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Short Contribution

Long-term Sensor Drift Found in Recovered Argo Profiling Floats

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We recovered three Argo profiling floats after 2 to 2.5 years of operation, and recalibrated their temperature, conductivity, and pressure sensors. The results demonstrate that these floats exhibited a significant drift in salinity of –0.0074 to –0.0125, primarily due to the conductivity sensor drift. Combined with the recalibration result for another previously recovered float, the indication is that the negative salinity drift increases nearly in proportion to the operating period of floats. The increasing rate is –0.0041 (±0.0015) year^{-1}, which yields a salinity drift of –0.016 (±0.006) for the expected float lifetime of four years. The present result suggests that reducing the float surfacing time would improve the accuracy of the salinity measurements.

Keywords:
· Argo,
· profiling float,
· sensor drift.

1. Introduction

Argo, an international project to deploy 3000 profiling floats over the global oceans to build a real-time monitoring system of temperature and salinity in the subsurface and middle layers, has been under way since 2000 (Argo Science Team, 2001). As of July 2004, 1300 floats are in operation, deployed by 17 countries and the European Union. The global float array is scheduled to be complete around 2007.

Argo floats drift freely at a predetermined parking pressure (typically 2000 dbar), and ascend to the sea surface at a predetermined interval (10 days) by increasing the volume of the external hydraulic bladder and thus increasing the buoyancy. During the ascent they measure temperature, conductivity, and pressure with a conductivity-temperature-depth (CTD) sensor module. While staying at the sea surface for roughly half a day, they transmit the temperature and computed salinity data at 60 to 110 sampling pressures to satellites, whereby their positions are also fixed. The battery capacity allows them to repeat 150 observation cycles, which is equivalent to an operating period of four years.

The data from Argo floats are freely available, and are utilized for the studies of mixed layer variation (e.g., Ohno *et al.*, 2004; Sato *et al.*, 2004), water mass formation and variation (e.g., Wong and Johnson, 2003; Uehara *et al.*, 2003; Oka and Suga, 2003), mid-depth circulation (e.g., Johnson *et al.*, 2004), heat and fresh water transports, etc. They are also exploited in data assimilation for climate prediction. The float network is particularly effective for wintertime mid-to-high latitude oceans, where shipboard CTD observations are difficult due to rough sea conditions.

The temperature and pressure sensors of Argo floats are considered relatively stable, while their conductivity sensor is considered vulnerable to bio-fouling, which causes a long-term drift in salinity (Davis, 1998). Since recovery of floats is not easy and recalibration of their sensors is usually not performed, salinities measured by floats are evaluated and, if needed, corrected by a delayed-mode calibration system established by Wong *et al.* (2003), which uses climatological potential temperature-salinity (θ-S) relations. In this system, the float salinities are compared with the climatological values on deep isotherms near the parking pressure, where θ-S relations are stable and well defined, assuming that the floats' temperature and pressure sensors have no drift.

This system works adequately for a salinity drift much greater than 0.01 (Kobayashi and Minato, 2005), which is the accuracy requirement of Argo (Argo Science Team, 2000). However, it cannot detect a drift of about 0.01 or less, due to temporal and spatial variation of salinity on the deep isotherms and to error in the historical data. Such a small drift may be negligible, particularly in

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the study of upper ocean processes, but it may grow with time and exceed the accuracy requirement during the expected Argo float lifetime of four years. In addition, the floats' temperature and pressure sensors may actually have some drift, causing an equivalent drift in salinity, but such drifts cannot be estimated by the method of Wong *et al.* (2003). It is therefore important to recover operating floats and recalibrate their temperature, conductivity, and pressure sensors, to examine the tendency of long-term drift of these sensors and the resultant drift in salinity.

