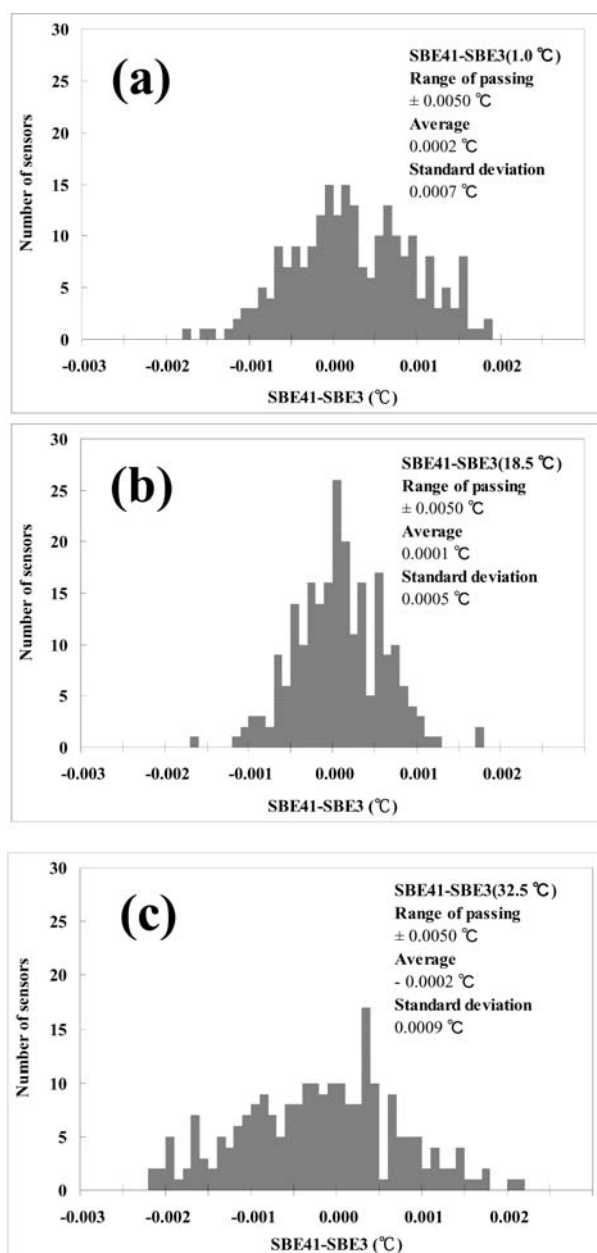


Figure 6: Histograms of temperature deviations at 1.0 °C (a), 18.5 °C (b), and 32.5 °C (c).

3.2 Conductivity sensor (C sensor)

Figure 7 shows the deviations of C sensor conductivity from SBE4 at (a) 1.0 °C, (b) 18.5 °C, and (c) 32.5 °C. In this calculation, we also use only first of each calibration series. As in the analysis of the T sensor, the deviations appear as normal distributions around zero. However, about 10 % of the C sensors fall outside of the thresholds. In Figure 7 (a), (b), and (c), the standard deviation of salinity at 3.0 and 6.0 S m⁻¹ is larger than that at 4.7 S m⁻¹ probably because of the same reason as the temperature case. Instead of salinity, the standard deviation of conductivity increases with temperature rising. As shown in the appendix, the conductivity value increases with temperature rising under a constant salinity. Therefore, although the standard deviation of conductivity at higher temperature looks to be larger, the standard deviation of salinity is not so large.

4. Classification of the C sensor calibration

4.1 Definition of “Good” or “bad” sensor

To understand the calibration results, we classify the calibrated C sensors into four categories. The numbers in each category are shown in Table 2.

(1) Good sensor

Good sensors pass at the first measurement of calibration series. From 2001 to 2005, 175 fall into this category (77% of all calibrated sensors).

