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New method of temperature and conductivity sensor calibration with improved efficiency for screening SBE41 CTD on Argo floats

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Abstract

The global ocean monitoring system would benefit from improvements in the efficiency of Conductivity, Temperature, and Depth Device (CTD) sensor screening. Here, we describe the development of a new screening system, J-Calibration, for use with the SBE41 CTD sensor on the Argo float (Sea Bird Scientific). This new system has crucial advantages over the traditional SBE-Calibration system. First, J-Calibration does not require removal of the CTD sensor unit from the Argo float body to operate in a laboratory. This feature enables technicians or operators to more efficiently check the Argo target accuracies (± 0.005 °C for temperature and ± 0.01 PSS-78 for salinity) and allows the manufacturer's warranty to remain intact. This also allows for a more efficient basic screening system which maintains screening accuracy without the need for specialized technicians. J-Calibration reduces the screening time to 1/6th that of SBE-Calibration and does not require the preparation of large amounts of artificial seawater. J-Calibration uses 1/23rd of the volume of seawater compared to SBE-Calibration by examining calibration at only 1 temperature point (22 °C), whereas SBE-Calibration requires 7 points to achieve calibration. The J-Calibration system does require careful temperature control of the artificial seawater as it is critical to maintain a uniform water temperature throughout the experiments. To satisfy this, using a vinyl greenhouse and covering sensors with adiabatic materials and cooling packs are effective. In comparison with the accuracy and system stability of SBE-Calibration, we show that the J-Calibration system is non-inferior and therefore is suitable for use in laboratory screening prior to deployment. Based on these advantages, the J-Calibration system will make a strong contribution to the deployment of healthy Argo fleets and to the maintenance of uniform data in the global ocean.

Keywords: CTD sensor, Sensor screening, SBE41, Simple calibration method, Water temperature control, Global Argo observation system

Introduction

Accurate data of uniform quality is critical to obtaining robust results in the Earth Sciences. However, this data can be very difficult to obtain in situations with a smaller signal-to-noise ratio when using spatially and temporally broad observation systems. For example, in physical oceanography, detection of the oceanic signals associated with long-term climate change is a key challenge as these tend to be more subtle and less specific than the signals which indicate shorter-term change (e.g., Meyers et al. 1982; White 1995). Especially in the middle depth of the ocean below 1000 m, the amplitude of long-term changes in signals such as temperature and salinity is 1/100~ 1/1000th that of the upper layer. For example, it has been reported that the Antarctic Bottom Water, which is known as the lowest water mass of the global ocean circulation system, has warmed and freshened

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within the range of 0.01~ 0.001 °C or PSS-78 (e.g., Jacobs and Giulivi 2010; Purkey and Johnson 2010). Although this seems quite small, this variability associated with climate change signals is meaningful. To detect such a small perturbation, high-quality controlled sensors with high, consistent accuracy are critical. Therefore, many scientists recognize that sensor calibration prior to deployment is an absolute requirement in order to detect such small signals. Here, we introduce a new method of pre-deployment sensor calibration and demonstrate its importance in Argo float sensor calibration as part of the framework of the Argo program in the global ocean observation system.

The Argo program, which was started in 1999, aims to detect the small-amplitude climate signals associated with long-term climate change in the global ocean. The goal of the Argo observation system is to sustainably obtain uniform quality-controlled temperature and salinity data from the upper layer of the global ocean. To achieve this, autonomous observation drifting buoys, named Argo floats, are deployed every 3° squared in the global ocean (Roemmich et al. 2001). All Argo floats are equipped with Conductivity Temperature and Depth Device (CTD) sensor devices. There are now over 3800 Argo floats deployed in collaboration with over 30 countries (Argo Science Team 1999).

Argo floats generally dive to a depth of 1000 m after deployment, and drift for 10 days. The floats then observe temperature, salinity, and pressure going up from a depth of 2000 m to the sea surface, continuously operating for 4–8 years. This automated ocean observation makes it possible to collect a huge amount of data from the global ocean over a long period. The target accuracies of the CTD sensors on the Argo floats are set to ± 0.005 °C for temperature, ± 0.01 PSS-78 for salinity, and ± 5 dbar for pressure, and these criteria must be maintained globally, both spatially and temporally. Once a float is deployed, direct confirmation of sensor accuracies is impossible, in contrast to a shipboard CTD observation, which can be compared by post-calibration in a laboratory. Therefore, when the Argo program began, it was decided by the Argo data management team that a data flow and quality control method would be established in order to maintain high-quality uniform data. This method involves real-time quality control (rQC), which is analyzed by the Argo data assembly centers (DAC) within 24 h after measurement, as well as a delayed-mode quality control (dQC), which is carried out for research purposes by the principal investigator (PI) within 1 year of the rQC. Historical shipboard CTD data and other Argo float data are used to detect sensitive climate change signals (Argo Data Management Team 2002, 2012). Then, all Argo float data is made available online at the Global Data Assembly Center (GDAC). Based on this quality-controlled data, small detailed signals in the interior ocean indicating climate and ocean environmental changes have been detected successfully (e.g., Riser et al. 2016).

The CTD sensor equipped on almost all Argo floats is currently the SBE41, manufactured by Sea Bird Scientific (https://www.seabird.com/sbe-41-argo-ctd/product?id=54627907875). The pre-production SBE41 CTD unit was installed on a University of Washington Webb/APEX float in 1997 and was deployed in the North Atlantic Ocean and operated successfully for 3 years. The first CTD on a profiling float was added to an autonomous Lagrangian circulation explorer (ALACE) float (Davis et al. 1992) by a group from the Scripps Institute of Oceanography (SIO, USA) around 1994. However, this was not a SBE41 but an inductive CTD sensor manufactured by Falumouth Scientific, Inc. (FSI CTD) and performed poorly with large salinity biases and temporal drift. Although a number of FSI CTD units were built and deployed over a few years, their use was discontinued due to poor results. Based on a review of the stability of the SBE41 CTD sensor, the sensor unit used on Argo floats is now primarily mounted with verifications of target accuracy and long-term stability (Oka 2005; Johnson et al. 2007). The SBE41 sensor units are equipped with temperature, salinity, and pressure sensors, which are the fundamental physical parameters in the ocean. Thermistor and piezoelectric sensors are used for temperature and pressure measurements, respectively. The conductivity sensor is used for salinity and measures seawater conductivity between electrodes inside a glass tube. The measured conductivity is transformed into salinity as a function of temperature and pressure, which are obtained from the equipped temperature and pressure sensors (UNESCO 1978). The specifications of the SBE41 CTD sensor unit are shown in Table 1.

We have conducted operating tests on all delivered Argo floats and screened sensor accuracies for many SBE41 sensors in the laboratory before deployment (Yokota et al. 2007). The screening system for the SBE41 temperature and salinity sensor is available and operated at JAMSTEC in a similar fashion to that of Sea Bird Scientific, the manufacturer of SBE41 (here, we refer to the calibration in JAMSTEC as "SBE-Calibration"). Prior to shipping SBE41 to users, optimal parameters are determined for each sensor based on the results of the manufacturer's calibration and are indicated in the calibration certifications. Thus, it is possible to check and screen

Table 1 Feature and specification of SBE41 CTD sensor unit manufactured by Sea Bird Scientific

Sensor	Range	Accuracy	Stability
Temperature	− 2 ~ 35 °C	± 0.002 °C	0.0002 °C/year
Conductivity	2 ~ 42 (equivalent salinity)	± 0.005 (equivalent salinity)	0.001/year (equivalent salinity)
Pressure	0 ~ 2500 dbar	± 2.4 dbar	0.8 dbar/year

sensor accuracies by conducting SBE-Calibration in JAMSTEC prior to float deployment through a comparison with the calibration result of the manufacturer. The University of Washington also uses a screening system for SBE41 sensors similar to the SBE-Calibration system at JAMSTEC, and reported that the system is stable and accurate (Riser et al. 2008). Since 2001, we have found over 50 faulty sensors in SBE41 prior to deployment through screening over 1000 sensors calibrated by SBE-Calibration. Furthermore, systematic faults in sensors have been found, which was raised as an international problem in the Argo community (e.g., Atlantic Ocean cooling by data bias; Lyman et al. 2006; Willis et al. 2008, Systematic SBE41 salty drift; Argo Steering Team 2018, 2019). Therefore, it is recognized in the Argo community that screening for faulty sensors prior to deployment is largely effective in reducing the issues of deployed floats with bad sensors (King et al. 2017). However, such screening of sensors calibrated by SBE-Calibration or a similar method tends to be complex and requires specialized skills and equipment, which makes it difficult to screen sensors operationally at a user level. In addition, user removal of the CTD sensor unit from the float body can create warranty issues.

Recent difficulties with hardware and software on Argo floats have occurred due to increased price competition among manufacturers. For float users, although a low-cost float is welcome, encountering difficulties which are results of cost-cutting results in delayed float deployment and poor data accuracy. Therefore, user monitoring float performance prior to deployment to avoid deployment of floats with faulty sensors is absolutely required.

Under these circumstances, we had developed a new method of SBE41 CTD sensor screening to be performed in a laboratory which does not require the removal of the CTD sensor unit from the float body. We have validated the accuracy of this system and call the system “J-Calibration.” The goals of the development of this system were (1) to achieve a CTD sensor screening system similar in accuracy to that of SBE-Calibration in JAMSTEC and (2) to be able to operate efficiently and without the need for specialized technicians. Finally, we desire to deliver this system to the other agencies and institutes in order to contribute to the achievement of uniform high-quality data for the international Argo program and observation system.

Methods/Experimental

J-Calibration system and its advantages

J-Calibration is an efficient calibration method of the SBE41 CTD sensor unit which does not require the separation of the sensor unit from the float body, while maintaining an accuracy similar to that of SBE-Calibration. Since the sensor unit of SBE41 is not separated, the temperature and conductivity sensors of SBE41 can be calibrated by instilling seawater directly into the sensor unit. In J-Calibration, measurement of temperature and conductivity of the seawater is carried out using standard sensors of SBE3 and 4 at the same time to validate accuracy. This validation procedure with standard sensors enables us to improve reliability and to maintain the accuracy of SBE-Calibration.

The J-Calibration system is shown in Figs. 1 and 2, and the components of J-Calibration are listed in Table 2. The J-Calibration system consists of a seawater tank (10 l), standard temperature and salinity sensors, SBE41 sensors (up to 3 sensor units), and a water pump, sequentially connected with water tubes. Each tube with sensors is trimmed to the same length. The system is controlled by laptop computers, communicating with each float body. Although SBE3 and 4 standard sensors are manufactured by SBE-sharing with SBE-Calibration, other items were purchased at affordable prices.

The artificial seawater is a NaCl solution seawater at 35 ± 0.1 PSS-78 and is prepared by degassing and minimizing the difference with room temperature in advance. The seawater flows to three SBE41 sensors and to SBE3 and 4 standard sensors separately and constantly via a pump through the tubes. The length of the tubes between the sensors and the seawater tank is consistent at 1.8 m in order to maintain a uniform exposure to the heat in the environment. In order to avoid excess water pressure and potential error, the flow of seawater is consistent at 200 ml/min for each tube. Calibration is started 3–5 min after starting water circulation and after ensuring

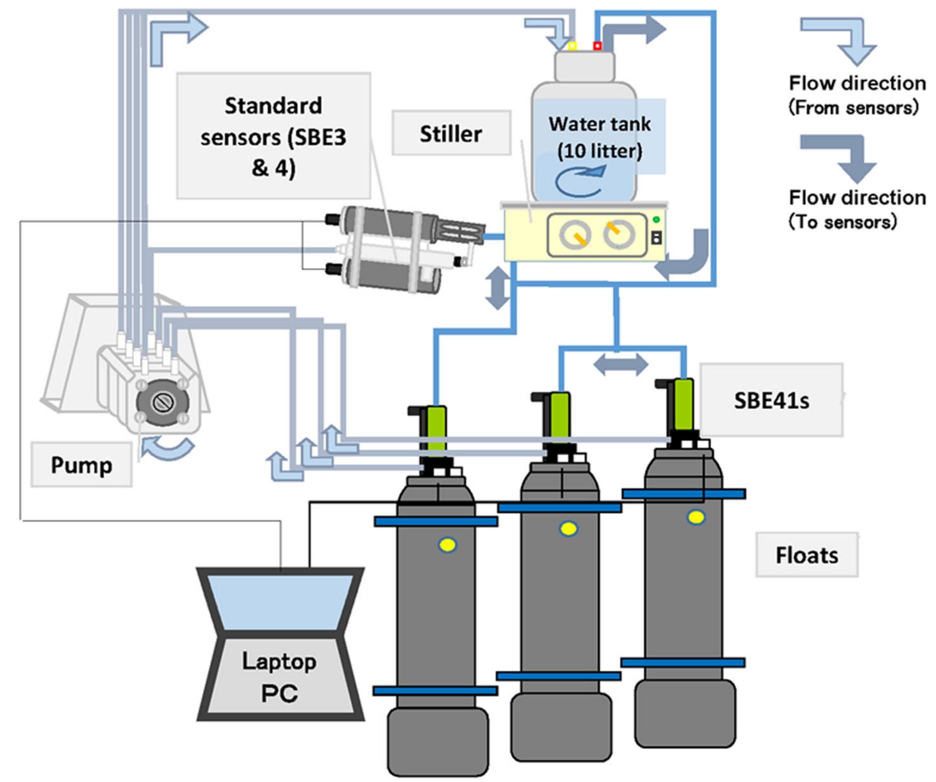

Fig. 1 Schematic figure of the J-Calibration system. The system consists of a small water tank (10 l), a stiller for mixing seawater, SBE3 and 4 standard sensors, and a water pump (see Table 4). Three floats with SBE41 and standard sensors (SBE3 and 4) are controlled by a laptop computer. The artificial seawater flows through water tubes

temperature stability (variability of water temperature within ± 0.01 °C). The period of one measurement is 5 min, but the time does depend on the season and the room temperature of the environment.