Operating floats have been recovered and their sensors recalibrated in two studies. Oka and Ando (2004) reported the recovery of three floats after four to nine months of operation. Two of these floats, equipped with an SBE-41 and SBE-41CP sensor module supplied by Sea-Bird Electronics, Inc. (Sea-Bird hereafter), exhibited a salinity offset of –0.002 to –0.004, that is, they indicated salinity values 0.002 to 0.004 lower than the reference sensors. Since the offset is comparable in magnitude to the precision of the calibration, Oka and Ando concluded that these floats did not exhibit significant salinity drift. The other float, equipped with an SBE-41CP sensor, indicated a salinity offset of –0.02. This offset was not a long-term occurrence; rather, it happened in a very short time just after float deployment, due to an operational error of the PROVOR type float (manufactured by METOCEAN Data System Limited), in which the surface water was pumped and fouled the conductivity sensor cell. Riser and Swift (2005) demonstrated that three floats, equipped with SBE-41 sensors, exhibited a salin-

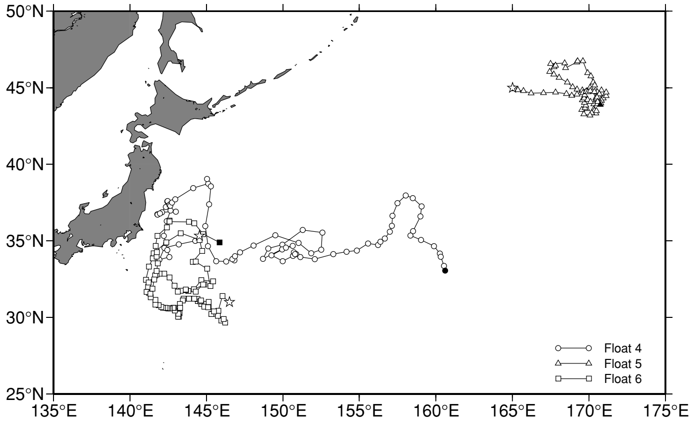

Fig. 1. Trajectories of Floats 4–6. Stars denote the deployment points. Circles, triangles, and squares indicate points of ascent for Floats 4–6. Black symbols denote points of the final ascent and recovery.

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

	Float 4	Float 5	Float 6
Float type	APEX	APEX	APEX
CTD sensor module	SBE-41	SBE-41	SBE-41
WMO ID	29045	2900056	29051
Parking pressure (dbar)	2,000	2,000	2,000
Ascent interval (days)	10	10	10
Surfacing time (hours)	8.5	8.5	8.5
Deployment date	16-Feb-01	14-Jun-01	17-Feb-01
Deployment location	35.332°N, 144.537°E	44.993°N, 165.009°E	31.005°N, 146.501°E
Recovery date	06-Jun-03	14-Jun-03	06-Aug-03
Recovery location	33.070°N, 160.621°E	43.886°N, 170.753°E	34.898°N, 145.865°E
Operation period (days)	840	730	900
Number of ascent	84	73	90

ity drift of magnitude 0.005 to 0.006, after operating for five and six months and three years. Thus, the floats recovered in the two studies, except for the third float of Oka and Ando (2004), have exhibited a salinity drift sufficiently smaller than 0.01. These floats, however, were mostly operating for a period much shorter than their expected lifetime of four years. Therefore, further recovery of floats, particularly those operating for much more than a year, was needed to investigate the long-term salinity drift.

In 2003, the Japanese Argo team recovered three operating Argo floats, successors to the three floats recovered in 2001 and 2002 (Oka and Ando, 2004). At the time of recovery, these floats had been operating for 2 to 2.5 years, which is a sufficiently long period for examining the long-term salinity drift. In this paper we report the results of the post-recovery sensor calibration for these floats and investigate the tendency of the long-term salinity drift. The status of the recovered floats is explained in Section 2. The results of post-recovery calibration are presented, and the trend of long-term salinity drift is investigated in Section 3. The accuracy of indirectly estimated drifts in salinity and pressure is examined in comparison with the calibration results in Section 4. A summary is given in Section 5.