(2) Conditionally good

While the T sensor passes in the first measurement of calibration series, the C sensor passes after repeated measurements. The sensors are repeatedly measured 2 to 11 times and most sensors passed after a few measurements (Figure 8). Of the total sensors calibrated, 30 fall into this category (13% of all sensors). Note that the final condition of these sensors is “good” when they are shipped from JAMSTEC.

(3) Bad

In “bad” sensors, the T sensor passes, but the C sensor fails to pass the test even after repeated measurements. Nine sensors are included in this category (4% of all the calibrated sensors).

(4) Unknown

“Unknown” sensors did not pass at the first measurement, however, repeated measurement could not be conducted because of insufficient time to ship them. Fourteen sensors (6% of the total) fall into this category.

4.2 Analysis of “Conditionally good” sensors

Figure 9, 10 and 11 display deviations of conductivity of C sensors from SBE4's (hereinafter we call it as “calibration curve”). Figure 9 shows an example of the calibration curve for a good sensor, and Cases 1, 2 and 3 of Figure 10 show examples of the calibration curves for the conditionally good sensors. In the category of the conditionally good, we classify calibration curves into three types as follows:

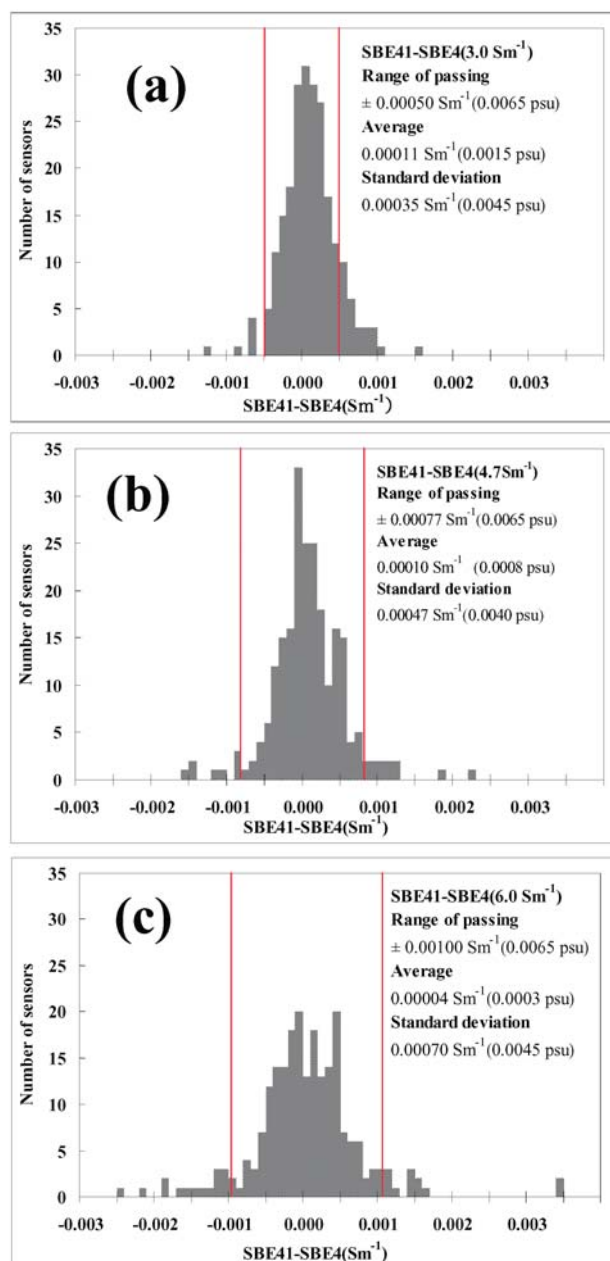


Figure 7: Histograms of conductivity deviations at (a) 3.0 S m⁻¹ (1.0 °C), (b) 4.7 S m⁻¹ (18.5 °C), and (c) 6.0 S m⁻¹ (32.5 °C). Red lines show the threshold of C sensor (± 0.0065 psu).

