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Short Contribution

Stability of Temperature and Conductivity Sensors of Argo Profiling Floats

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After recalibration of the temperature and conductivity sensors of three Argo profiling floats recovered after operations for four to nine months, the results indicate that the floats basically showed no significant drift, either in temperature or salinity, and adequately fulfilled the accuracy requirement of the Argo project (0.005°C for temperature and 0.01 psu for salinity). Only the third float showed a significant offset in salinity of about –0.02 psu, as expected from comparison between the float data and the shipboard conductivity-temperature-depth data. This offset was caused by the operational error of the PROVOR-type float, in which the surface water was pumped immediately after the launch, fouling the conductivity sensor cell.

Keywords:
· Argo project,
· profiling float,
· sensor stability.

1. Introduction

An international project, Argo, has been under way since 2000 (Argo Science Team, 2000). In this project roughly 3000 profiling floats will be deployed over the world ocean during several years, in order to build a real-time monitoring system of temperature and salinity in the subsurface and middle layers. By April 2003 about 770 Argo floats had been deployed by 15 countries and unions, about 130 of them by Japan. The Japanese float observation system is implemented by the Frontier Observational Research System for Global Change and the Japan Marine Science and Technology Center (JAMSTEC) in cooperation with other agencies (Iwasaka *et al*., 2003).

Argo floats drift freely at a predetermined parking depth, which is typically 2000 decibars, rising up to the sea surface every ten days by changing their volume and buoyancy. During the ascent they measure temperature, salinity, and pressure with a conductivity-temperature-depth (CTD) sensor module. They send the observed temperature and salinity data, obtained at about 70 sampling depths, to satellites during their stay at the sea surface, and then return to the parking depth. The floats' battery capacity is equivalent to more than 150 CTD profiles, which determines their lifetime of about four years.

The accuracy requirement of the float measurements in Argo is 0.005°C for temperature and 0.01 practical salinity units (psu) for salinity. The temperature requirement is relatively easy to attain, while that for salinity is not easy, due to drift of the conductivity sensor. As recalibration of the float sensors is generally not possible, the equivalent drift in salinity is usually checked by an indirect method, viz., by comparing the salinities from floats with those obtained from climatology or measured by a shipboard high-resolution CTD. This comparison is done on deep isotherms near the parking depth, assuring that the temperature sensor of the floats shows no drift and that salinity on the deep isotherms is almost steady and uniform (e.g., Iwasaka *et al*., 2003; Riser and Swift, 2003).

This method is useful, but it has limitations. First, it cannot detect an equivalent drift in salinity smaller than about 0.01 psu, since salinity on the deep isotherms varies both temporally and spatially by that magnitude (T. Kobayashi, personal communication). Furthermore, the temperature sensor of the floats actually shows some drift, causing an equivalent drift in salinity, but such a drift in temperature and salinity, of course, cannot be examined by this method. In order to assess accurately both the temperature and salinity drifts of an operating float, we

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Table 1. Status of the recovered floats. WMO ID is a World Meteorological Organization identifier.

	Float 1	Float 2	Float 3
Float type	APEX	PROVOR	PROVOR
CTD sensor module	SBE-41	SBE-41CP	SBE-41CP
WMO ID	29050	—	2900186
Parking depth (decibar)	2,000	2,000	2,000
Cycle (days)	10	3	10
Date of launch	17-Feb-01	13-Oct-01	30-Jan-02
Date of recovery	24-Nov-01	28-Mar-02	09-Jun-02
Period (days)	280	166	130
Number of CTD profiles	28	8	13
Remarks	Normal operation	Surface drift after 8th ascent	Normal operation

needed to recover the float and recalibrate its temperature and conductivity sensors.

Riser and Swift (2003) reported recovery of three profiling floats. One of these, the PALACE type manufactured by Webb Research Corporation, was recovered in summer 2000 after operating for three years in the North Atlantic. The other two, both of the APEX type supplied by Webb, were picked up by fishing boats in spring 2000 after operating for five and six months in the Japan Sea. Recalibration of the sensors of these floats, all of the SBE-41 type supplied by Sea-Bird Electronics, Inc., showed that the equivalent drift in salinity is 0.005–0.006 psu. This value is substantially smaller than the Argo accuracy requirement, implying that the float sensors remain satisfactorily stable during long-term measurement periods.