2. Status of Recovered Floats

We recovered three Argo profiling floats in June and August 2003. They are called Floats 4–6 in this paper, in order of their recovery date (Table 1). All the floats are of the APEX type manufactured by Webb Research Corporation, equipped with an SBE-41 sensor module supplied by Sea-Bird. The SBE-41 pressure sensors are all of the Ametec type, which is among the three types used for SBE-41. The parking pressure and ascent interval of

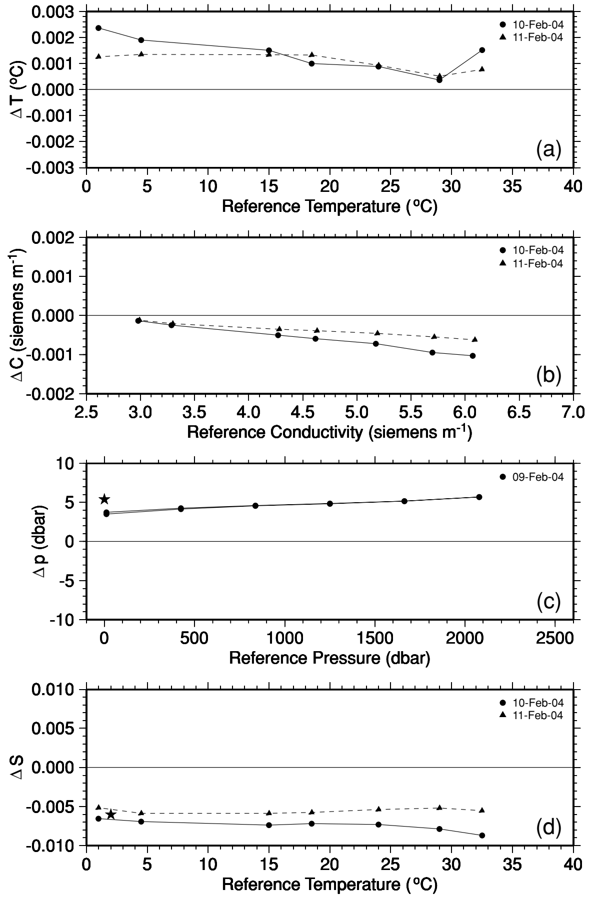

Fig. 2. Results of post-recovery sensor calibration for Float 4. (a) Residual in temperature (ΔT) relative to the reference temperature, as a function of the reference temperature. (b) As (a) but for conductivity (ΔC). (c) As (a) but for pressure (Δp). The star at 0 dbar indicates the sea surface pressure measured by this float, just before the start of the final descent, ten days before recovery. (d) As (a) but for equivalent salinity (ΔS), as a function of the reference temperature. The star at 2°C denotes an offset in equivalent salinity at the time of recovery, estimated using the shipboard CTD data presented in Fig. 6 (see text for details).

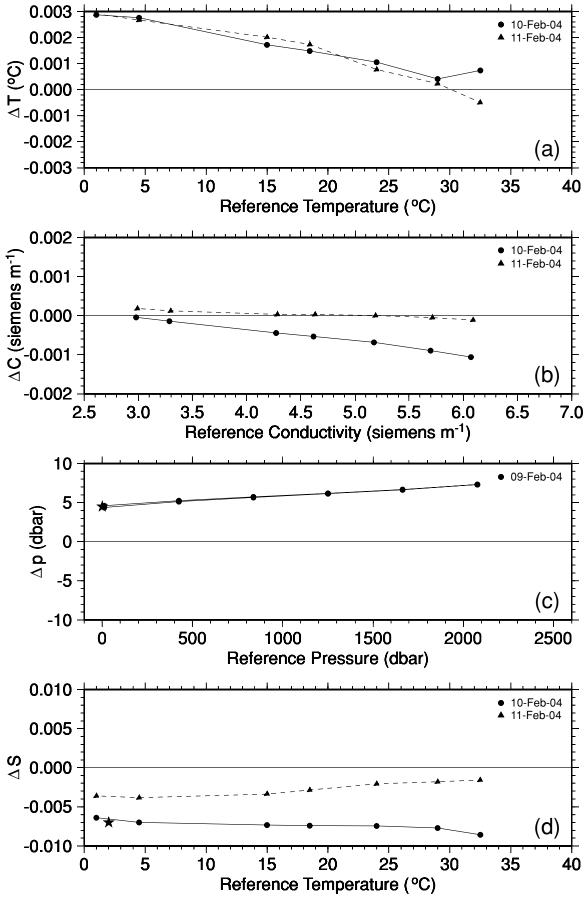

Fig. 3. As Fig. 2 but for Float 5.