(1) Case 1

As shown in Figure 10, all calibration curves gather in the negative side. However, successive measurements approach the standard and finally fall within the threshold. This case contains 11 sensors which are 5% of all calibrated sensors.

(2) Case 2

Calibration curves show a reverse tendency to the Case

1 to approach the standard from the positive side. This case contains 5 sensors which are 2% of all calibrated sensors.

(3) Case 3

Measurements distribute on either side, however, they finally fall within the threshold. This case contains 14 sensors which are 6% of all calibrated sensors.

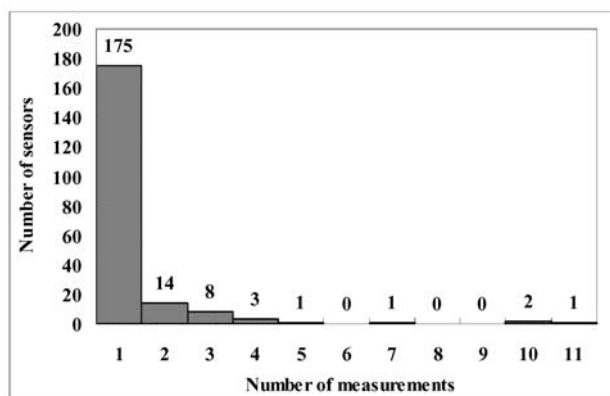


Figure 8: Number of repeated measurements of calibration series.

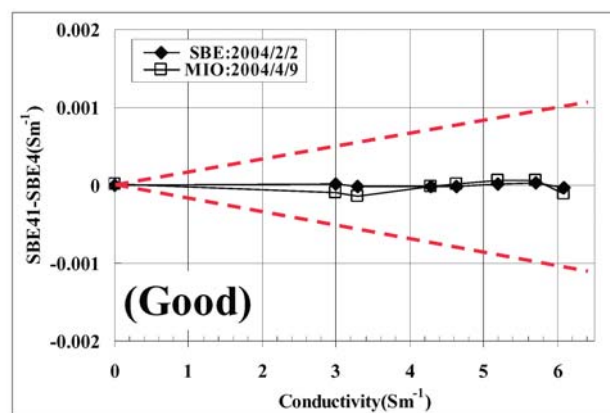


Figure 9: Example of calibration curve for a good sensor. The horizontal axis is conductivity ($S m^{-1}$) of sample water in the bath. Red dashed lines show the threshold of C sensor. The legend shows the calibration date at SBE (SBE) and JAM-STECC Mutsu Institute of Oceanography (MIO). The average and standard deviation for all measurements at $6.0 S m^{-1}$ are also described in the square on the panels.

Table 2: Numbers and ratios of good, conditionally good, bad, and unknown sensors.

Calibration result	Number	Ratio (%)
Good	175	77
Conditionally Good	30	13
Bad	9	4
Unknown	14	6