Since conductivity is a function of water temperature, it is generally difficult to calibrate salinity sensors accurately as it is largely influenced by the temperature of the environment. Therefore, it is

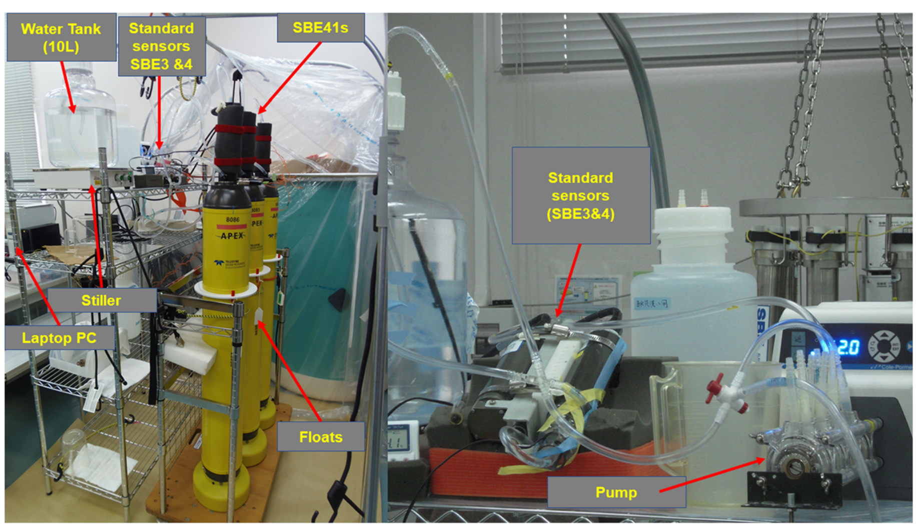

Fig. 2 (Left) The J-Calibration system in an open Vinyl greenhouse. Using a steel rack, a required space is minimized (within 1 m^2). (Right) A detailed photo of the pump and SBE3 and 4

Table 2 List of items used in J-Calibration (see Figs. 1 and 2)

	Items
1	Water tank (10 l)
2	Water tube (length is 1.8 m every part, connecting among water tank, pump, and sensors)
3	Pump for seawater (flow speed sets 0.2 l/min which is the same as actual flow speed of SBE41 sensor pump)
4	Vinyl house (1.7 m width × 1.7 m length × 2.0 m height)
5	Laptop computer (connecting to SBE41s and SBE3 and 4)
6	Cooling packs (15 cm × 10 cm, 2 or 4 packs)
7	Rack (1.0 m width × 0.5 m length × 1.2 m height)
8	Stiller (2 cycles/s)
9	Timer (measurement every second)
10 *	SBE3 and 4 (manufactured by SBE, sharing with SBE-Calibration system)

Note: * mark at number column means an item from SBE-Calibration system

important to maintain a uniform seawater temperature. However, in contrast with SBE-Calibration, maintenance of the water temperature and conductivity in the J-Calibration system is not easy, as the sensors are not fully submerged in seawater, and the water insulating/cooling controller is not used as it is in SBE-Calibration. Therefore, we need to manage J-Calibration carefully (see items in Table 2). A detailed explanation and evaluation are documented later.

Differences between the SBE-Calibration system and J-Calibration

The SBE-Calibration system is shown in Figs. 3 and 4, and the differences between the J-Calibration and SBE-Calibration systems are summarized in Table 3. SBE-Calibration, which was previously operated as a basic calibration system in the laboratory of JAMSTEC, compares measurements of seawater in SBE41s with SBE3 and 4 standard sensors whose accuracies are already validated by the manufacturer of SBE. The SBE-Calibration system consists of a calibration bath, a water insulating/cooling controller, a deck unit controller, and a bath controller (using a laptop computer for the bath controller). The deck unit controls SBE41 sensors and the SBE3 and 4 standard sensors to send control commands, and strictly maintains water temperature. The SBE-Calibration system evaluates several SBE41s (up to 5 units) to compare with the output of the standard sensors (SBE3 and 4; accuracies are ± 0.001 °C for temperature and ± 0.001 PSS-78 for salinity) by measuring artificial seawater (230 l) in a water bath. The artificial seawater is a NaCl solution and its salinity concentration is set at 35.0 PSS-78, which is the same as in J-Calibration.

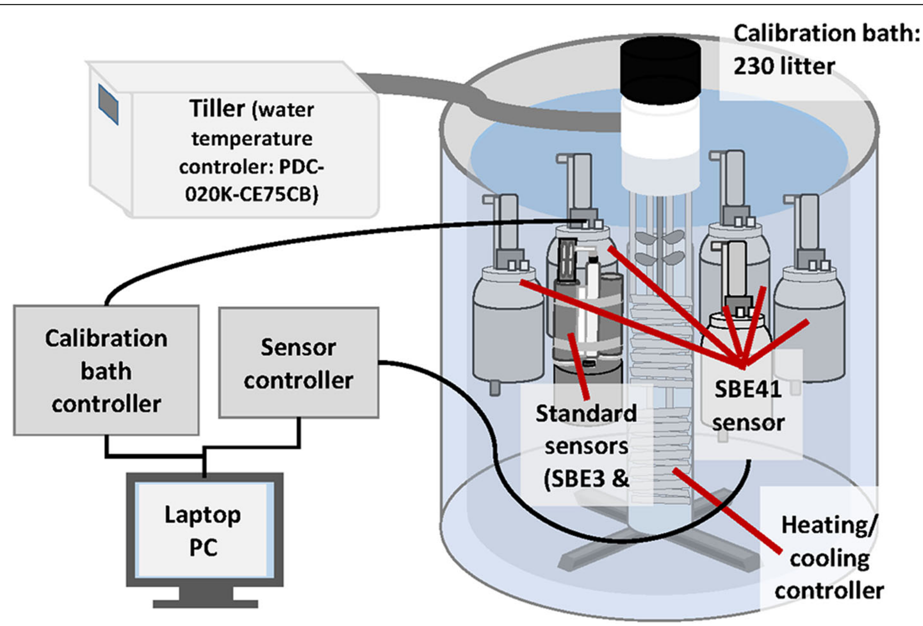

Fig. 3 Schematics of the SBE-Calibration system. The system consists of a large water tank (230 l), an insulating/cooling controller (tiller), a calibration bus controller, a sensor controller for SBE3 and 4, and a laptop computer. The laptop computer can send a command to sensors via the controllers and receive signals, and vice versa. The SBE41 sensors and standard sensors (SBE3 and 4) are placed into the tank flowing into the artificial seawater in the bath. Temperature in the tank is maintained with a heating/cooling controller and a water temperature controller surrounded the calibration bath by adiabatic materials

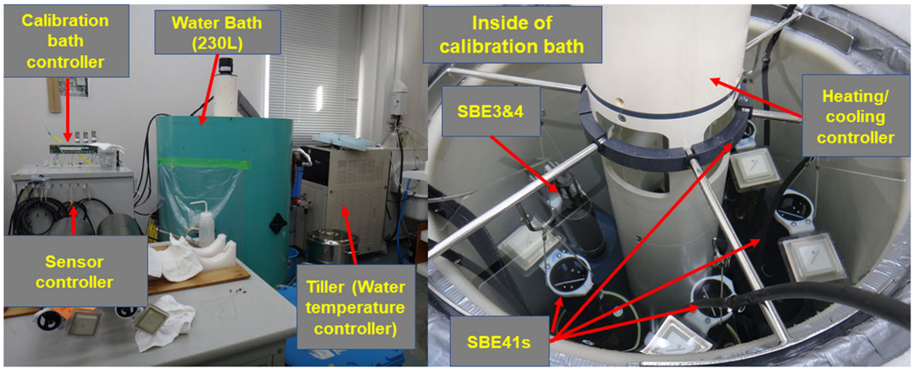

Fig. 4 (Left) Overall SBE-Calibration system. The system is separated into three components; two controllers, and a calibration bath. (Right) A detailed photo inside of the calibration bath for the SBE-Calibration system. The SBE41 sensor units (4 of 5 sensor units are shown in this photo) and SBE3 and 4 of the standard sensors were placed into the bath of artificial seawater. The artificial seawater is maintained at a uniform temperature and monitored by a water temperature controller and heating/cooling controllers

Although the sensors are submerged in the artificial seawater bath using adiabatic materials in SBE-Calibration, the water temperature still varies with heating from the stiller, sensors, and other items. To maintain a stable water temperature, a water insulating/cooling controller is used.

In the calibration of SBE41 sensors by the manufacturer, measurements for the calibration are conducted at 7 conductivity points varying the temperature under the same salinity, which is the same as that of SBE-Calibration. Regarding SBE-Calibration at JAMSTEC, if the differences in temperature and conductivity are larger than the criteria that satisfy the Argo accuracies, we check the sensors and occasionally change their coefficients or return the device to the manufacturer to repair the sensors. This screening before deployment is effective because the sensor error can occur accidentally either before delivery from the manufacturer or through a failure of calibration during the sensor manufacturing process. At this time, we have calibrated over 1000 SBE41 sensors and have successfully used SBE-Calibration to screen faulty SBE41 sensors prior to deployment (Yokota et al. 2007).

However, since the SBE-Calibration system is expensive to operate in a general laboratory and requires a great deal of time from specialized technicians, it is challenging to implement the entire system. For this reason, we decided to develop a new, efficient, and simple calibration method with the goal of a shorter procedure time while still maintaining an accuracy similar to that of SBE-Calibration.

Method of maintaining water temperature in J-Calibration

Unlike in SBE-Calibration, it is not necessary to set a fixed water temperature in J-Calibration, as J-Calibration carries out validation through a comparison of measurements between standard sensors (SBE3 and 4) and a calibrated sensor (SBE41). However, the temperature and salinity of the seawater in J-Calibration must be maintained as much as possible at every calibration in order to achieve a higher

Table 3 Differences of operational method between J-Calibration and SBE-Calibration

	J-Calibration	SBE-Calibration
Artificial seawater	Flowing directly from the tank to sensors through tubes	Filling water in a big tank, put sensors into filling water.
Amount of seawater per one experiment	10 L	230 L
Maintaining seawater temperature	Spot insulation of sensors and a part of tubes with insulating material and housing.	Tank surrounded by adiabatic material, controlling water automatically with a tiller.
Removing CTD unit	Not necessary.	Necessary with special skills.
Controlling system	Sending command to sensors and standard sensor by laptop computers.	Using a special computer unit manufactured by SBE.

precision. To achieve stable water temperature during experiments, the temperature environment of the water flow system must be carefully maintained, especially since the conductivity (salinity) sensor is largely influenced by both room temperature and water temperature. For example, as the length of the tubes with J-Calibration is longer than with SBE-Calibration, there tend to be many points of potential heat penetration through sensors, connectors, and tubes. The calibration accuracy tends to be worse if the water temperature is not controlled well.

To minimize the influence of heating and cooling of seawater on the J-Calibration system, we utilized adiabatic materials for each SBE41 CTD sensor unit (Fig. 5a, b). The adiabatic materials serve to increase or decrease temperatures by heating or cooling from the outside.