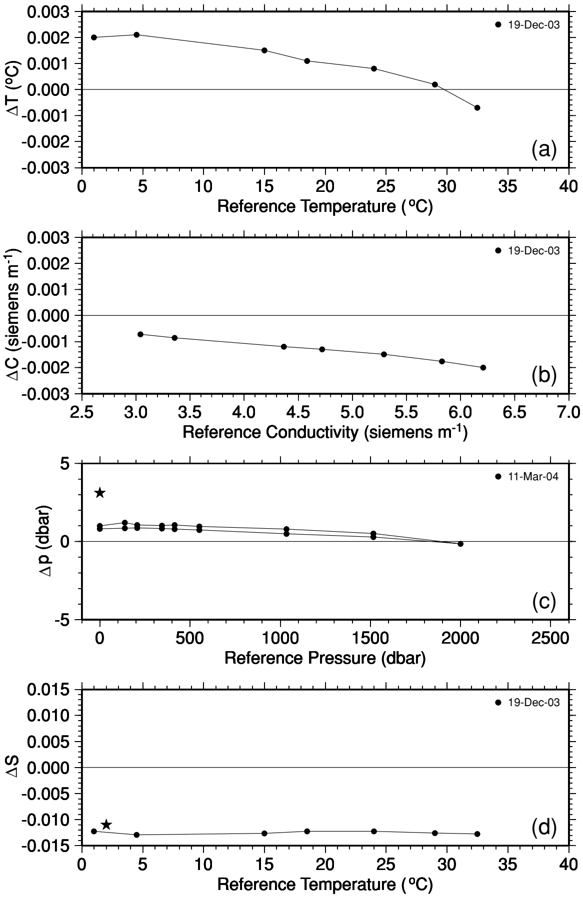

Fig. 4. As Fig. 2 but for Float 6.

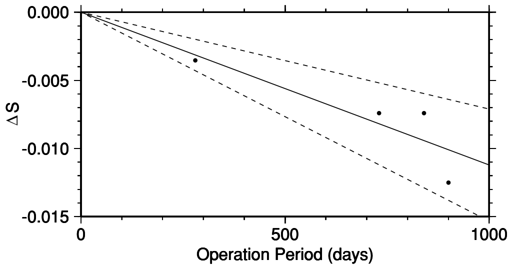

Fig. 5. Plots of the mean residual in equivalent salinity for the first post-recovery calibration (ΔS) against the operating period for Floats 1, 4, 5, and 6. The solid and dashed lines indicate the regression line through the origin and its 95% confidence interval.

these floats are set to 2000 dbar and 10 days. The surfacing time in each observation cycle is approximately 8.5 hours.

The floats were deployed in the western North Pacific, east of Japan (Fig. 1). They made 73 to 90 ascents during the operating period of 730 to 900 days. Each of them was searched and recovered during the final surfacing, in a procedure explained in Oka *et al.* (2002).

3. Results of Post-recovery Calibration

Post-recovery calibration of the temperature, conductivity, and pressure sensors of the recovered floats was performed at Sea-Bird for Floats 4 and 5 and at the Japan Marine Science and Technology Center (JAMSTEC, currently the Japan Agency for Marine-Earth Science and Technology) for Float 6. The precision of the calibration is 0.002°C for temperature and 0.003 for equivalent salinity, both at Sea-Bird and JAMSTEC (Inoue *et al.*, 2002; Oka and Ando, 2004). The precision for pressure is 0.3 dbar at Sea-Bird (Ken Lawson, personal communication), while it is 0.2 dbar at JAMSTEC (Ueki and Nagahama, 2005).