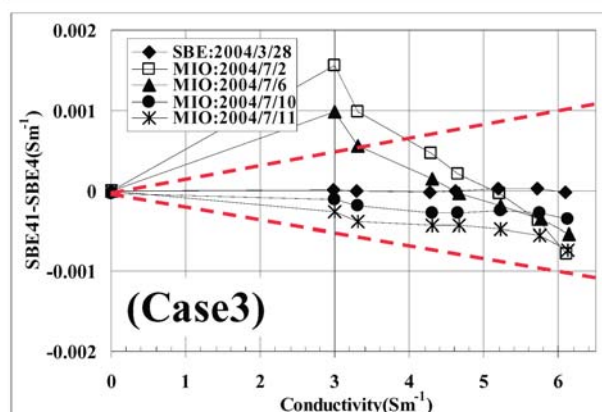
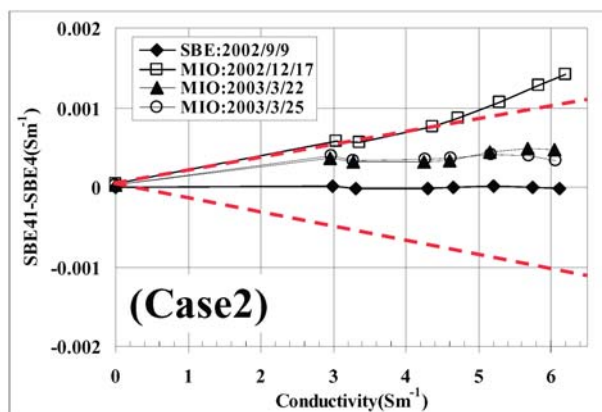
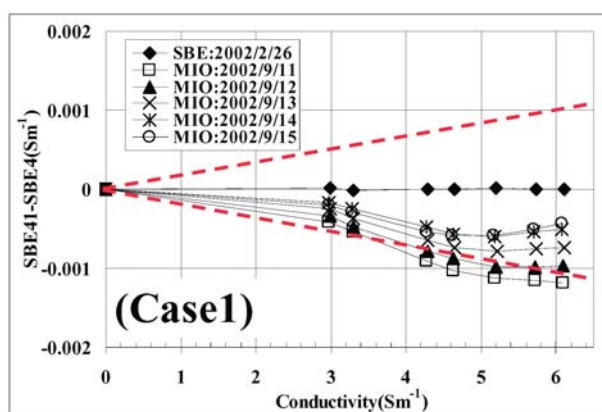


Figure 10: Example of calibration curve for conditionally good sensors; upper panel is for Case 1, middle for Case 2, and lower for Case 3.

4.3 Analysis of “bad” sensors

Unlike the good and the conditionally good sensors, the calibration curves of bad sensors are plotted outside the threshold. In the category of bad sensors, we classify calibration curves into two types as follows:

(1) Case 4

As shown in Figure 11, repeated measurements widely spread outside the threshold. This case contains two sensors.

(2) Case 5

In Case 5, the calibration curves have almost the same gradient and distribute outside one of two threshold lines. If Case 5 is re-plotted for salinity, they appear a salinity offset from standard (data not shown). This case contains seven sensors among which three show positive differences and four negative.

Table 3 shows the number of bad sensors in Case 4, Case 5, and Case 4 + Case 5 every fiscal year from 2001 to 2005. The percentage of bad sensors to total calibrated

Table 3: Numbers of Case 4 and Case 5 sensors and percentage of sum of Case 4 and Case 5 to number of calibrated sensors.

Fiscal year	Case 4	Case 5	Case4+Case5	Calibrated sensor	Percentage of Case4+Case5 (%)
2001	0	0	0	2	0.0
2002	0	1	1	42	2.4
2003	1	2	3	46	6.5
2004	1	3	4	66	6.1
2005	0	1	1	72	1.4

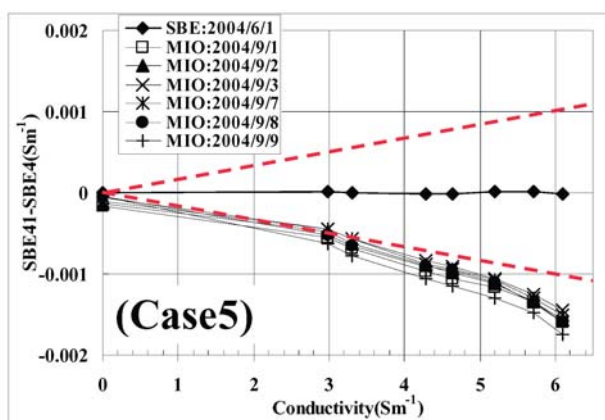
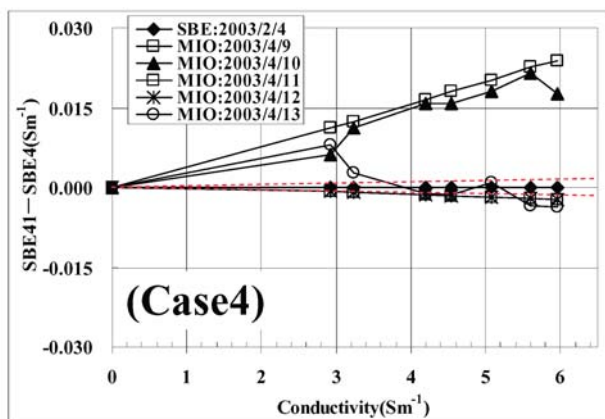


