In Situ Calibration of Moored CTDs Used for Monitoring Abyssal Water

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ABSTRACT

To monitor changes in heat content and geostrophic volume transport of abyssal water accurately, 50 moored conductivity–temperature–depth (CTD) recorders used for density measurements were calibrated in situ by simultaneous observations with accurate shipboard CTDs. Comparisons of the data from the moored and shipboard CTDs showed pressure sensitivities of 0–3 mK at 6000 dbar for the temperature sensors of the moored CTDs. From the in situ calibrations, the uncertainties of the moored CTD data for the deep ocean (≥3000 dbar) were estimated to be 0.6 dbar, 0.6 mK, and 0.0026 for pressure, temperature, and salinity, respectively, relative to the shipboard CTD reference. Time drifts of the moored CTD data, estimated from the in situ calibrations before and after 17- or 14-month mooring deployments in the deep ocean, were considerably smaller than typical stabilities as specified by the manufacturer. However, time drifts of the pressure sensors tended to be negative and the result suggests that pressure data from most present Argo floats, which use the same type of pressure sensor, may have a systematic negative bias. Time series salinity data calculated from the in situ–calibrated CTDs were slightly biased (mean of +0.0014) with respect to the shipboard CTD salinity data, based on potential temperature–salinity relationships, possibly due to a disequilibrium of the moored CTD conductivity sensors during the in situ calibrations.

1. Introduction

The abyssal waters of the Pacific Ocean are renewed by flow from the Southern Ocean; there is no abyssal source in the North Pacific Ocean. The northward abyssal flow plays an important role in earth's climate as a part of meridional overturning circulation, transporting heat and materials. In recent decades, bottom-water warming (5–10 mK) along the pathway of the abyssal water in the North Pacific was revealed by repeat visits to some trans-Pacific hydrographic lines (Fukasawa et al. 2004; Kawano et al. 2006b; Johnson et al. 2007a). Kawano et al. (2006b) suggested that this warming was associated with a decreased bottom-water formation rate around Antarctica. To validate such suggestions based on "snapshot" hydrographic observations, the short-term variability of water properties and transport of the abyssal water must be evaluated.

The Wake Island Passage Flux Experiment (WIFE) was carried out from 2003 to 2005 to clarify and accurately quantify the temporal means and variations of heat content and volume transport of abyssal water in the North Pacific. WIFE consisted of repeated shipboard hydrographic surveys and mooring array observations along a line across a deep passage just south of Wake Island Passage (Uchida et al. 2007b). This study was designed to obtain time series measurements of heat content by using moored conductivity–temperature–depth (CTD) recorders and of volume transport by geostrophic calculations based on density measurements from the moored CTDs referenced to velocity measurements by moored current meters also deployed during the WIFE. Since changes in temperature and salinity of the abyssal water are small, moored CTD data must be accurately calibrated to shipboard CTD data.

During WIFE, we used 50 CTDs of a type (model SBE-37 SM; Sea-Bird Electronics, Inc., Bellevue, Washington) widely used around the world [e.g., in the Tropical Atmosphere Ocean/Triangle TransOcean Buoy Network (TAO/TRITON) in the tropical Pacific (Ando et al. 2005) and the Meridional Overturning Variability Experiment (MOVE) in the tropical Northwest Atlantic (Kanzow et al. 2006)]. Ando et al. (2005)

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investigated the time-drift characteristics of a large number (160) of SBE-37s based on laboratory calibrations before mooring deployment and after mooring recovery. Kanzow et al. (2006) demonstrated in situ calibrations for 45 SBE-37s and showed long-term (4 yr) stability and performance in temperature and conductivity sensors better than specified by the manufacturer. However, neither study investigated the performance of the SBE-37 pressure sensor. Furthermore, no study has considered the pressure sensitivity of moored CTD temperature sensors, although shipboard CTD temperature sensors have been known to show pressure dependency (Uchida et al. 2007a).