Additionally, the SBE3 and 4 standard sensors tend to radiate heat during experiments because their electric power consumption is larger than SBE41. This can cause a large change in water temperatures. In the case of SBE-Calibration, this increase in water temperature by the standard sensor unit is minimized because a large amount of water used (230 l) has a larger heat capacity and water temperature is controlled through the water insulating/cooling controller. To avoid temperature

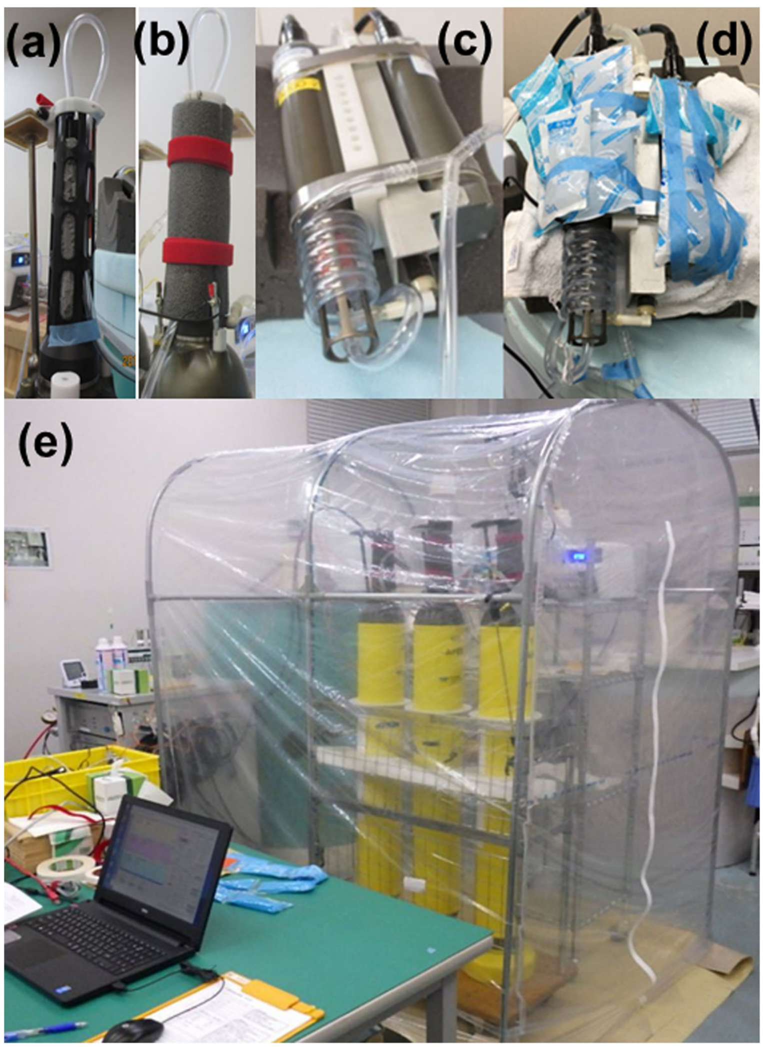

Fig. 5 **a** SBE41 sensor unit. Conductivity and temperature sensors are surrounded by a black plastic cover. In J-Calibration, inside of the cover, a cushioning material wraps around the sensors as an adiabatic material. **b** In addition to **a**, another adiabatic material covers the outside of the plastic cover. This double covering material effectively maintains the stability of temperature measurements using SBE41 sensors. **c** SBE3 and 4 standard sensors. A tube connecting the tank to the standard sensor is wound around the sensors. **d** In addition to **c**, cooling packs are attached to SBE3 and 4. The cooling packs can be easily obtained from any supermarket in Japan. **e** Vinyl greenhouse covering floats

increase in J-Calibration, we introduced two methods. One is to install tubing around the SBE3 and 4 standard sensors and cool them by pumping water into the tube wound around the sensors (Fig. 5c). The effect is to warm up the water and cool down the sensors themselves. Another method is to use cooling packs around SBE3 and 4 standard sensors to decrease water temperature and therefore that of the sensors (Fig. 5d). The number of packs required depends on the season, for example, two packs are required for each sensor in summer, while four packs are required in the winter.

It is critical to control the temperature of the air in order to ensure a stable water temperature. During the screening procedure, we kept an air conditioner at 22 °C just before starting the experiments, and then stopped it to avoid disturbing the air during actual measurements. Further, we used a vinyl greenhouse to maintain a stable air temperature. When the J-Calibration system is prepared with a water tank, the greenhouse was placed on the entire system to cover the entire experimental setup (Fig. 5e). The sheet of greenhouse was subsequently opened for an hour to adjust to room temperature. Here, we put a small table for a workspace inside of the greenhouse, the height of which was 10–30 cm below that of the SBE41 sensors, for our convenience. When the experiment was started, the sheet of the greenhouse was closed.

Based on the above factors which affect water temperature, we carried out four experiments to evaluate methods of maintaining room and water temperature involving (1) turning off the air-conditioner, (2) insulating/cooling the SBE41, SBE3, and 4 standard sensors, and (3) covering with the vinyl greenhouse. These experiments were used to carry out our evaluation of J-Calibration by estimating the differences between the SBE41 and standard sensors (Table 4).

Table 4 Water temperature control experiments for J-Calibration

Experiments		(1)	(2)	(3)	(4)
Off air conditioner			○	○	○
Insulating/cooling packs				○	○
Vinyl greenhouse					○
SBE41-Ref. (20 min avg.)	ΔT (×10^{-3} °C)	26.2	− 3.9	− 0.6	0.3
	ΔC (×10^{-3} S m^{-1})	1.3	− 1.1	− 0.6	0.1
	ΔS (× 10^{-3} PSS-78)	− 10.9	−5.5	− 3.8	0.7

ΔT, ΔC, and ΔC mean difference between SBE41 and standard sensor (float S/N 914), being measured and averaged for 20 min

In comparing differences in air temperature when utilizing the air conditioner, we found that smaller differences in amplitudes (1/7 and 1/2) for temperature and salinity, respectively, were achieved ((2) in Table 4). This indicates that the mixing of air in the room by the air conditioner tends to create turbulence, which in turn leads to differences in temperatures that are likely to be large ((1) in Table 4). Because of the large influence of the air conditioner on the stability of the calibration system, the air conditioner must be stopped during the experiments. It also means that the time for each experiment must be shortened as much as possible to avoid gradual temperature drift.

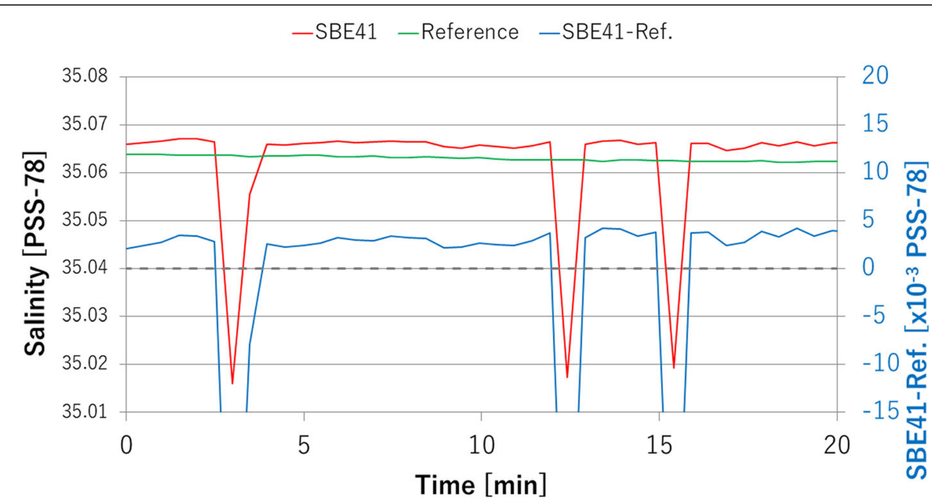

Fig. 6 Salinity of experiments contaminated with bubbles in the water. Salinity measured by the SBE41 sensor (red line), SBE3 and 4 standard sensors (green line), and the difference between the two (blue line). Salinity is measured as PSS-78 except for the difference of salinity which is × 10^{-3} PSS-78

Next, adiabatic materials and cooling packs are attached at temperature and conductivity sensors on SBE41 and to the standard sensors, to avoid increasing water temperature through heating from the sensors themselves and cooling by temperature differences between the air and water temperature ((3) in Table 4). Based on these materials and packs, the differences tended to be stable, decreasing them by 1/3rd to 1/5th as shown by case (2) in Table 4. Further, covering the J-Calibration system makes it

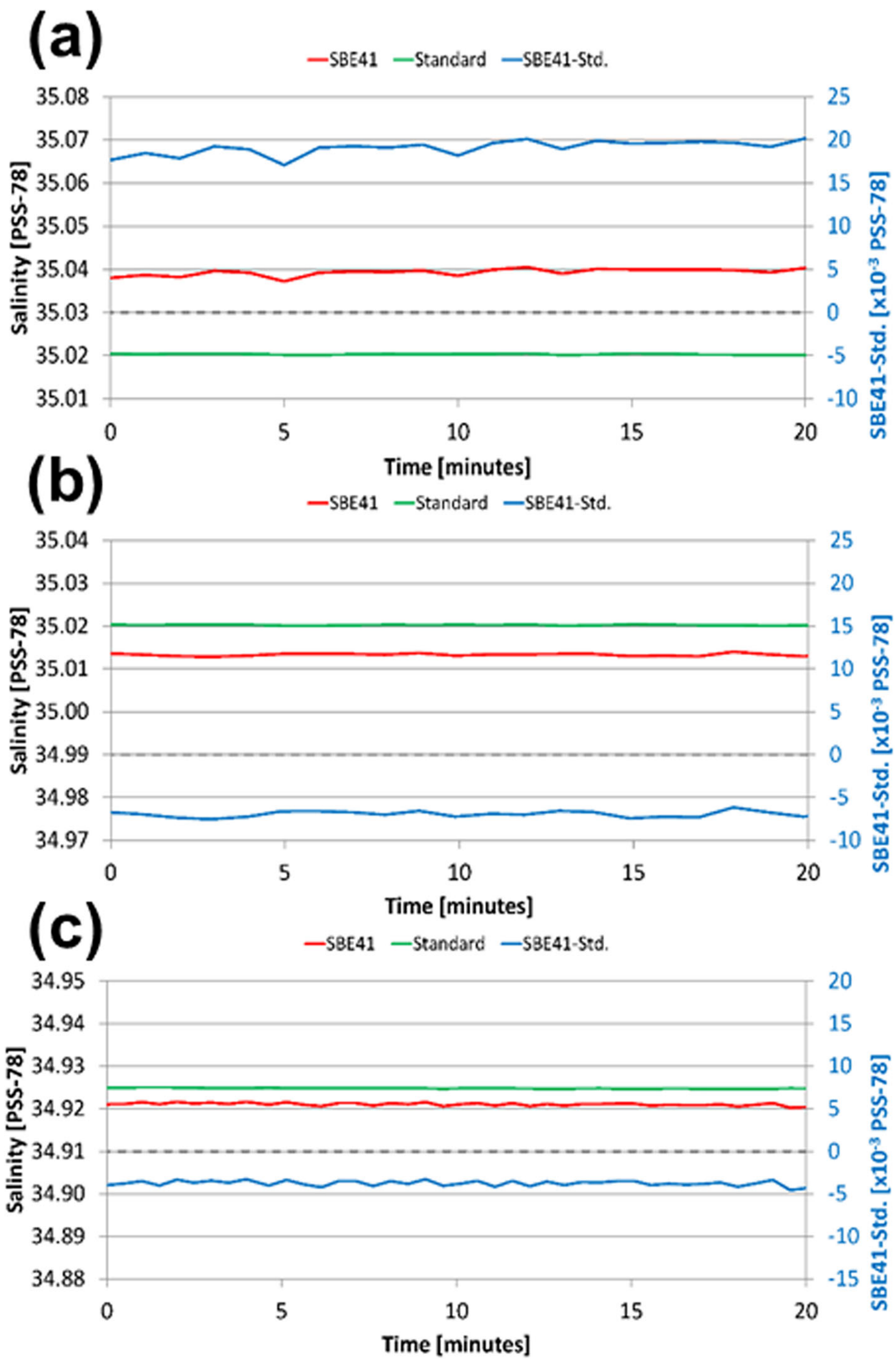

Fig. 7 The same as Fig. 6 except for salinity of calibration experiments without adiabatic material (**a**), with adiabatic material (**b**), and with adiabatic material and cooling packs (**c**)

possible to minimize water temperature variability within ± 1 °C to avoid the increased turbulence outside of the vinyl greenhouse ((4) in Table 4).