Figure 11: Example of calibration curve for bad sensors; upper panel is for Case 4, and lower for Case 5.

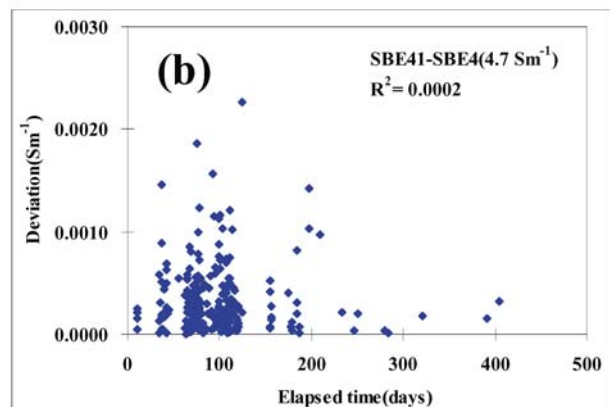
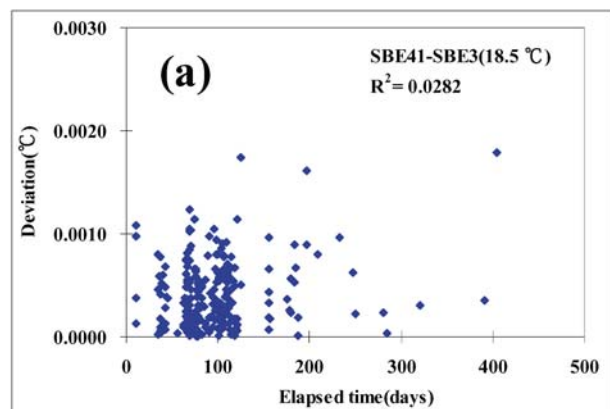


Figure 12: Deviation of temperature (a) at 18.5 °C and conductivity (b) at 4.7 S m⁻¹ for elapsed time. R2 represents the square of the correlation coefficient.

ones is less than 6.5% and does not show a clear tendency in this period.

4.4 Handling of bad sensors

Bad sensors must be repaired and checked again before being affixed to a float and deployed in the ocean. At JAMSTEC, Case 4 bad sensors are returned to SBE to repair and calibrate. After receiving, we again calibrate all repaired sensors. To date, all repaired sensors passed and were classified as good sensor. Case 5 sensors usually undergo the same return/calibration process as for Case 4 sensors. As there was insufficient time to return and repair the bad sensors, the calibration coefficients memorized in the sensor were rewritten to fit the calibration curve at JAMSTEC without returning them to SBE. After rewriting the calibration coefficients, we again calibrate the sensors and confirm them to be good.

5. Influence of elapsed time for quality of C sensors

We examined whether the calibration results for T and C sensors relate to elapsed time between calibration dates at SBE and those at JAMSTEC. Usually, calibration should be performed just before shipping to research vessels. At JAMSTEC, we stored major part of floats for a hundred days and for about four hundreds in several cases.

Figures 12 (a) and (b) show the deviation of temperature and conductivity as time elapses, respectively. In Figure 12 (a) and (b), there can be seen no systematic relation between the difference and the elapsed time. Thus, we think there is no evidence that the C and T sensors deteriorate if they are retained at JAMSTEC for a long time.