The current study presents the results of in situ calibration of the SBE-37 CTD, including consideration of the pressure dependency of temperature sensors. The SBE-37s were attached to a water-sampling frame during shipboard hydrographic casts before mooring deployment and after mooring recovery, using a method similar to that of Kanzow et al. (2006), to obtain data from both the SBE-37s and the well-calibrated shipboard CTD. The SBE-37s were calibrated in situ by comparing these simultaneously measured CTD data, and the long-term performance of the SBE-37s was evaluated.

2. Materials and methods

The SBE-37s used had no pump, but included an optional pressure sensor with a measurement range of 7000 dbar, developed by Druck, Ltd., Leicester, United Kingdom. The time required for one measurement cycle (pressure, temperature, and conductivity) was 1.6 s and a sampling interval was set to 6 s for in situ calibration. The laboratory calibrations of the SBE-37s before use were performed by Sea-Bird Electronics, Inc. The nominal uncertainties as specified by the manufacturer (Sea-Bird Electronics, Inc.) for each sensor are listed in Table 1. Twenty-five SBE-37s out of a total of 50 were used for the first set of mooring observations (from May 2003 to October 2004) and 36 SBE-37s were used for the second set of mooring observations (from October 2004 to December 2005).

For in situ calibration during hydrographic casts before mooring deployment and after mooring recovery, up to 10 SBE-37s were attached to the water-sampling frame at about the same height as the shipboard CTD. These comparisons were made on three casts during the R/V *Mirai* cruise MR03-K02 (27–28 May 2003), seven casts during the R/V *Hakuho-maru* cruise KH-04–4 leg 2 (13–18 October 2004), and five casts during the R/V *Mirai* cruise MR05–05 leg 2 (16–18 December 2005). The shipboard CTD used on these cruises was an SBE 9*plus* CTD system (Sea-Bird Electronics, Inc.). The accuracy of the CTD temperature and pressure (measured with a Digiquartz model 415K-187 sensor; Paroscientific Inc., Redmond, Washington) data were evaluated as 0.4 mK and 2 dbar, respectively (Uchida et al. 2007b). Accuracy of the CTD salinity data was estimated to be 0.0020 by summing the expanded uncertainty ($k = 2$) of the standard seawater measurements (0.0006), expanded uncertainty of the difference between CTD salinity and bottle salinity data (0.0009; Uchida et al. 2007b), and maximum batch-to-batch difference (0.0005) of standard seawater for batches P141, P144, and P145, from the average of recent batches (P130–P145; Kawano et al. 2006a).

TABLE 1. Nominal uncertainties of the model SBE-37 CTD used in mooring observations. Full-scale range of the Druck pressure sensor was 7000 dbar. Accuracy of calculated salinity was estimated by summing 0.0021 from the temperature error, 0.0037 from the conductivity error, and 0.0029 from the pressure error for the deep ocean (at a pressure of 4000 dbar, a temperature of 1.5°C, and conductivity of 31.5 mS cm^{-1}).

Sensor	Initial accuracy	Typical stability	Resolution
Temperature	2 mK	2.4 mK yr^{-1}	0.1 mK
Conductivity	3 μS cm^{-1}	36 μS cm^{-1} yr^{-1}	0.1 μS cm^{-1}
Pressure	7 dbar	3.4 dbar yr^{-1}	0.14 dbar
(Salinity)	0.0087	—	—

The SBE-37 data obtained at a sampling interval of 6 s were compared with the 24 samples s^{-1} CTD data that was averaged over 1-s intervals. Seven SBE-37s leaked during the mooring observations, so comparisons after mooring recovery were not made for these. For 20 SBE-37s, a failure of the Druck pressure sensor occurred during the mooring observation period. The nature of the failure was an internal short to the Druck transducer body, and the failure appears randomly in a significant number of sensors (perhaps 20%) for serial numbers below 4550 (Sea-Bird Electronics, Inc., 2004, personal communication). The Druck transducer body was grounded to seawater via the SBE-37 housing. When the pressure sensor fails, the current can flow from the housing through seawater to the conductivity sensor's ground electrode (Sea-Bird Electronics, Inc., 2005, personal communication). This caused an uncorrectable error in the conductivity data. Therefore comparisons after the first or second mooring recovery were made only for temperature for the 20 SBE-37s. A total of 106 comparisons were made for the 50 SBE-37s.