We then carried out several experiments to determine if undertaking the measures described above was effective or not. Figure 6 depicts an example of an experiment introducing contaminating bubbles into artificial seawater, which occurs when the degassing procedure is not used. During a 20-min experiment, a few negative salinity spikes appear caused by passing

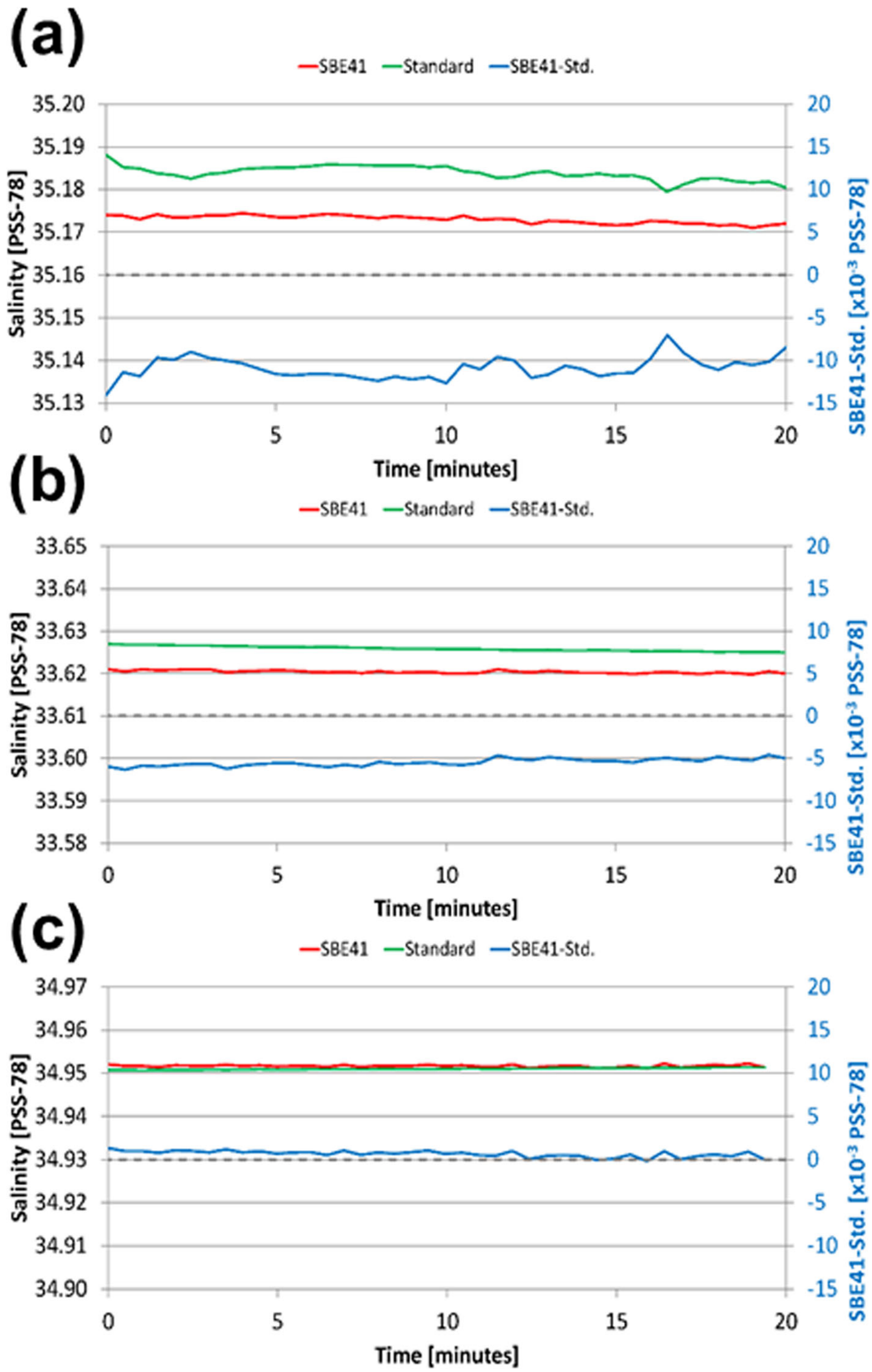

Fig. 8 Same as Figs. 6 and 7 except for salinity of calibration experiments with air conditioner (**a**), without air conditioner (**b**), and without air conditioner and with vinyl greenhouse (**c**)

bubbles through the glass tube containing the electrodes of the conductivity sensor. Figure 7 shows the salinity change of SBE41 and the standard sensor and their difference with adiabatic materials and cooling packs. Under the conditions of stable air conditioning using adiabatic materials and removing the bubbles, the difference of salinity becomes smaller than that without the materials and packs. Figure 8 shows the effect of salinity change by maintaining a room temperature environment and the effectiveness of stopping the air conditioner (middle) and covering a vinyl greenhouse. Under the condition that adiabatic materials and cooling packs are attached, salinity becomes more stable if the air conditioner is turned off. Furthermore, the vinyl greenhouse is quite effective in that the salinity difference between the SBE41 and the standard sensor is nearly 0.

Water temperature setting in J-Calibration: best choice to minimize missing screening

In SBE-Calibration, SBE41 sensors are calibrated using artificial seawater, varying the conductivity with temperature at 7 points. Because conductivity is mainly a function of temperature, changing the temperature is an alternative way to calibrate the salinity sensors. However, since changing the temperature at 7 points is very time consuming, the number of screenings of SBE41 sensors that can be completed is limited. If J-Calibration is conducted by varying temperatures at 7 points, it takes even more time than SBE-Calibration, even though the size of the tank is smaller in J-Calibration, as the water temperature needs to be homogenous.

Therefore, we must find the most appropriate temperature to calibrate SBE41 sensors to minimize missing screening. Here, we evaluate the temperature based on the results of experiments with SBE-Calibration, which were conducted from 2011 to 2016. The number of SBE41 sensor units with faults from SBE-Calibration at JAMSTEC was 20, and these were sent to the manufacturer to check and recalibrate whether the sensors were truly faulty or not. Table 5 summarizes the number and the rate of SBE41 CTDs that were judged as faulty in SBE-Calibration at JAMSTEC but were healthy in the calibration by the SBE manufacturer. Essentially, SBE-Calibration is conducted repeatedly for each SBE41 sensor unit when it is judged as a faulty sensor during its first SBE-Calibration. In total, we completed 65 experiments of SBE-Calibration for 20 SBE41 CTD units. The number of misjudged CTD units is clearly minimal at 5.2 S m^{-1} (equivalent to 24 °C for 35 PSS-78), which is a rate of less than 1.5%. Based on this result, we used one temperature point (24 °C) to screen faulty SBE41 sensors in J-Calibration with the goal of finding faulty sensors using a short experiment time.

As mentioned in the previous subsection, the important point of this J-Calibration system is not only to precisely control water and air temperature but to also minimize the variability in differences between the calibrated sensor (SBE41) and the standard sensors (SBE3 and 4). Therefore, it is crucial for J-Calibration to keep a uniform temperature during an experiment for approximately 10 min. Here, the target precision of seawater temperature is 24 ± 0.5 °C, which is empirically responsible for a stable J-Calibration result. Figure 9a, b shows the stability of temperature and salinity during every experiment of J-Calibration. The result shows that the seawater temperature and salinity are almost unchanged and uniform within ± 0.001 °C and ± 0.001 PSS-78, respectively, during the first 10 min of the calibration.

Use of artificial seawater for J-Calibration

The artificial seawater for J-Calibration is degassed in advance for 24 h to be stable during calibrations. Before starting screening, pure water is placed into a bucket (40 l) with salt (1.4 kg NaCl) and mixed at 300 rpm by a stirrer. After 20 min, when the water fully dissolves the salt, the rotating speed of the stirrer is changed to 100 rpm, and the standard sensors are put into the bath, conditioning salinity to 35 ± 0.1 PSS-78. To degas the conditioning artificial seawater, the water heats and is kept at 33 °C for some time, then is naturally cooled overnight to stabilize at room temperature. Before screening, the water stirrers are again placed in the bucket to achieve a uniform salt concentration. Then, we expose the water to a vacuum to help remove bubbles (0.04 MPa), and re-stirring of the water is conducted in a smaller water tank (10 l) to degas it completely. The

Table 5 Missing screening and its rate of conductivity sensor error at 7 temperature points on SBE-Calibration at JAMSTEC

Conductivity (S m^{-1})	3.0 (1.0 °C)	3.3 (4.5 °C)	4.2 (15.0 °C)	4.6 (18.5 °C)	5.2 (24.0 °C)	5.7 (29.0 °C)	6.0 (32.5 °C)
No. of inconsistency	20	11	5	3	1	3	22
Rate of inconsistency (%)	30.8	16.9	7.7	4.6	1.5	4.6	33.9

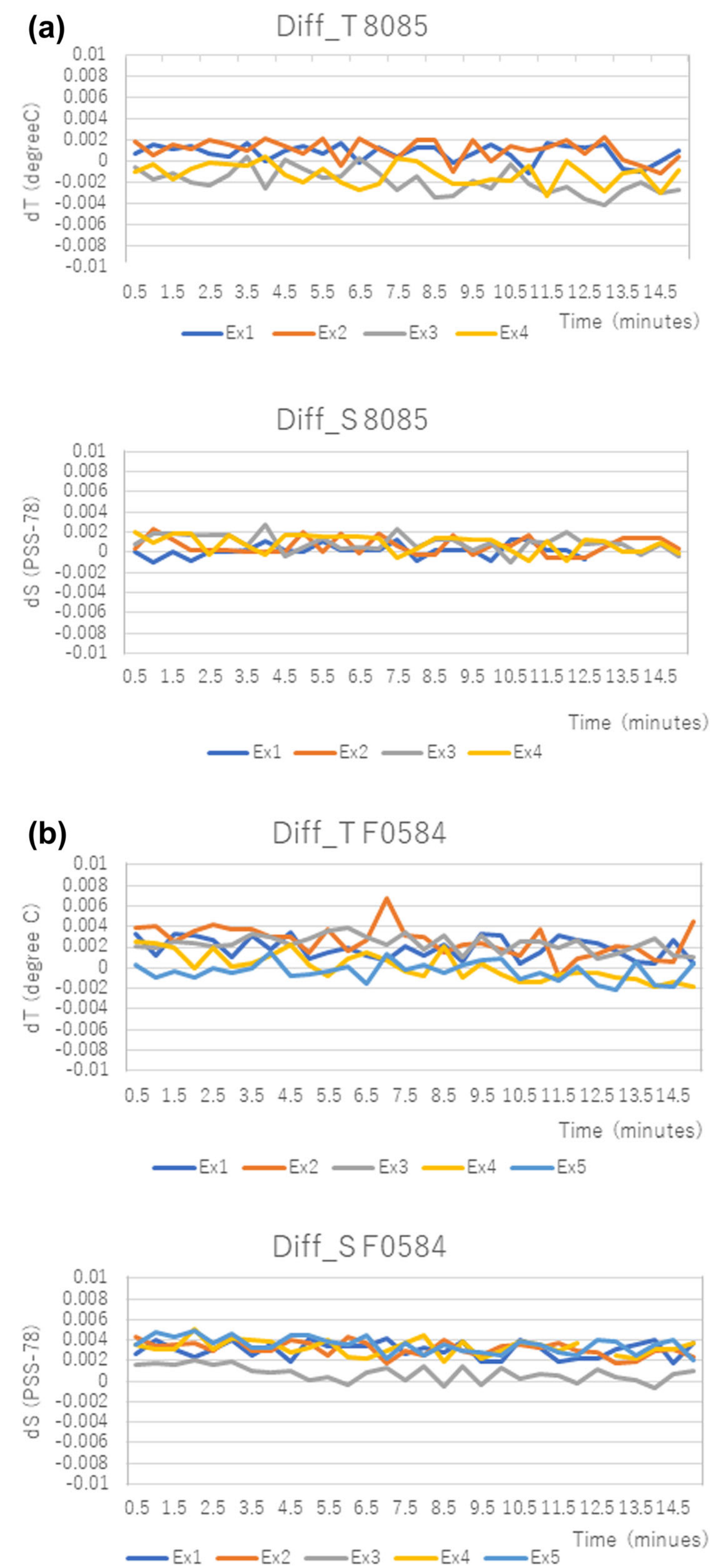

Fig. 9 (See legend on next page.)

(See figure on previous page.)

Fig. 9 a Temperature (upper) and salinity (lower) differences (shown in the legend as “dT” and “dS,” respectively) of measurements between SBE41 and SBE3 and 4 sensors during four experiments (Ex1~Ex4) for float S/N 8085 of J-Calibration. J-Calibration system uses cooling packs, adiabatic materials, and a Vinyl greenhouse to keep a uniform environment during the experiments. In 15 min allotted for each measurement, actual calibration is done in 5 min when the dT and dS are within ± 0.01 °C and ± 0.01 PSS-78, respectively. **b** The same as Fig. 9a except for 5 experiments (Ex1 ~ Ex5) for float S/N F0584 of J-Calibration

degassed water is kept in the same laboratory room throughout.

Here, we use a NaCl solution seawater as the artificial seawater in both SBE- and J-Calibration, because handling and creating the artificial seawater is easier than using real seawater. In the manufacturer SBE, the SBE41 sensor calibration is conducted using artificial seawater, in the same manner as our method. When using real seawater for SBE3 and 4 calibration, the coefficients and slope are different from those found when using the artificial seawater. To avoid this discrepancy, we corrected the salinity measurement of SBE3 and 4 using a salinometer “Autosal” (Guildline Instruments 1981) to modify the coefficients and slope of the equation, which is the same method used by the manufacturer SBE.

Results

Experiments using J-Calibration system

J-Calibration was carried out for Navis and APEX type floats, which were delivered to JAMSTEC from 2017 to 2018. The number of floats in total was 33, and that of the calibration experiments was 88, as listed in Table 6. Measurement values of temperature, conductivity, and salinity calculated from pressure, and conductivity and temperature for SBE41 and SBE3 and 4 standard sensors are described. The differences between the three parameters between the SBE41 and the standard sensors are also shown. The measurement values of temperature and salinity are approximately 22 °C and 35.0 PSS-78, respectively, and the differences are within the order of 10^{-3}. Based on the values in Table 6, all experiments in J-Calibration are clearly stable. Both J-Calibration and SBE-Calibration were conducted 8 times for 3 of the 33 floats to evaluate the accuracy and stability of J-Calibration in comparison with SBE-Calibration (Table 7). The three floats were the only Navis type we were able to obtain permission from the manufacturer to remove the SBE41 sensors from the float body for SBE-Calibration. Using the artificial seawater (salinity concentration of about 35 PSS-78) that is already degassed, we calculated a difference of temperature and conductivity between SBE41 and SBE3 and 4 standard sensors to evaluate J-Calibration, averaging those measurement values for about 5 min.