6. Summary and conclusion

We have discussed statistics of calibrations for SBE41 C and T sensors that are affixed on the APEX-type Argo floats. Calibrations have been conducted at JAMSTEC since 2001, using the same method as that used by SBE. From 2001 to 2005, 228 sensors were calibrated. All T sensors fell within the threshold (± 0.0050 °C). However, some C sensors fell outside the thresholds (± 0.00050 S m^{-1} at 3.0 S m^{-1} and ± 0.00100 S m^{-1} at 6.0 S m^{-1} ; both are equivalent to ± 0.0065 psu). Nine sensors were “bad”, which was 4% of all of the calibrated sensors. Some sensors had to be measured repeatedly and were labeled “conditionally good” sensors (13% of the total). The “conditionally good” sensors were categorized into Cases 1, 2 and 3 on the basis of the tendency of calibration curves. The Cases 1, 2 and 3 contain 11, 5 and 14 sensors, respectively. The “bad” sensors were further categorized into Cases 4 and 5. In Case 4, the calibration curve widely

spread outside the thresholds. In Case 5, the calibration curves had almost the same gradient and distribute outside one of two threshold lines. Usually, we returned the bad sensors to repair at SBE. In some cases, there was insufficient time to return and repair the bad sensors, the calibration coefficients memorized in the sensor were rewritten to fit the calibration curve at JAMSTEC. After rewriting the calibration coefficients, we again calibrate the sensors and confirm them to be “good”. We examine whether the calibration results for T and C sensors relate to elapsed time between calibration dates at SBE and those at JAMSTEC. The results suggest that the deviation from standard sensors do not depend on the elapsed time.

At JAMSTEC’s facility, calibration is conducted using almost the same method and conditions as that of SBE. Usually, researchers buy a float and deploy it without recalibration. However, occasionally, some trouble may develop with the sensor during delivery from SBE to the users. Our results suggest that approximately 4% of floats may have faulty sensors with insufficient quality. In addition, C sensors did not pass the first measurement of calibration series but passed after repeated measurements. Of the sensors we calibrated, 13% fell into this category (although the reason is unclear).

S. Riser (personal communication) investigated the change of observed salinity obtained from C sensors affixed on floats (the same type of float and sensors as we use). In some floats, he found that lower salinity was observed a few times after deployment, and gradually returned to normal. He concluded that a biofouling inhibitor on the C sensor dissolved and contaminated the C sensor cell to make the measurement area in the sensor cell smaller, and got the measured conductivity to be lower. Case 1 of the conditionally good sensors is similar to his finding of the observed salinity. However, in the other conditionally good sensors, there were sensors with Case 2 and Case 3. We think that these phenomena may not be caused by such contaminations. Regarding of the Cases 2 and 3 of conditionally good, we think that the deviation might be caused not by contamination cell but by a strain of electrode in the C sensor cell due to shocks of transportation.

Acknowledgements

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Appendix

Here, we describe the definition of salinity. Practical salinity (referred to here as salinity, S) is defined by the conductivity ratio (R_t) relative to a standard solution of PSS78 KCl at 1 bar and 15 °C (UNESCO, 1981)². Under 1 bar and an arbitrary temperature (t °C), the salinity value is calculated by a measured R_t as follows:

$$S = a_0 + a_1 R_t^{1/2} + a_2 R_t + a_3 R_t^{3/2} + a_4 R_t^2 + a_5 R_t^{5/2} + dS. \quad (1)$$

Here, dS is the value of temperature correction,

$$dS = \frac{t - 15}{1 + k(t - 15)} b_0 + b_1 R_t^{1/2} + b_2 R_t + b_3 R_t^{3/2} + b_4 R_t^2 + b_5 R_t^{5/2} + dS, \quad (2)$$

and the other parameters, a , b , are k , are as follows:

$$a_0 = 0.0080, a_1 = -0.1692, a_2 = 25.3851, a_3 = 14.0941, \\ a_4 = -7.0261, a_5 = 2.7081,$$

$$b_0 = 0.0005, b_1 = -0.0056, b_2 = -0.0066, b_3 = -0.0375, \\ b_4 = 0.0636, b_5 = -0.0144,$$

and

$$k = 0.0162.$$

Actually, the output of a C sensor is conductivity C (S , t , p); the R_t value must be converted to C .