To accurately compare the SBE-37 and shipboard CTD data, the offsets between the time stamps of these data must be carefully corrected for fast-profiling CTD observations (typical descent and ascent rates of 1.2

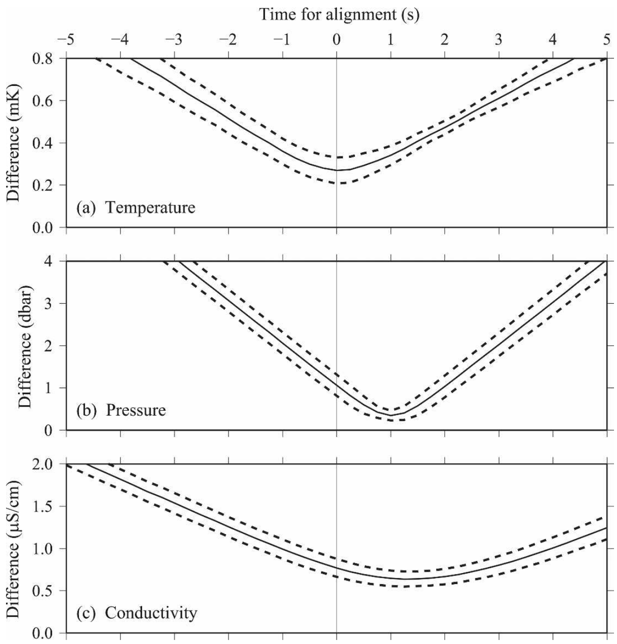

FIG. 1. Differences between the SBE-37 and shipboard CTD data for depths deeper than 3000 dbar, from down- and upcasts. Mean (solid line) and standard deviation (dashed lines) of root-mean-square differences from a fitted line are calculated from 25 comparisons on the R/V *Mirai* cruise MR03-K02. Differences for temperature, pressure, and conductivity are shown as a function of time for alignment of the SBE-37 data, relative to minimizing time of the temperature difference.

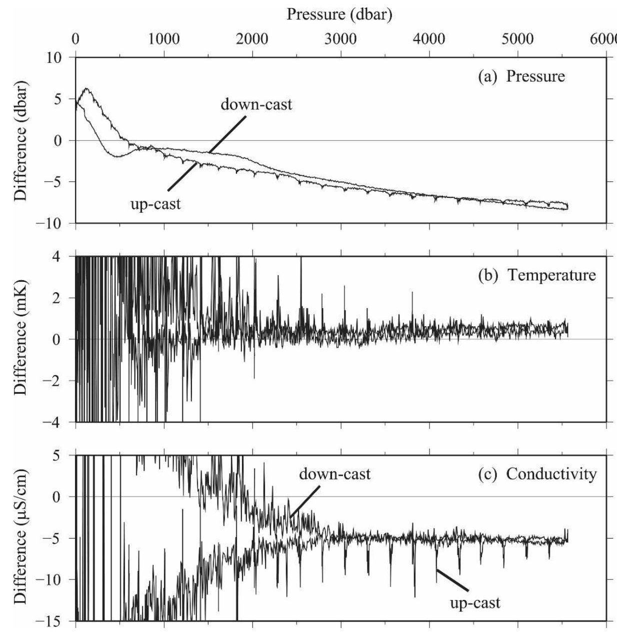

FIG. 2. An example of differences in pressure, temperature, and conductivity between an SBE-37 (No. 24 in Fig. 3) and the shipboard CTD. The SBE-37 data, sampled at 6-s intervals, were compared with the shipboard CTD data averaged over 1 s for down- and upcasts.