Table 8 shows temperature, conductivity, and salinity differences for 8 experiments of 3 floats using J-Calibration. Table 9 shows the average and statistical values of 8 experiments of SBE-Calibration for the 3 floats. Since the salinity differences between SBE41 and SBE3 and the 4 standard sensors are within ± 0.01 PSS-78 through all the experiments of SBE-Calibration, SBE41 sensors were considered to satisfy the Argo criteria with the same result as in J-Calibration. Considering the standard deviation of temperature difference ($\Delta T \sim \pm 0.0015$ °C) and salinity difference ($\Delta S \sim \pm 0.0033$ PSS-78), those three SBE41 sensor samples are all stable and satisfy the criteria for Argo accuracy. The results of both SBE- and J-Calibration and their statistical values demonstrate that J-Calibration can accurately validate floats without any faults.

Evaluation of J-Calibration results

Figure 10 shows a scatter plot of conductivity differences between SBE41 and SBE 4 standard sensors using J-Calibration and SBE-Calibration. Regarding the three SBE41 sensors (S/N 914, 918, and 922), we conducted SBE-Calibration at 7 point-calibrations (● marks) in the same manner as the manufacturer SBE and J-Calibration (▲ marks). The result was that the differences in conductivity tend to be small within mostly $\pm 0.5 \times 10^{-3}$ S m^{-1}, although two sensors (S/N 914 and 918) were biased a little to the positive side, while one sensor (S/N: 922) had a small negative bias around -0.5×10^{-3} S m^{-1}. In those cases, we can judge that the three SBE41 sensors are healthy based on SBE-Calibration results. Here, we define two criteria for failure of a sensor (red dashed; over ± 0.015 PSS-78 at 5.2 S m^{-1}) and re-calibration (red dotted; ± 0.0075 PSS-78 at 5.2 S m^{-1}) as references. In the case of faults, we could find large biases with both positive or negative signs outside of the criteria lines of the fault sensors, and these may be caused by difficulty during transportation or by fluctuations during experiments.

The differences of conductivity between SBE41 and the SBE4 standard sensors in J-Calibration (88 times

Table 6 Specification of 88 experiments of J-calibration based on 33 floats. All SBE41 sensors are examined with J-Calibration more than twice

Float type	Float S/N	Date (2017)	Float (SBE41)			Standard sensor			Difference (× 10^{-3})		
			T [°C]	C [Sm^{-1}]	S [PSS-78]	T [°C]	C [Sm^{-1}]	S [PSS-78]	ΔT [°C]	ΔC [S m^{-1}]	ΔS [PSS78]
APEX	7849	August 14	23.2411	5.11240	34.9093	23.2389	5.11326	34.9177	2.26	− 0.861	− 8.40
APEX	7849	August 21	22.4158	5.02942	34.9253	22.4158	5.03046	34.9334	− 0.03	− 1.035	− 8.05
APEX	7849	August 21	22.4637	5.05372	35.0764	22.4664	5.05522	35.0859	− 2.70	− 1.500	− 9.53
APEX	7849	August 24	22.2976	5.00687	34.8440	22.2990	5.00818	34.8531	− 1.34	− 1.306	− 9.14
APEX	7849	August 24	23.1198	5.09107	34.8415	23.1229	5.09260	34.8509	− 3.03	− 1.528	− 9.35
APEX	7849	April 26	22.5755	5.04418	34.9123	22.5779	5.04475	34.9148	− 2.36	− 0.566	− 2.51
APEX	7849	April 26	22.1196	4.99755	34.9140	22.1210	4.99804	34.9167	− 1.43	− 0.489	− 2.69
APEX	7907	August 14	23.2399	5.11377	34.9208	23.2390	5.11328	34.9177	0.81	0.489	3.12
APEX	7907	August 21	22.4158	5.03079	34.9359	22.4160	5.03048	34.9334	− 0.20	0.310	2.58
APEX	7907	August 21	22.4643	5.05513	35.0869	22.4666	5.05524	35.0859	− 2.27	− 0.109	0.98
APEX	7907	August 24	22.2980	5.00827	34.8546	22.2992	5.00821	34.8531	− 1.21	0.066	1.48
APEX	7907	August 24	23.1198	5.09252	34.8528	23.1231	5.09262	34.8509	− 3.34	− 0.097	1.90
APEX	8084	August 15	22.5776	5.04404	34.9095	22.5755	5.04347	34.9068	2.12	0.568	2.73
APEX	8084	August 17	22.4651	5.02755	34.8712	22.4643	5.02723	34.8694	0.83	0.321	1.83
APEX	8084	August 22	21.9148	4.93533	34.5895	21.9119	4.93483	34.5879	2.91	0.496	1.57
APEX	8084	August 22	22.2110	4.96531	34.5882	22.2100	4.96501	34.5867	1.04	0.295	1.48
APEX	8085	August 15	22.5765	5.04361	34.9071	22.5756	5.04349	34.9068	0.83	0.119	0.26
APEX	8085	August 17	22.4653	5.02741	34.8700	22.4644	5.02724	34.8694	0.92	0.172	0.60
APEX	8085	August 22	21.9101	4.93473	34.5886	21.9121	4.93486	34.5879	− 2.05	− 0.124	0.67
APEX	8085	August 22	22.2086	4.96498	34.5875	22.2101	4.96503	34.5867	− 1.49	− 0.051	0.79
APEX	8086	August 15	22.5761	5.04387	34.9094	22.5758	5.04350	34.9068	0.37	0.371	2.59
APEX	8086	August 17	22.4644	5.02713	34.8685	22.4646	5.02726	34.8694	− 0.15	− 0.130	− 0.90
APEX	8086	August 22	21.9117	4.93471	34.5871	21.9124	4.93488	34.5879	− 0.70	− 0.172	− 0.79
APEX	8086	August 22	22.2105	4.96497	34.5860	22.2103	4.96505	34.5867	0.20	− 0.076	− 0.76
APEX	8087	August 16	23.0446	5.09439	34.9267	23.0430	5.09393	34.9245	1.67	0.457	2.20
APEX	8087	August 23	22.1860	5.00377	34.9094	22.1870	5.00357	34.9070	− 1.05	0.200	2.41
APEX	8087	August 23	22.4708	5.03274	34.9071	22.4715	5.03246	34.9044	− 0.69	0.279	2.72
APEX	8088	August 16	23.0416	5.09384	34.9250	23.0431	5.09395	34.9245	− 1.59	− 0.109	0.42
APEX	8088	August 23	22.1851	5.00322	34.9058	22.1873	5.00360	34.9070	− 2.22	− 0.379	− 1.19
APEX	8088	August 23	22.4700	5.03232	34.9045	22.4716	5.03248	34.9044	− 1.64	− 0.158	0.08
APEX	8089	August 16	23.0416	5.09394	34.9256	23.0433	5.09396	34.9245	− 1.65	− 0.027	1.11
APEX	8089	August 23	22.1877	5.00345	34.9054	22.1875	5.00362	34.9070	0.19	− 0.179	− 1.55
APEX	8089	August 23	22.4695	5.03235	34.9051	22.4718	5.03250	34.9044	− 2.37	− 0.146	0.77
APEX	8262	April 16	22.9391	5.09810	35.0395	22.9372	5.09758	35.0370	1.89	0.514	2.46
APEX	8262	April 16	22.6803	5.07164	35.0417	22.6798	5.07106	35.0376	0.49	0.575	4.07
APEX	8263	April 16	22.9372	5.09791	35.0396	22.9374	5.09761	35.0370	− 0.24	0.306	2.56
APEX	8263	April 16	22.6802	5.07151	35.0408	22.6799	5.07108	35.0376	0.28	0.437	3.16
APEX	8264	April 16	22.9365	5.09793	35.0399	22.9376	5.09763	35.0370	− 1.08	0.302	2.82
APEX	8264	April 16	22.6793	5.07158	35.0421	22.6801	5.07109	35.0376	− 0.80	0.493	4.46
APEX	8265	April 17	23.1576	5.11128	34.9669	23.1565	5.11127	34.9678	1.18	0.005	− 0.90
APEX	8265	April 17	23.0436	5.09961	34.9678	23.0432	5.09955	34.9677	0.32	0.052	0.15
APEX	8266	April 17	23.1586	5.11174	34.9697	23.1567	5.11130	34.9678	1.87	0.440	1.90

Table 6 Specification of 88 experiments of J-calibration based on 33 floats. All SBE41 sensors are examined with J-Calibration more than twice *(Continued)*

Float type	Float S/N	Date (2017)	Float (SBE41)			Standard sensor			Difference (× 10^{-3})		
			T [°C]	C [Sm^{-1}]	S [PSS-78]	T [°C]	C [Sm^{-1}]	S [PSS-78]	ΔT [°C]	ΔC [S m^{-1}]	ΔS [PSS78]
APEX	8266	April 17	23.0446	5.10010	34.9708	23.0434	5.09957	34.9677	1.22	0.533	3.14
APEX	8267	April 17	23.1586	5.11187	34.9707	23.1570	5.11133	34.9678	1.65	0.546	2.89
APEX	8267	April 17	23.0446	5.10014	34.9711	23.0436	5.09959	34.9677	1.03	0.553	3.44
APEX	8416	April 18	23.2711	5.12112	34.9524	23.2725	5.12115	34.9515	− 1.44	− 0.027	0.93
APEX	8416	April 18	22.8732	5.08021	34.9539	22.8736	5.08000	34.9519	− 0.43	0.218	2.02
APEX	8417	April 18	22.8749	5.08081	34.9571	22.8737	5.08001	34.9519	1.21	0.800	5.22
APEX	8417	April 20	24.1304	5.19782	34.8593	24.1308	5.19756	34.8571	− 0.35	0.260	2.22
APEX	8417	April 20	23.7884	5.16263	34.8609	23.7872	5.16198	34.8569	1.24	0.651	3.97
APEX	8418	April 18	23.2715	5.12142	34.9544	23.2728	5.12117	34.9515	− 1.25	0.253	2.93
APEX	8418	April 18	22.8737	5.08046	34.9554	22.8739	5.08002	34.9519	− 0.16	0.439	3.52
APEX	8419	April 19	23.7940	5.16733	34.8922	23.7948	5.16709	34.8898	− 0.77	0.235	2.39
APEX	8419	April 19	23.6412	5.15155	34.8925	23.6414	5.15119	34.8896	− 0.25	0.361	2.95
APEX	8420	April 19	23.7945	5.16744	34.8927	23.7950	5.16712	34.8898	− 0.58	0.320	2.89
APEX	8420	April 19	23.6422	5.15175	34.8932	23.6416	5.15121	34.8896	0.61	0.541	3.64
APEX	8421	April 19	23.7964	5.16765	34.8928	23.7953	5.16715	34.8898	1.07	0.505	2.99
APEX	8421	April 19	23.6424	5.15177	34.8932	23.6417	5.15122	34.8896	0.64	0.544	3.64
APEX	8422	April 20	24.1284	5.19773	34.8602	24.1302	5.19750	34.8571	− 1.77	0.231	3.13
APEX	8422	April 20	23.7866	5.16247	34.8612	23.7869	5.16195	34.8569	− 0.33	0.529	4.28
APEX	8423	April 20	24.1291	5.19774	34.8597	24.1305	5.19753	34.8571	− 1.33	0.210	2.63
APEX	8423	April 20	23.7883	5.16267	34.8613	23.7871	5.16196	34.8569	1.23	0.703	4.37
Navis	584	August 14	23.2405	5.11382	34.9207	23.2387	5.11325	34.9177	1.74	0.575	3.04
Navis	584	August 21	22.4179	5.03106	34.9364	22.4157	5.03044	34.9334	2.24	0.620	3.03
Navis	584	August 21	22.4685	5.05551	35.0864	22.4662	5.05521	35.0859	2.29	0.300	0.49
Navis	584	August 24	22.3003	5.00872	34.8562	22.2987	5.00815	34.8531	1.62	0.569	3.14
Navis	584	August 24	23.1222	5.09297	34.8542	23.1226	5.09257	34.8508	− 0.44	0.392	3.36
Navis	913	April 23	23.3763	5.14524	35.0538	23.3767	5.14491	35.0509	− 0.39	0.334	2.87
Navis	913	April 23	23.1729	5.12431	35.0550	23.1740	5.12398	35.0516	− 1.10	0.330	3.41
Navis	914	April 23	23.3775	5.14553	35.0551	23.3769	5.14492	35.0509	0.66	0.614	4.18
Navis	914	April 23	23.1745	5.12461	35.0560	23.1741	5.12398	35.0516	0.40	0.626	4.49
Navis	915	April 23	23.3783	5.14542	35.0536	23.3770	5.14493	35.0509	1.25	0.487	2.74
Navis	915	April 23	23.1742	5.12440	35.0547	23.1741	5.12399	35.0516	0.06	0.412	3.12
Navis	916	April 24	23.3022	5.12756	34.9771	23.3033	5.12758	34.9764	− 1.11	− 0.020	0.73
Navis	916	April 24	22.6258	5.05820	34.9810	22.6263	5.05816	34.9800	− 0.49	0.033	1.01
Navis	917	April 24	23.3056	5.12839	34.9807	23.3034	5.12759	34.9764	2.23	0.796	4.33
Navis	917	April 24	22.6273	5.05887	34.9850	22.6264	5.05817	34.9800	0.94	0.697	5.03
Navis	918	April 24	22.6274	5.05795	34.9778	22.6264	5.05818	34.9800	0.98	− 0.222	− 2.14
Navis	918	April 26	22.5774	5.04438	34.9124	22.5778	5.04474	34.9148	− 0.44	− 0.359	− 2.44
Navis	918	April 26	22.1215	4.99783	34.9147	22.1209	4.99803	34.9167	0.61	− 0.202	− 2.08
Navis	919	April 25	21.9950	4.98649	34.9276	21.9949	4.98577	34.9221	0.08	0.715	5.56
Navis	919	April 25	22.4174	5.02985	34.9273	22.4195	5.02940	34.9222	− 2.06	0.449	5.16
Navis	920	April 25	21.9948	4.98670	34.9293	21.9949	4.98578	34.9221	− 0.08	0.918	7.29
Navis	920	April 25	22.4186	5.03011	34.9284	22.4195	5.02940	34.9222	− 0.90	0.708	6.24