Since November 2001 we have recovered three Argo floats after operations for four to nine months, as one of the activities of Japanese Argo (Oka *et al*., 2002). At the time of recovery, two of the floats were operating normally, while the other was drifting on the sea surface after an emergency ascent. The temperature and conductivity sensors of these floats were recalibrated. This paper reports the results of recalibration and discusses their implications for the Argo data management. The status of the recovered floats is explained in Section 2. The results of recalibration are given in Section 3, and a summary and discussion are given in Section 4.

2. Status of Recovered Floats

We recovered three profiling floats in November 2001 and March and June 2002 (Oka *et al*., 2002). They are called Floats 1–3 in order of recovery date in this paper (Table 1). Float 1 is an APEX type manufactured by Webb Research Corporation, equipped with an SBE-41 sensor module supplied by Sea-Bird Electronics, Inc. Both Floats 2 and 3 are of the PROVOR type manufactured by METOCEAN Data Systems Limited, equipped with a SBE-41CP sensor module supplied by Sea-Bird. Floats 1 and 3 are Argo floats with World Meteorological Organization (WMO) ID 29050 and 2900186, respectively, while Float 2 is a test float with no WMO ID.

All the floats were deployed in the North Pacific, not far from Honshu (the main island of Japan) (Fig. 1). Float 1 (3) was launched in February 2001 (January 2002) and made repeated CTD measurements at ten-day intervals for about nine (four) months until recovery. Float 2 was launched in October 2001 and made repeated measurements at three-day intervals, but made an emergency ascent two and a half days after its seventh ascent, probably because its buoyancy control failed, causing it to overshoot the critical depth of 2200 decibars and thus triggering the emergency ascent. The float subsequently drifted on the sea surface for about five months until recovery. It is worth noting that at the time of recovery the waterline of the float was much higher than the normal state, due to the weight of shellfishes attached during the surface drift. It was estimated from a subsequent laboratory experiment that the float would sink beneath the water in about one month, that is, a half year from the start of the surface drift (Oka *et al*., 2002; Mizuno, 2003).

Float 3 had had a problem measuring salinity since its first ascent. Figure 2(a) shows a temperature-salinity profile measured by the shipboard CTD just before this float was launched, and that measured by the float during its first ascent ten days later. The profile reported by the float is located on the less saline side of that given by the shipboard CTD throughout the temperature range, except in the surface mixed layer around 19.3°C. The difference in salinity on isotherms between the float and the shipboard CTD is mostly negative between –0.043 psu and 0.002 psu in a temperature range less than 19°C, and is

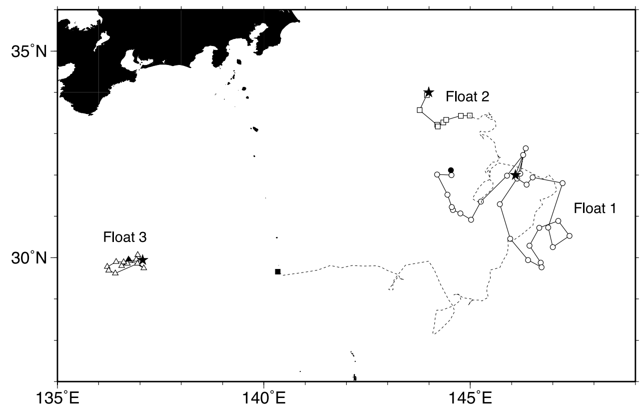

Fig. 1. Trajectories of Floats 1–3. Closed stars show float launching points. Open (closed) circles, squares, and triangles indicate points of the CTD measurements (recovery) of Floats 1–3, respectively. Dashed line for Float 2 shows the trajectory during surface drift after emergency ascent.