The first post-recovery calibration demonstrates that the temperature offset for Floats 4–6, which is the difference of indications between the float and reference sensors, is mostly positive, being smaller at high temperature, and has a mean and standard deviation of 1.36 (±0.62), 1.58 (±0.88), and 1.00 (±0.93) × 10^{-3}°C (Figs. 2–4, Table 2). The conductivity offset is all negative, being larger in magnitude at high conductivity, with –0.60 (±0.31), –0.54 (±0.34), and –1.33 (±0.43) × 10^{-3} siemens m^{-1}. The pressure offset for Floats 4 and 5 is positive, being slightly larger at high pressure, with 4.68 (±0.66) and 5.92 (±0.93) dbar, while that for Float 6 is small, with 0.72 (±0.36) dbar. The offset in equivalent salinity was calculated for each calibration point, using the temperature and conductivity indications and the pressure indications at 0 dbar from the float and reference sensors. The offset for Floats 4–6 is all negative, being slightly larger in magnitude at high temperature, with –7.40 (±0.64), –7.40 (±0.62), and –12.51 (±0.25) × 10^{-3}.

The temperature offset for the three floats is within the precision of the calibration, except for the value at 1°C for Float 4 and the two values at 1° and 4.5°C for Float 5. These floats therefore generally did not exhibit significant drift in temperature, comparable to our three previously recovered floats (Oka and Ando, 2004). However, the offset in equivalent salinity is much greater in magnitude than the precision. The floats exhibited a significant drift in equivalent salinity, in contrast with our previously recovered floats. The pressure offset also greatly exceeds the precision, and is significant.

We also calculated an offset in equivalent salinity, assuming that only one of the offsets in temperature, conductivity, and pressure exists (denoted by ΔS_T, ΔS_C, and ΔS_p in Table 2). The sum of these quantities almost equals the original offset in equivalent salinity (ΔS) for each calibration point (not shown). For each of Floats 4–6, means of ΔS_T, ΔS_C, and ΔS_p are all negative. That is, the positive drifts in temperature and pressure and the nega-

Table 2. Summary of the post-recovery calibration results for Floats 4–6. (a) Means (standard deviations) of the residual in temperature (ΔT), conductivity (ΔC), and equivalent salinity (ΔS). The mean and standard deviation were calculated for the seven points of each calibration. ΔS_T, ΔS_C, and ΔS_p denote means (standard deviations) of the residual in equivalent salinity, calculated assuming that only one of the offsets in temperature, conductivity, and pressure exists. (b) Means (standard deviations) of the residual in pressure (Δp), calculated for the six (nine) points of the calibration for Floats 4 and 5 (Floats 6).

(a)

	Date	ΔT (10^{-3}°C)	ΔC (10^{-3} siemens m^{-1})	ΔS (10^{-3})	ΔS_T (10^{-3})	ΔS_C (10^{-3})	ΔS_p (10^{-3})
Float 4	10-Feb-04	1.36 (0.62)	−0.60 (0.31)	−7.40 (0.64)	−1.26 (0.76)	−4.68 (1.69)	−1.45 (0.43)
	11-Feb-04	1.07 (0.31)	−0.39 (0.16)	−5.54 (0.28)	−0.97 (0.39)	−3.11 (0.78)	−1.45 (0.43)
Float 5	10-Feb-04	1.58 (0.88)	−0.54 (0.34)	−7.40 (0.62)	−1.51 (1.06)	−4.10 (2.14)	−1.79 (0.53)
	11-Feb-04	1.40 (1.18)	0.03 (0.09)	−2.72 (0.85)	−1.40 (1.25)	0.48 (0.99)	−1.80 (0.53)
Float 6	19-Dec-03	1.00 (0.93)	−1.33 (0.43)	−12.51 (0.25)	−1.02 (0.97)	−11.11 (1.11)	−0.37 (0.11)

(b)

	Date	Δp (dbar)
Float 4	09-Feb-04	4.68 (0.66)
Float 5	09-Feb-04	5.92 (0.93)
Float 6	11-Mar-04	0.72 (0.36)

tive drift in conductivity all contribute to the negative drift in equivalent salinity. While ΔS_T and ΔS_p are within the precision of the calibration, ΔS_C exceeds it. Thus, the negative salinity drift for the three floats is primarily due to the conductivity sensor drift, which is consistent with our previous experience.