Table 6 Specification of 88 experiments of J-calibration based on 33 floats. All SBE41 sensors are examined with J-Calibration more than twice *(Continued)*

Float type	Float S/N	Date (2017)	Float (SBE41)			Standard sensor			Difference (× 10^{-3})		
			T [°C]	C [Sm^{-1}]	S [PSS-78]	T [°C]	C [Sm^{-1}]	S [PSS-78]	ΔT [°C]	ΔC [S m^{-1}]	ΔS [PSS78]
Navis	921	April 25	21.9928	4.98619	34.9270	21.9950	4.98578	34.9221	− 2.19	0.409	4.99
Navis	921	April 25	22.4156	5.02955	34.9265	22.4196	5.02941	34.9222	− 4.04	0.140	4.33
Navis	922	April 26	22.5770	5.04524	34.9193	22.5777	5.04473	34.9148	− 0.69	0.505	4.48
Navis	922	April 26	22.1209	4.99860	34.9212	22.1208	4.99802	34.9167	0.09	0.576	4.45

based on the other sensors) are also over-plotted. As the temperature at one point (22 °C corresponding to 5.2 S m^{-1}) is chosen, all plots are gathered around conductivities of 5.0–5.3 S m^{-1}. Generally, the conductivity differences of all J-Calibration are distributed within ± 0.0075 PSS-78, corresponding to salinity values (red dotted lines), although several experiments were outside of these differences. However, all the conductivity sensors are still judged as sufficient for Argo criteria, namely, ± 0.01 PSS-78 for salinity. As a result, no conductivity sensors on SBE41 needed to be returned to the manufacturer and repaired. If a faulty sensor of SBE41 existed, it is expected that the difference from the standard sensor will fall outside the fault-tolerance threshold, requiring the sensor to be returned to the manufacturer. In this case, we would need further information from the manufacturer to analyze other technical data and investigate whether the case is a serious and systematic error.

Figure 11 shows the frequency histograms of differences between the SBE41 and SBE3 and 4 standard sensors for temperature (a), conductivity (b), and salinity (c) in J-Calibration. In the 88 experiments (see Table 6), the histogram of temperature difference is almost a normal distribution, with 0 at the center of the histogram (Fig. 11a). The histograms of conductivity and salinity (Fig. 11b, c) have a positive bias at a center of 0.19×10^{-3} S m^{-1} and 1.6×10^{-3} PSS-78, respectively. The positive biases in J-Calibration are the same as described in Fig. 10, but all the sensors satisfy the Argo criteria.

Furthermore, we investigated the dependency of the salinity concentration on the differences between SBE41 and the standard sensors in all calibration experiments of both SBE-Calibration and J-Calibration (Fig. 12). The salinity concentration in SBE-Calibration was set to 34.975 PSS-78, while that in J-Calibration is dispersed between 34.85 and 35.10 PSS-78. There is no systematic dependency or bias on the concentration of artificial seawater salinity for salinity differences. This means that we do not need to strictly control the salinity concentration of the seawater, which is different from SBE-Calibration. Based on those experiments, we summarize the results of 33 floats in J-Calibration and 3 floats in SBE-Calibration as follows:

1. Accuracy and precision of J-Calibration for temperature and conductivity sensors are enough to screen faulty sensors of SBE41.
2. Conductivity and salinity differences in J-Calibration have a small positive bias but this influence on the screening result can be ignored.
3. It is not necessary to control the salinity concentration of artificial seawater in J-Calibration.

Although the number of experiments for J-Calibration is not still enough to be significant at this time, the J-Calibration system is effective to find faulty sensors and to avoid deployment of faulty floats in advance, with similar accuracy to that of the SBE-Calibration system.

Discussion

In the "Results" section, we confirmed the screening accuracy of J-Calibration for temperature and conductivity. Here, we investigate the stability of J-Calibration depending on different environments such as seasonality and room conditioning, and J-Calibration performance regarding the screening result is correct or faulty by

Table 7 Float and sensor S/N and calibration date of SBE-Calibration and J-Calibration for the three SBE41 sensors

Float type	S/N	Sensor S/N	SBE-Calib. (no. of exp)	Experiment date	J-Calib. (no. of exp)	Experiment date
Navis (SBE)	914	10,532	3	April 6, 2018	2	April 23, 2018
Navis (SBE)	918	10,540	3	April 6, 2018	3	April 24, 2018
Navis (SBE)	922	10,558	2	April 6, 2018	2	April 26, 2018

Note: SBE-Calibration is repeatedly conducted one or two times for each sensor

Table 8 Eight experiments of J-Calibration for the three sensors (S/N 914, 918, and 922).

Float number	Exp. Date	Float data (X_{float})			Standard sensor data (X_{ref})			Difference (X_{float}–X_{ref})		
		T (°C)	C (S m^{-1})	S (PSS-78)	T (°C)	C (S m^{-1})	S (PSS-78)	ΔT (× 10^{-3} °C)	ΔC (× 10^{-3} S m^{-1})	ΔS (× 10^{-3} PSS78)
914	April 23, 2018	23.38	5.146	35.06	23.38	5.145	35.05	0.66	0.614	4.18
914	April 23, 2018	23.17	5.125	35.06	23.17	5.124	35.05	0.40	0.626	4.49
918	April 24, 2018	22.63	5.058	34.98	22.63	5.058	34.98	0.98	− 0.222	− 2.14
918	April 26, 2018	22.58	5.044	34.91	22.58	5.045	34.91	− 0.44	− 0.359	− 2.44
918	April 26, 2018	22.12	4.998	34.91	22.12	4.998	34.92	0.61	− 0.202	− 2.08
922	April 26, 2018	22.58	5.045	34.92	22.58	5.045	34.91	− 0.69	0.505	4.48
922	April 26, 2018	22.12	4.999	34.92	22.12	4.998	34.92	0.09	0.576	4.45

Differences between SBE41 sensors and standard sensors for temperature, conductivity, and salinity (ΔT, ΔC, and ΔS) are described. Units are 10^{-3} °C, 10^{-3} S m^{-1}, and 10^{-3} PSS-78, respectively. In those experiments, the artificial sea water is set to 35 PSS-78 for salinity and 22–24 °C for temperature

comparing with rQCed data after float deployment. Then, the small positive bias described in the "Results" section is investigated and related to the use of artificial seawater.

J-Calibration system assessment: seasonal dependency

Based on the importance of stable room temperature as shown with some of the items in Table 2, we investigate the seasonal dependency of J-Calibration results. Here, we use the experiment results of 3 SBE41 sensors (S/N 914, 918, and 922) in April 2018 (winter) and August 2017 (summer) when the average outside temperatures are 7.4 °C and 21.7 °C in Mutsu City in Japan, respectively (based on monthly air temperature climatology from the Japan Meteorological Agency). In Mutsu City, room heating and cooling devices are used in April to August. As shown in the "Methods/Experimental" section, the air conditioner is stopped during the experiments, and the experiment environment is separated from the room environment to achieve greater stability by using a vinyl greenhouse. Figure 13 shows the histograms of the results for temperature (a), conductivity (b), and salinity (c) for each experimental season (April, blue; August, orange), which is separated by the results shown in Fig. 11. The histogram of temperature differences from standard sensors is an almost normal distribution around 0 in both seasons. While conductivity and salinity distributions are different from temperature, there is a larger positive bias in April than in August. Vertical temperature distribution inside the greenhouse is observed between the floor and sensor level due to a temperature stratification, especially in April. In the winter season, the heater warms the upper layer of the atmosphere while the floor tends to be cold. This temperature discrepancy causes strengthened vertical air stratification. In fact, during the experiments, the average temperature difference between the height at the conductivity sensor (160 cm) and the float body (60 cm) reaches 0.5 °C in experiments conducted in April when it is still the winter season in Mutsu. By cooling from the floor of the laboratory, the contrast of air temperature between the upper and lower level becomes large, which causes the conductivity sensor to be cold due to heat loss from the floor. On the other hand, cooling with the air conditioner causes vertical air mixing and such stratification is not formed. Therefore, careful attention should be paid to the vertical temperature difference during J-Calibration experiments in the winter or early spring seasons.

In Fig. 13, although almost all histograms show a Gaussian distribution in both SBE-Calibration and J-Calibration, these histograms are dispersed and widely spread. If the dispersion generally appears in every experiment on the same sensors, J-Calibration

Table 9 Average, standard deviation, minimum and maximum values for temperature, conductivity, and salinity of 8 SBE-Calibration results

	Temp (float)	Cond. (float)	Sal (float)	Temp (Ref.)	Cond. (Ref.)	Sal. (Ref.)	ΔT (× 10^{-3})	ΔC (× 10^{-3})	ΔS (× 10^{-3})
Average	22.8337	5.0714	34.9161	22.8339	5.0712	34.9145	− 0.1471	0.1936	1.6148
Standard deviation	0.5665	0.0634	0.1088	0.5663	0.0633	0.1084	1.4358	0.4754	3.2851
Maximum	24.1304	5.1978	35.0869	24.1308	5.1976	35.0859	2.9100	0.9180	7.2900
Minimum	21.9101	4.9347	34.5860	21.9119	4.9348	34.5867	− 4.0400	− 1.5280	− 9.5300

Note: *Temp* temperature, *Cond* conductivity, *Sal* salinity, *Ref.* reference sensors

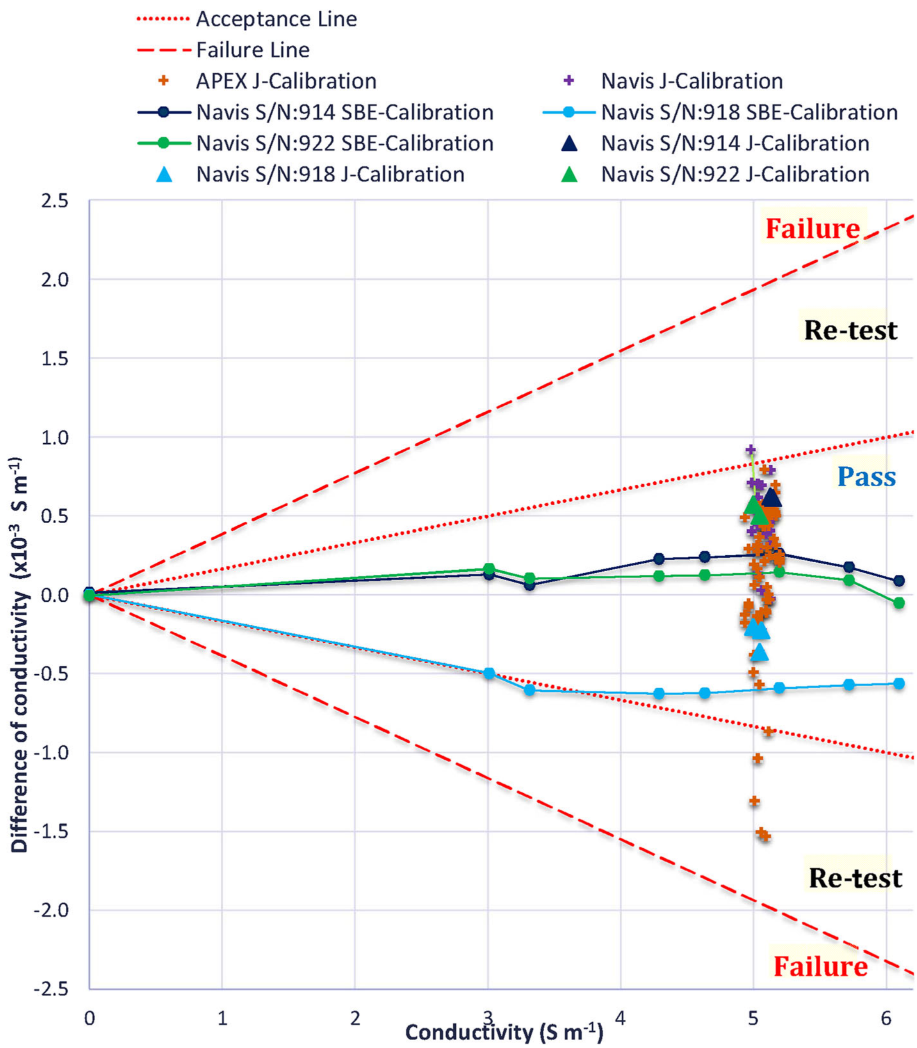

Fig. 10 Conductivity calibration results to judge whether sensors are acceptable or not. *X*-axis is conductivity on standard sensor, *Y*-axis is conductivity differences of SBE41 and standard sensor. ● and ▲ represent SBE-Calibration and J-Calibration results (S/N 914, 918, and 922), respectively. Colors (dark blue, light blue, and green) indicate sensor S/N (914, 918, and 922), respectively. + means J-Calibration only for APEX (dark orange) and Navis (purple) type floats. The result of SBE calibration for each sensor is shown as a line graph (7 conductivity/temperature points). Area within red dotted lines defines acceptable Argo accuracy, while the area within red dashed lines defines acceptable accuracy requiring re-calibration at least twice

system cannot be relied on for faulty sensor screening. Here, we evaluate the stability of calibration results for conductivity/salinity in J-Calibration and SBE-Calibration to quantify dispersions of conductivity measurements from all available experiments in our laboratory. We used 88 calibration experiments by J-Calibration conducted on 33 floats in 2017 and 83 calibration experiments by SBE-Calibration conducted on 18 floats in 2012–2017 (Table 10). Here, only one temperature point, 24 °C (5.2 S m^{-1}), is used in SBE-Calibration and J-Calibration. We then calculate the root mean square (RMS) of conductivity differences from screening results based on SBE41 sensors that were calibrated twice or more. In order to confirm the accuracy of our results, the 83 calibration experiments performed on SBE-Calibration were generally conducted at least twice for each SBE41 sensor.