m s^{-1}). The SBE-37 data from the down- and upcasts were aligned in time relative to the shipboard CTD data to minimize the difference between the SBE-37 and shipboard CTD data for depths deeper than 3000 dbar, considering slight nonconformities of sampling timing and response time between pressure, temperature, and conductivity sensors of the SBE-37 (Fig. 1). When temperature data were selected as a reference (i.e., the difference between shipboard CTD and SBE-37 was minimized), the shipboard CTD pressure data agreed well with the SBE-37 pressure data 1 s later (Fig. 1b), and shipboard CTD conductivity data agreed well with the SBE-37 conductivity data 1.5 s later (Fig. 1c). These time differences were used to align data from the SBE-37s. Pressure data was selected as a reference when it was available, because it provided a better overall data alignment than temperature or conductivity data.

In an example of these comparisons (Fig. 2), the differences in temperature and conductivity data from the SBE-37 and shipboard CTD were too large to calibrate the SBE-37 for depths shallower than 2500 dbar. However, at depths greater than 3000 dbar, differences in pressure, temperature, and conductivity were tight and linear with increasing pressure, although spikes were seen at bottle firing depths due to slight mismatches of time alignment and sensor response. Data obtained for depths greater than 3000 dbar were suitable for the in situ calibration, since the SBE-37s were placed deeper than 3360 dbar during the WIFE mooring observations.

3. In situ calibrations

The SBE-37s were calibrated using the data from the in situ comparisons for depths from 3000 to 5757 dbar. Since ranges of the temperature and conductivity data over the depth range were quite small (from 1.342° to 1.625°C for temperature and from 31.397 to 32.205 mS cm^{-1} for conductivity), the differences between the SBE-37 and shipboard CTD data with pressure (depth) were approximated using linear equations. The offsets and slopes of the linear equations were obtained from 50 CTD comparisons made before mooring deployment (Fig. 3). The comparisons were made in May 2003 and October 2004. Laboratory calibrations for the SBE-37s were performed in January and February 2002 for units 1 to 18, and in January 2003 for units 19 to 50 (see Fig. 3), except for pressure sensors for numbers 2–4, which were calibrated in May and June 2001. There was no notable difference when laboratory calibration was, or was not, performed just before use.