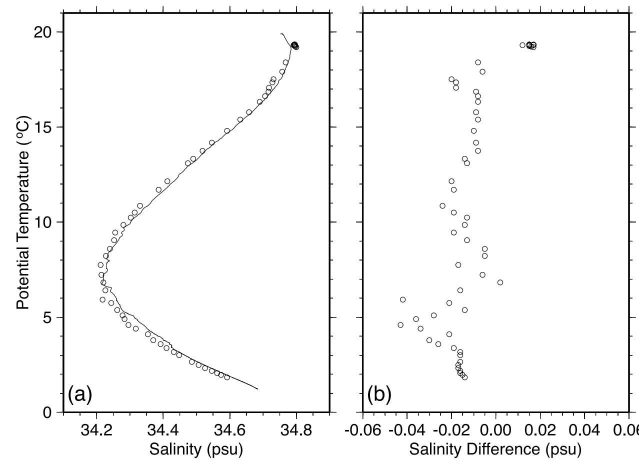

Fig. 2. (a) Temperature-salinity profile measured by FSI Triton CTD of Falmouth Scientific, Inc. aboard R/V Ryofu-maru of the Japan Meteorological Agency on 30 Jan. 2002 just before the launch of Float 3 (solid line) and that measured by Float 3 during its first ascent on 9 Feb. 2002 (circles). (b) Difference in the salinity on isotherms between Float 3 and the FSI Triton CTD (float minus FSI Triton).

coherently between –0.019 psu and –0.014 psu at temperatures <3.5°C in particular, despite the short intervals of ten days in time and 18 kilometers in space between the two measurements (Fig. 2(b)). This difference implies an equivalent offset in the float salinity of about –0.02 psu, which is believed to have occurred in the short period between the launch and the first ascent. The float salinity reported in the succeeding ascents was also lower than the shipboard CTD salinity at the time of launch by about 0.02 psu on deep isotherms (not shown), indicating a salinity offset of about –0.02 psu.

3. Results of Recalibration

After recovery of Floats 1 and 3, the sensors were recalibrated at JAMSTEC. Using the calibration bath at JAMSTEC, manufactured by Sea-Bird, we can simultaneously calibrate both temperature and conductivity sensors of a float, in ranges of 1–32°C and 3–6 siemens/m, respectively (Inoue *et al*., 2002). We estimate that the precision of our calibration is 2×10^{-3}°C for temperature and 3×10^{-3} psu for equivalent salinity, as follows: in the temperature calibration the accuracy (1×10^{-3}°C) of the reference sensor and the nonuniformity (1.7×10^{-3}°C) of the temperature distribution in the bath (Inoue *et al*., 2002) affect the calibration uncertainty, resulting in a total error of 2×10^{-3}°C, which is the square root of the sum of squares of the errors. The total error of 3×10^{-3} psu in equivalent salinity results from the equivalent error (2×10^{-3} psu) of the temperature calibration, the accuracy (2×10^{-3} psu in equivalent salinity) of the conductivity reference sensor, and the uncertainty (2×10^{-3} psu) related to the water sampling and the Autosal measurements. The sensor of Float 2 was sent to Sea-Bird after recovery and was calibrated there. As the precision of calibration at Sea-Bird is thought to be comparable to that at JAMSTEC (N. Larson, personal communication), all the sensors were calibrated with the same precision. The calibrations were conducted twice within a few days for each of Floats 1–3 in order to confirm the results.

Figure 3 (Fig. 4) shows residuals in temperature, conductivity, and equivalent salinity relative to the reference sensors of the calibration bath for Float 1 (2). The temperature sensor of Float 1 indicates higher values than the reference sensor by 1.1–2.0 $\times 10^{-3}$°C, while that of Float 2 shows lower values by 0.7–1.9 $\times 10^{-3}$°C. The conductivity sensor of both Floats 1 and 2 indicates lower values than the reference sensor by 1.0–4.4 $\times 10^{-4}$ siemens/m and 1.7–7.6 $\times 10^{-4}$ siemens/m, respectively, to a greater degree as the reference conductivity increases. As a result, the floats indicate lower values of salinity than the reference sensors by 2.5–4.7 $\times 10^{-3}$ psu and 1.1–3.7 $\times 10^{-3}$ psu. These residuals in temperature and salinity for both floats are comparable in magnitude to the precisions of calibration. It is therefore concluded that the floats did not show significant drift, either in temperature or salinity, during the operations for nine and six months. The floats adequately fulfill the accuracy requirement of Argo.