The second post-recovery calibration for Floats 4 and 5 was performed after cleaning their conductivity sensor cell. The mean conductivity offset reduces to two-thirds of the first calibration for Float 4, and to nearly zero for Float 5 (Figs. 2 and 3, Table 2). The conductivity sensor of Float 5 almost recovered to the pre-deployment calibration after cleaning. These results indicate that the major part of the conductivity sensor drift is due to bio-fouling. The mean offset in equivalent salinity reduced from –7.40 to –5.54 × 10^{-3} for Float 4, and from –7.40 to –2.72 × 10^{-3} for Float 5.

The relation between the salinity drift and the operating period is examined for Floats 4–6 and our first previously recovered float (called Float 1 in Oka and Ando, 2004), which has the same CTD sensor module and the same operating parameters as Floats 4–6. Our second and third previously recovered floats (Floats 2 and 3) are not considered here, since the former operated in a rather different manner from the other floats, that is, it drifted at the sea surface for five months before recovery, in an emergency mode of the PROVOR type float, and the latter experienced a large salinity offset of –0.02 just after deployment, due to an operational error of the float, which is obviously different from the long-term salinity drift that is our present concern (Oka and Ando, 2004). The result for the four floats demonstrates that negative salinity drift increases nearly in proportion to the operating period (Fig. 5). When the regression line is fitted through the origin, it has a slope of –0.0041 (±0.0015) year^{-1}. At this rate, the salinity drift would reach –0.01 (the accuracy requirement of Argo) about 2.4 (1.7 to 3.9) years after the deployment, and –0.016 (±0.006) at the end of the expected float lifetime of four years. Since bio-fouling of the floats' conductivity sensor is considered to occur mostly at the sea surface, the negative salinity drift is expected to increase not only with the operating period of floats, but also with their total surfacing time. Therefore, the present result suggests that reducing the floats' surfacing time, which is currently 8.5 to 10.5 hours in each cycle for our typical floats, would improve the accuracy of the salinity measurements.

4. Accuracy of Indirectly Estimated Drift

4.1 Salinity drift

The Japanese Argo team conducts shipboard CTD measurements concurrently with the float deployment and the subsequent float measurements, if at all possible. The θ-S profiles obtained are compared with those obtained by floats, to check the accuracy of float salinities (e.g., Iwasaka *et al.*, 2003; Oka and Ando, 2004). This is a simplified version of the Wong *et al.* (2003) calibration system, and is widely performed for profiling floats over the world ocean (e.g., Bacon *et al.*, 2001).

Shipboard CTD measurements were conducted concurrently with the recovery of Floats 4–6 (Fig. 6). For each float, differences between a few float salinities near the parking pressure and the shipboard CTD salinities at the same θ were averaged and regarded as the float salinity drift, since the temperature drift is negligible, as shown in the previous section. The estimated salinity drifts for Floats 4–6 are –0.006, –0.007, and –0.011 (star in Figs. 2(d), 3(d), 4(d)). Each of them nearly coincides with the salinity drift at 1°C determined by the first post-recovery calibration. This demonstrates that the accuracy check of float salinities using nearby shipboard CTD data is precise and useful.

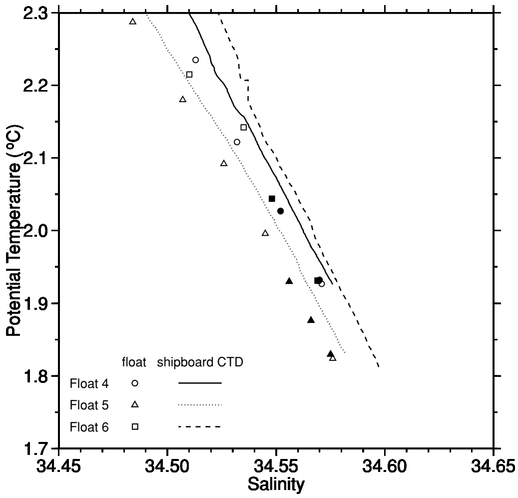

Fig. 6. Potential temperature–salinity profiles obtained by Floats 4–6 during their final ascent (symbols) and by a shipboard CTD at the time of their recovery (lines), for a temperature range less than 2.3°C. The float values denoted by black marks are used to estimate the salinity drift for these floats (see text for details).