When N times calibrations are conducted for each sensor, the difference of conductivity between SBE41 and SBE3 and 4 standard sensors is defined as X_{Mi}, while the difference of conductivity from the last experiment for each sensor is X_{Bi}, where i is the number of experiments ($i = 1 \sim N$). The RMS of conductivity difference (X_{rep}) between X_{Mi} and X_{Bi} is estimated as follows.

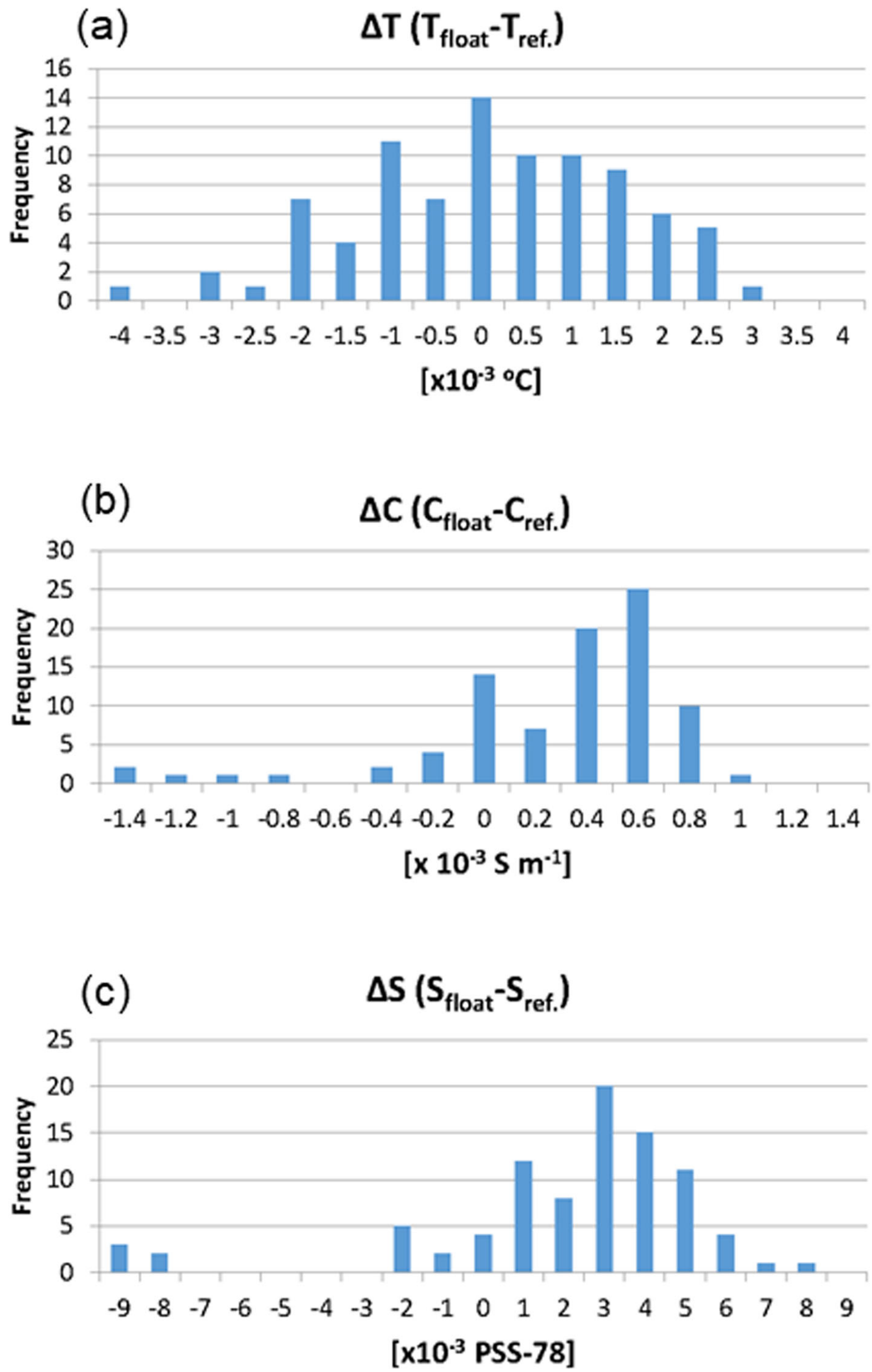

Fig. 11 Histograms of differences for temperature (**a**), conductivity (**b**), and salinity (**c**) on J-Calibration experiments. The number of experiments is 88, binning 0.5×10^{-3} °C, 0.2×10^{-3} S m^{-1}, and 1×10^{-3} PSS-78 widths, respectively. Averages of ΔT, ΔC, and ΔS are -1.5×10^{-3} °C, 0.19×10^{-3} S m^{-1}, and 1.6×10^{-3} PSS-78, respectively. Standard deviations of ΔT, ΔC, and ΔS are 1.44×10^{-3} °C, 0.48×10^{-3} S m^{-1}, and 3.3×10^{-3} PSS-78, respectively. The experiments for some of SBE41 sensors are conducted for more than twice

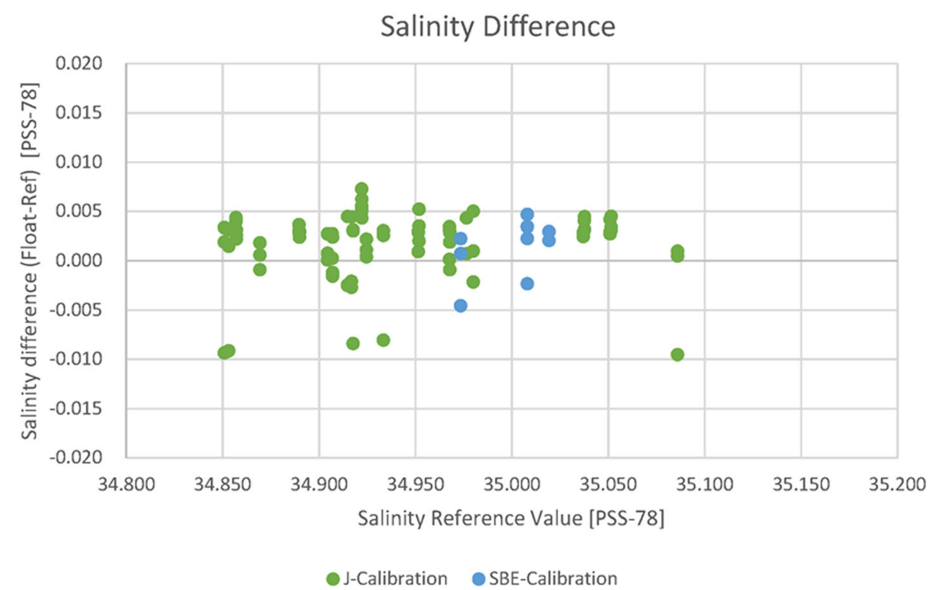

Fig. 12 Salinity differences plot based on 88 experiments for J-Calibration (● green) and 9 experiments for SBE-Calibration (● light blue)

$$X_{\text{rep}} = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{N} X_{Mi} - X_{Bi}\right)^2} \tag{1}$$

Here, the X_{rep} is referred to as frequent RMS (F-RMS). Since the F-RMS can be analyzed for SBE-Calibration ($X_{\text{rep\_SBE}}$) and J-Calibration ($X_{\text{rep\_}J}$), the difference of conductivity dispersions between both systems is estimated by the following equation.

$$\Delta X_{\text{rep}} = X_{\text{rep\_}J} - X_{\text{rep\_SBE}} \tag{2}$$

Histograms of F-RMS in SBE-Calibration and J-Calibration are shown in Fig. 14 and their statistical values are summarized in Table 11. The histograms of F-RMS in J-Calibration (88 in total) tend to be close to 0, while that of SBE-Calibration (83 in total) is a little larger, which can be seen in the average, median, and standard deviation. Based on the result of F-RMS, the reliability of the screening result seems to be more J-Calibration than SBE-Calibration due to smaller dispersion. Although the laboratory environments and seasons are different between the two screening experiments, J-Calibration provides the same stability as SBE-Calibration based on the F-RMS results.

Evaluation of J-Calibration based on QCed deployed float data

Argo data quality control is generally carried out with nearby shipboard CTD data and other Argo float data to validate the Argo float data and to place a rQC and dQC flag, based on the rQC and dQC procedures as mentioned in the "Introduction" section. Here, we confirm whether the results of J-Calibration are appropriate to compare with the results of Argo float quality control. Although the dQC described in the "Introduction" section is conducted after 6 months ~ 1 year to check whether the Argo data meets its criteria, we carried out the same dQC procedures within 6 months to check the result of J-Calibration. However, we cannot address the issue of long-term drift in conductivity data using this method.

Table 12 shows a status list of deployed floats which had J-Calibration conducted in advance, the number of which is 16 of 33 floats until August 2018. As a result, all 16 floats conducting J-Calibration can be validated using the results of the data quality check. Regarding S/N 8262 (WMOID 2903348) and 8263 (2903349), the data quality check can be completed after profile no. 17, and the quality of data was found to be within the range of the Argo criteria. This indicates that the results of J-Calibration are appropriate, although the first profile in both floats was not collected. Regarding S/N 414 (WMOID 2902974) and 672 (5905056), the data quality check can be done from profile no. 1 even though there was a buoyancy system failure, as the ability to obtain healthy data was not impaired. S/N 415, 416, and 417 are labeled as "positive salinity drift" or "gray list," as these profiles are out of range of Argo accuracy and uncorrectable within the framework of Argo data flow. Profiles which were within the Argo accuracy criteria for at least the before profile were nos.