The temperature (conductivity) sensor of Float 3 indicates higher (lower) values than the reference sensor by 0.2–1.6 $\times 10^{-3}$°C (1.4–3.1 $\times 10^{-3}$ siemens/m), resulting in lower values of salinity by 1.7–2.1 $\times 10^{-2}$ psu (Fig. 5). The residual in temperature is comparable in magnitude to the precision of calibration, which shows that the

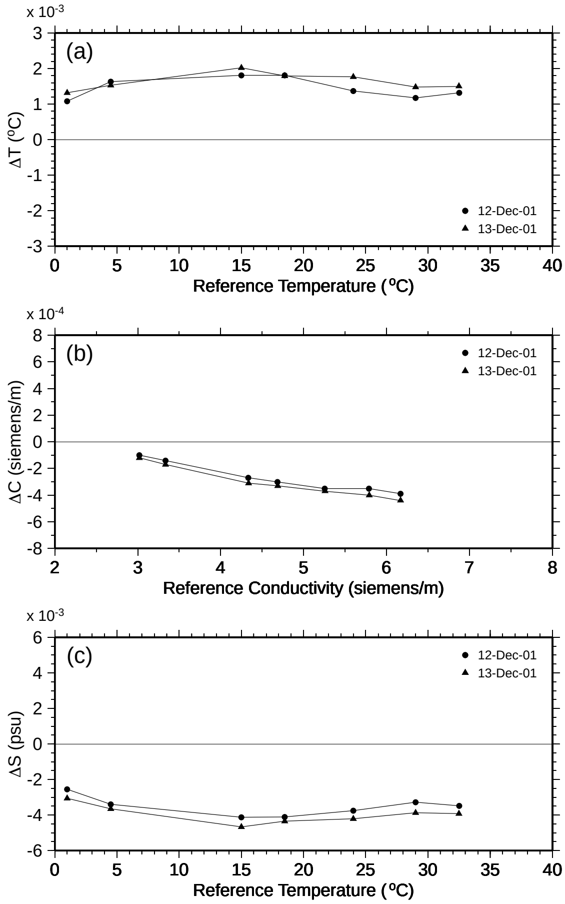

Fig. 3. Results of sensor calibration for Float 1, conducted twice in December 2001 at JAMSTEC. (a) Residual in temperature (ΔT) relative to the reference sensor of calibration bath, as a function of the reference temperature. (b) As (a) but for conductivity (ΔC), as a function of the reference conductivity. (c) As (a) but for equivalent salinity (ΔS) calculated from the temperature and the conductivity.

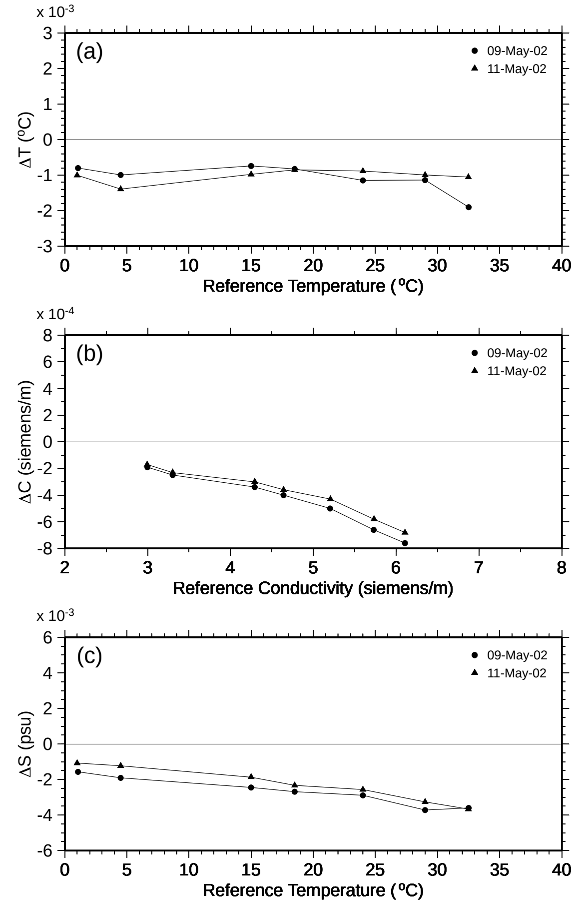

Fig. 4. As Fig. 3 but for Float 2 in May 2002 at Sea-Bird Electronics, Inc.

temperature sensor did not show significant drift during the operation for four months. However, the residual in salinity is about five times greater than the precision of calibration, which means that the float showed a significant offset in equivalent salinity about double the accuracy requirement of Argo, mostly due to an offset of the conductivity sensor. The calibration result coincides with the estimation of salinity offset by comparison between the float data and the shipboard CTD data mentioned in the previous section.

After the recovery of Float 3 we sought the cause of the conductivity sensor offset and found an operational error of the PROVOR float: the pump of the CTD sensor module operated while the float remained at the sea surface for 3–4 hours immediately after the launch. The pumped surface water must have fouled the cell of the conductivity sensor. We accordingly modified the firmware of PROVOR floats to stop the pump operating at the sea surface, and since then this problem has not reoccurred.