$$\begin{aligned} R_t &= R / (R_p r_t) \\ R &= C(S, t, p) / C(35, 15, 0) \\ R_p &= C(S, t, p) / C(S, t, 0) \\ r_t &= C(35, t, 0) / C(35, 15, 0) \end{aligned} \quad (3)$$

$p = 0$ indicates air pressure, and $C(35, 15, 0)$ is given with 4.2914 S m^{-1} (Sea Bird Electronics, 1989)⁸. R_p and r_t are rewritten in t and p ($\times 10^5 \text{ Pa}$) as follows:

$$R_p = 1 + \frac{p(e_1 + e_2 p + e_3 p^2)}{1 + d_1 t + d_2 t^2 + (d_3 + d_4 t) R}, \quad (4)$$

and d and e are defined as:

$$e_1 = 2.070 \times 10^{-4}, e_2 = -6.370 \times 10^{-8}, e_3 = 3.989 \times 10^{-12}$$

$$d_1 = 3.426 \times 10^{-2}, d_2 = 4.464 \times 10^{-4}, d_3 = 4.215 \times 10^{-1}, d_4 = -3.107 \times 10^{-3} .$$

Further,

$$r_t = C_0 + C_1 t + C_2 t^2 + C_3 t^3 + C_4 t^4 , \quad (5)$$

and C is:

$$C_0 = 0.6766097, C_1 = 2.00564 \times 10^{-2}$$

$$C_2 = 1.104259 \times 10^{-4}, C_3 = -6.9698 \times 10^{-7}$$

$$C_4 = 1.0031 \times 10^{-9}.$$

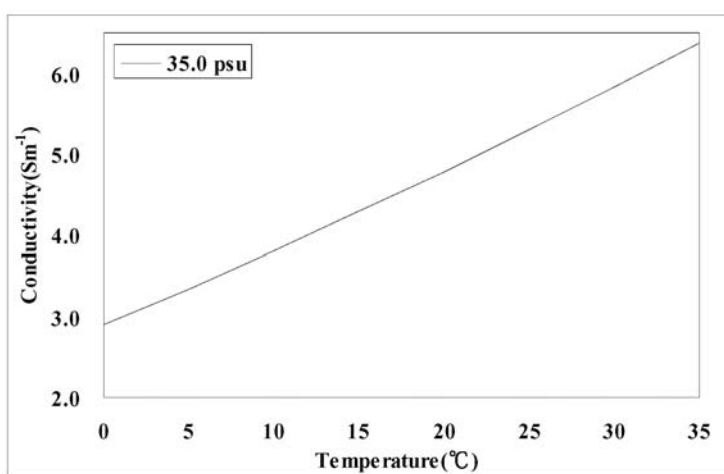


Figure A1: Relation between temperature ($^{\circ}\text{C}$) and conductivity (S m^{-1}) at 35.0 psu.

Note that pressure is usually described by Pascal (Pa) in SI units, while in the ocean, units of bar or dbar are used (1 bar is 1×10^5 Pa).

Using t ($^{\circ}\text{C}$), p ($\times 10^5$ Pa), and R , S is defined from equations (1), (2), and (3). The equations (1) through (5) should be applied in the range of $-2 \leq t \leq 35$ ($^{\circ}\text{C}$), $0 \leq p \leq 1000$ ($\times 10^5$ Pa), and $2 \leq S \leq 42$ (psu), respectively. Figure A1 shows an example of the relation between temperature and conductivity following equation (1) at 35.0 psu. If the salinity is constant, the relation between temperature and conductivity is almost proportional.