4.2 Pressure sensor drift

Argo floats measure the sea surface pressure just before the start of each descent, and transmit the data during the next surfacing (Fig. 7). The surface pressure jumps by a few decibar through the first dive, and changes gradually afterwards. This gradual change is considered to primarily reflect long-term drift of the pressure sensor, since variation of the atmospheric pressure is much less than 0.5 dbar under normal conditions. The Japanese Argo team has used this surface pressure to correct float pressures, in which the former value is subtracted from the latter values for each profile. It was their view that this correction is adequate for float pressures near the sea surface to some extent, but may not be so for those in the subsurface, since the dependence of the pressure sensor drift on pressure down to 2000 dbar was unknown.

The first post-recovery calibration for Floats 4–6 demonstrates that the surface pressure measured by each float ten days before recovery agrees with the pressure sensor drift at 0 dbar, with a difference less than 2 dbar (Figs. 2(c), 3(c), 4(c)). Furthermore, the pressure sensor drift changes by less than 3 dbar between 0 and 2000 dbar. As a result, the sea surface pressure agrees with the pressure sensor drift at all depths, with differences less than 3 dbar. This agreement implies that our pressure correction using the surface pressure data can suppress the pressure error of Argo floats at all depths to less than a few dbar, and the resultant salinity error to less than about 0.002, a negligibly small amount.

5. Summary

We recovered three Argo profiling floats after 2 to 2.5 years of operation, and recalibrated their temperature,

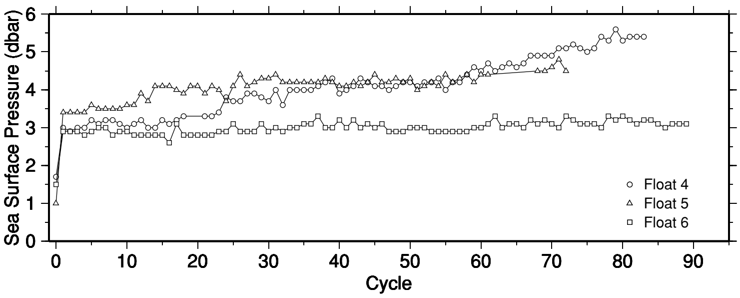

Fig. 7. Time history of the sea surface pressure, measured by Floats 4–6 just before the start of each descent.

conductivity, and pressure sensors. The results demonstrate that these floats did not exhibit significant drift in temperature, but had a significant drift in salinity of –0.0074 to –0.0125, primarily due to the conductivity sensor drift, in contrast with the results for our three floats previously recovered after four to nine months of operation. The salinity drift agrees with that estimated using shipboard CTD data obtained concurrently with the float recovery, indicating that the accuracy check of float salinities using nearby shipboard CTD data is precise and useful. The recovered floats also exhibited a significant drift in pressure of 0.7 to 5.9 dbar, with changes less than 3 dbar between 0 and 2000 dbar for each float. This pressure error can be suppressed to less than a few decibar at all depths, through a correction using the sea surface pressure, which the floats measure in every observation cycle.

The recalibration results for the three floats and one of the previously recovered floats indicate that the negative salinity drift increases nearly in proportion to the floats' operating period. The increasing rate is –0.0041 (±0.0015) year^{-1}, which yields a salinity drift of –0.016 (±0.006) for the expected float lifetime of four years. This suggests that reducing the float surfacing time, which is currently 8.5 to 10.5 hours in each cycle for our typical floats, would improve the accuracy of the salinity measurements. The possible future use of the Iridium satellite system, with which one Argo profile can be transmitted in less than a minute (Argo Science Team, 2002), may greatly improve the accuracy.

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