4. Summary and Discussion

Three Argo profiling floats were recovered after operating for four to nine months and their temperature and conductivity sensors were recalibrated. The recalibration results indicate that the floats basically showed no significant drift, either in temperature or salinity, during the operations, and adequately fulfilled the accuracy requirement of Argo, comparable to the floats of Riser and Swift (2003). Only Float 3 showed a significant offset in salinity of about –0.02 psu, caused by an operational error of the PROVOR float, in which the pump of the CTD sensor module operated at the sea surface immediately after the launch, allowing the pumped surface water to foul the conductivity sensor cell. The recalibration result for Float 3 coincides with our estimation of salinity offset

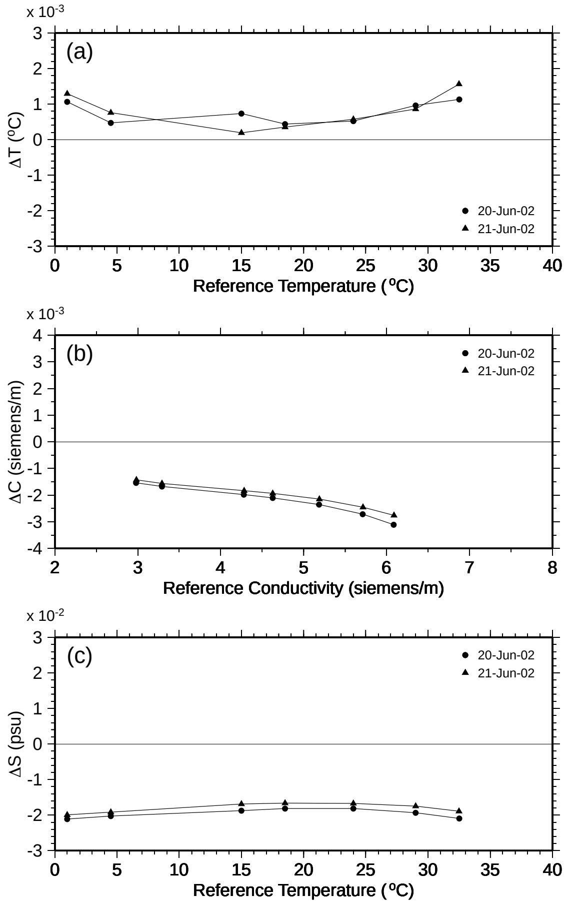

Fig. 5. As Fig. 3 but for Float 3 in June 2002.

using the shipboard CTD data at the time of launch.

As both the float type and the CTD sensor module are the same in Floats 2 and 3, the sensor fouling immediately after the launch could also have happened to Float 2. This did not actually happen, probably because the surface water at the launch point was sufficiently clean. The conductivity sensor of Float 2 did not show significant drift, even after drifting on the surface for five months. This was probably because the sensor module pump was inoperative and the antifouling biocide in the module was effective during the surface drift. In Argo we have tried to minimize the time of a float's surface stay to prevent sensor fouling, but the case of Float 2 may imply that the surface period does not significantly influence the sensors as long as the pump is inoperative at that time.

In the present study we did not recalibrate the pressure sensor of the floats, any drift of which also causes an equivalent drift in salinity. Our experience with about 160 Japanese floats shows that pressure measured by the floats at the sea surface in every observational cycle, which is equal to the offset of the pressure sensor at the sea surface, has a magnitude of less than several decibars and the resultant drift in salinity is less than $2–3 \times 10^{-3}$ psu in most cases (H. Nakajima, personal communication). Furthermore, the depth-independent portion of the pressure offset can be corrected using the surface pressure. We assume that this correction decreases the influence of the pressure drift on the salinity measurements to a point where it can be neglected.

As Argo floats are designed to operate for more than four years, the results of the present study may be insufficient to conclude that the float sensors will operate stably during the entire operational period. If one supposes that the residuals for Floats 1 and 2 (Figs. 3 and 4) are accurate and increase linearly with time, the resultant drifts exceed the accuracy requirement of Argo, not only for salinity but also for temperature. Our efforts to recover the floats, particularly those in operation for a few years, should be continued to clarify the cause of long-term sensor drift and to establish a method for correcting the observed data.

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