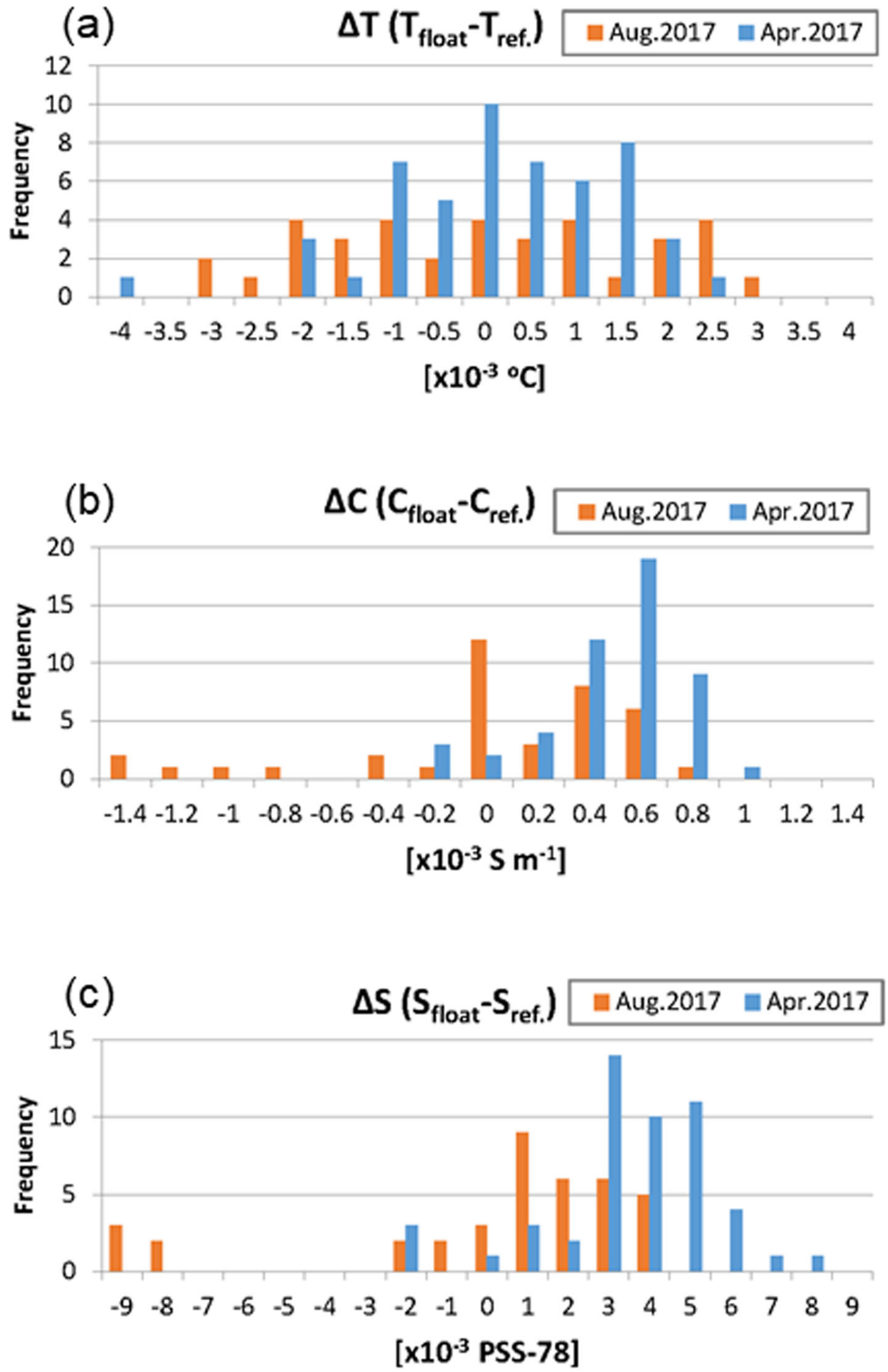

Fig. 13 Histograms of differences for temperature (**a**), conductivity (**b**), and salinity (**c**) in different seasons (April, winter; August, summer) in all 88 experiments of J-Calibration. Averages of ΔT, ΔC, and ΔS in April/August are – 0.00009/– 0.00023 °C, 0.00035/– 0.000004 S m^{-1}, and 0.00282/– 0.00012 PSS-78, respectively. Standard deviations of ΔT, ΔC, and ΔS in April/August are 0.00124/0.00171 °C, 0.00032/0.00057 S m^{-1}, and 0.00224/ 0.00381 PSS-78, respectively

30, 39, and 20, respectively. Since we can judge that such error profiles with salinity drift or on the gray list are posteriori errors, the results of J-Calibration for the three floats are still appropriate. Although it is necessary to judge accuracy by comparing J-Calibration results with dQC Argo float data for

Table 10 Information of used data of SBE-Calibration and J-Calibration to estimate F-RMS

	SBE-Calibration	J-Calibration
Float type	Arvor (nke inc)	Navis (SBE), APEX (TWR)
No. of examined floats	18	33
No. of calibration test	83	88
Frequency of calibration test	61	27
Period	April 11, 2012–February 8, 2013	August 14, 2017–August 24, 2017

greater than 6 months, the results indicate that salinity values are still satisfied within the Argo accuracy criteria in all normal operational floats without any software/hardware failure in temperature and salinity.

Therefore, we conclude that the results of J-Calibration correspond to that of the dQC process, suggesting that J-Calibration is effective to avoid deployment of the Argo float with faulty sensors.

Diagnostic of small positive salinity bias appeared in J-Calibration results

The small positive salinity bias ($+0.2\sim0.4\times10^{-3}$ S m^{-1}) in J-Calibration (< 0.01 PSS-78) shown in Fig. 10 is diagnosed in this section. We conducted calibration of SBE3 and 4 standard sensors of temperature and salinity by returning any with faults to the manufacturer SBE every year. After the calibration by the manufacturer, coefficients of calibration functions are occasionally modified based on the calibration of SBE.

The amount of salinity sensor drift based on the manufacturer's calibration is − 0.0048 PSS-78. Since the calibration was carried out in November 2018, the period of J-Calibration (April and August 2018) is about a half year before the manufacturer's calibration, and the amount of salinity bias correction is considerable at − 0.0024 PSS-78 if we assume that this value was drifting linearly for a year. Therefore, the standard conductivity sensor had a negative bias. As a result, it is possible to that about a half of the total positive salinity bias is from standard sensors (average in + 0.0033 PSS-78), suggesting that the method of J-Calibration is still appropriate even though it includes negative bias from the standard sensors. However, a small positive bias still remained. We also checked and monitored the possibility of a very small change in salinity concentration during the flow of artificial seawater through the tubes using the auto salinometer "Autosal" (Guildline instruments 1981). However, this did not detect any significant salinity bias that could explain the positive salinity bias. Further investigation of the salinity bias is required to improve the J-Calibration system.

Possible applications to other fields

All Earth Sciences fields encounter similar themes of difficulty in collecting high-quality and accurate data which can capture and reflect subtle changes over a long period of time. To implement such large-scale

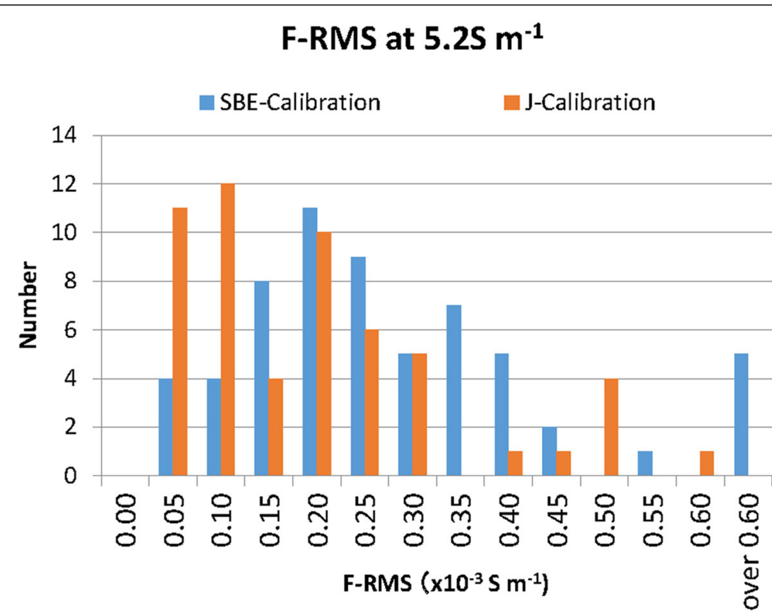

Fig. 14 Histograms of F-RMSs in J-Calibration (orange) and SBE-Calibration (blue) at 5.2 S m^{-1} (22 °C). Bin of F-RMS is 0.05×10^{-3} S m^{-1}. Values close to 0 for F-RMS mean a small fluctuation of calibration

Table 11 Statistical values of F-RMSs for SBE-Calibration and J-Calibration

	No. of experiments	No. of floats	Average ($\times 10^{-3}$ S m^{-1})	Median ($\times 10^{-3}$ S m^{-1})	Standard deviation ($\times 10^{-3}$ S m^{-1})
SBE-Calibration	61	18	0.27	0.23	0.22
J-Calibration	27	33	0.20	0.18	0.17

observations, the use of autonomous observation robots is effective for decreasing human resources and costs, although this does introduce the possibility of hardware or software errors. Also, this technology is required to operate under extreme environments such as in the deep ocean which has high pressures and low temperatures. These extreme elements also introduce the complication of mechanical failures. Therefore, all of these factors could decrease the reliability of the collected data resulting in inaccurate conclusions. To avoid misleading data, quality management must be employed. This was the goal of our development of a calibration system such a J-Calibration which could introduce pre-deployment calibration.

We have shown J-Calibration to be effective in decreasing the time needed to achieve calibration and to not require the detachment of the CTD sensor unit from the Argo float, thereby avoiding float warranty issues. As well, J-Calibration is non-inferior to SBE-Calibration with respect to accuracy. We hope that the methods and investigations which we have demonstrated in developing this calibration method, such as international collaboration and collaboration between the user and the manufacturer, can be extrapolated to other fields in Earth Sciences.

Conclusions

We developed an efficient method of pre-deployment calibration for the SBE41 CTD sensor (J-Calibration). In comparison with the previous standard calibration method that is normally operated by the SBE manufacturer, there are some advantages. That is, no need for specially skilled technicians, shorter time for calibration, and increased efficiency, summarized in Table 13. The development is successful in that the screening procedure of SBE41 sensors is more efficient than before, and it is therefore possible to screen a larger number of sensors. An important consideration in the

Table 12 List of deployed floats and their status that J-Calibration has been conducted (as of August 29, 2019)

Type	Float no.	WMO ID	Sensor S/N	Deployment date	Deployment position	Profile no.	Data quality check
APEX	7907	5905231	8530	May 17, 2018	21.3 N, 176.5 E	48	Healthy data in normal operation.
APEX	8084	2903211	9344	October 4, 2017	38.0 N, 145.0 E	71	Healthy data in normal operation.
APEX	8085	2903346	9345	May 20, 2018	30.0 N, 151.0 E	49	Healthy data in normal operation.
APEX	8086	2903347	9348	May 23, 2018	24.0 N, 165.0 E	48	Healthy data in normal operation.
APEX	8262	2903348	9444	May 26, 2018	32.4 N, 146.1 E	47	Healthy data in normal operation except for prof. no. ~ 17 which were no delivered data due to float trouble.
APEX	8263	2903349	9465	May 28, 2018	39.5 N, 145.5 E	46	Healthy data in normal operation except for prof. no.~ 17 which were no delivered data due to float trouble.
Navis	414	2902974	6167	June 10, 2016	40.1 N, 170.0 E	285	Healthy data but unstable control due to buoyancy system failure.
Navis	415	5905051	6128	February 20, 2017	58.0 S, 126.0 W	92	Healthy data but positive salinity drift after prof.no. 30.
Navis	416	4902368	6236	July 17, 2016	50.6 N, 144.8 W	115	Healthy data but flagged in gray list after prof. no. 39.
Navis	417	4902369	6151	July 16, 2018	51.0 N, 148.4 W	114	Healthy data but positive salinity drift after prof. no. 20.
Navis	583	5905050	7507	August 21, 2016	6.1 N, 165.0 E	111	Healthy data in normal operation.
Navis	584	5905221	7624	March 1, 2018	17.0 N, 140.3 E	260	Healthy data in normal operation.
Navis	588	5905060	7955	September 20, 2017	23.0 N, 170.0 E	167	Healthy data in normal operation.
Navis	628	5905059	8002	September 14, 2017	21.5 N, 170.0 W	167	Healthy data in normal operation.
Navis	672	5905056	8086	August 1, 2017	17.0 N, 149.0 E	345	Healthy data but unstable control due to buoyancy system failure.
Navis	675	5905058	8091	August 31, 2017	23.0 N, 150.0 W	170	Healthy data in normal operation.

Table 13 Comparison of work time and difficulty of J-Calibration and SBE-Calibration. Unit is hours

	J-Calibration	SBE-Calibration
Preparation	1	4
Calibration	0.5 (1 point)	14 (7 point)
Post-calibration	0.5	6
Total	2	24
Difficulty	Simple	Difficult

development is that the temperature of calibration is changed from 7 to 1 based on our experiences. As it is necessary to deploy a large number of 800 Argo floats to achieve sustainability under the framework of the international Argo program, the J-Calibration system is advantageous as it helps to avoid the deployment of floats with faulty sensors. Another point is to control room and water temperature appropriately during calibration experiments by applying some devices and materials. Those applications help the J-Calibration system to become stable and to improve its accuracy.

On the other hand, some improvements in J-Calibration still remain. For example, a small positive bias is still observed in comparison with SBE-Calibration as described in the "Results" and "Discussion" sections. Although correction of standard sensor bias is done with a half positive bias, further investigation of the J-Calibration system is needed to improve the system.

As technical progress is ongoing with the Argo floats, the Argo community recognizes more than previously that checks of Argo floats and screening of sensors before deployment are both important to improve and maintain the global Argo array. Continued improvements will require discussion with scientists, technicians, and manufacturers in the Argo Technical workshop (King et al. 2017). An efficient system for SBE41 users, like J-Calibration, must be broadly used in the Argo community and its standardization will be required in the near future. Further, with the improvement and promotion of pre-calibration systems such as J-Calibration, the volume of erroneous data will decrease and small climate signals in the ocean will be detected more accurately. This will make a significant contribution to our knowledge of climate change and the accuracy of climate change predictions.

Abbreviations

ALACE: Autonomous Lagrangian circulation explorer; CTD: Conductivity, Temperature, and Depth device; dQC: Delayed mode quality control; F-RMS: Frequency of root mean square; RMS: Root mean square; rQC: Real-time mode quality control

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Authors' contributions

SH proposed the topic, conceived, and designed the study. MH developed the system and organized the technicians for the experimental study. TH carried out the experiments, suggested the modification of system, and analyzed the data. SA helped to construct the system, carried out the experiments, and analyzed the data. NK supported the experiments and analyses. All authors read and approved the final manuscript.

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Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study. Please contact the corresponding author for data requests.

Competing interests

The authors declare that they have no competing interests.

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