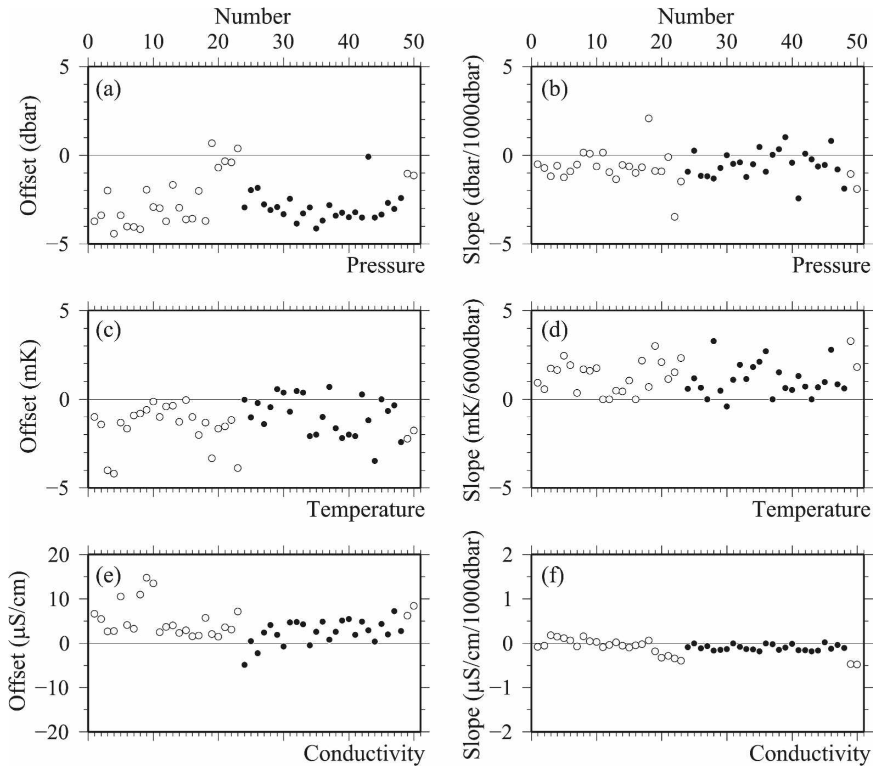

FIG. 3. Calibration coefficients obtained from comparisons between SBE-37s and shipboard CTDs before mooring observation plotted against the sequential number of the 50 SBE-37s. Filled circles show results from May 2003 and open circles show results from October 2004.

For the pressure sensors, the offset and slope tended to be negative [mean offset of −2.7 dbar, SD of 1.2; mean slope of −0.63 dbar $(1000\ \mathrm{dbar})^{-1}$, SD of 0.87]. The mean difference at depth (−6.5 dbar at 6000 dbar) was comparable to the initial accuracy (Table 1), although the variability (SD of 5.2) was large. For most of the temperature sensors the offset was less than the initial accuracy (mean of −1.2 mK, SD of 1.2), but the temperature sensors had pressure sensitivity that exceeded the initial accuracy [range from 0 to 3 mK; mean of 1.2 mK $(6000\ \mathrm{dbar})^{-1}$, SD of 0.9], as did the shipboard CTD temperature sensors (Uchida et al. 2007a). For the conductivity sensors, the offset tended to be greater than the initial accuracy (mean of 3.9 $\mu\mathrm{S\ cm}^{-1}$, SD of 3.5), although the conductivity sensors were not as sensitive to pressure [mean of 0.6 $\mu\mathrm{S\ cm}^{-1}$ $(6000\ \mathrm{dbar})^{-1}$, SD of 0.6].

Differences between data from the SBE-37s that were calibrated in situ and the shipboard CTDs (Fig. 4) had standard deviations of 0.3 dbar for pressure, 0.3 mK for temperature, and 0.7 $\mu\mathrm{S\ cm}^{-1}$ for conductivity. The corresponding standard deviation of the calculated salinity for the deep ocean was estimated to be 0.0013 (sum of 0.0001 from the pressure error, 0.0003 from the

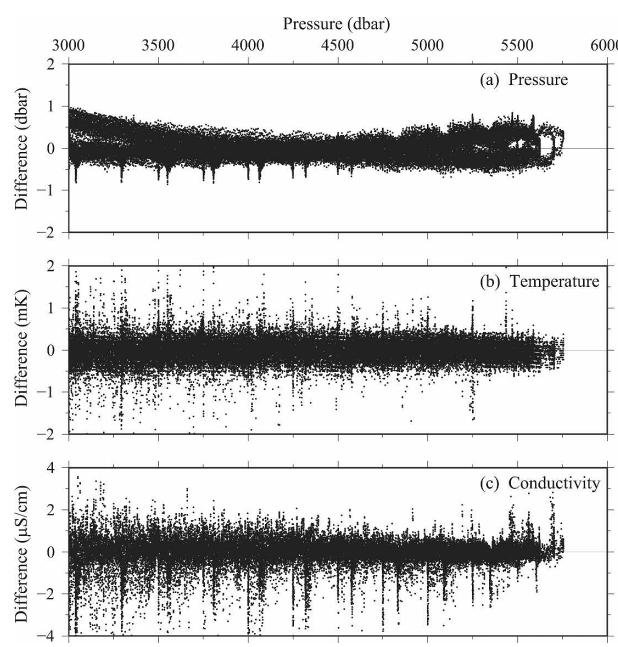

FIG. 4. Differences between SBE-37 and shipboard CTD data plotted against pressure. Results of the in situ calibration before mooring deployment of the 50 SBE-37s are shown for pressure, temperature, and conductivity.

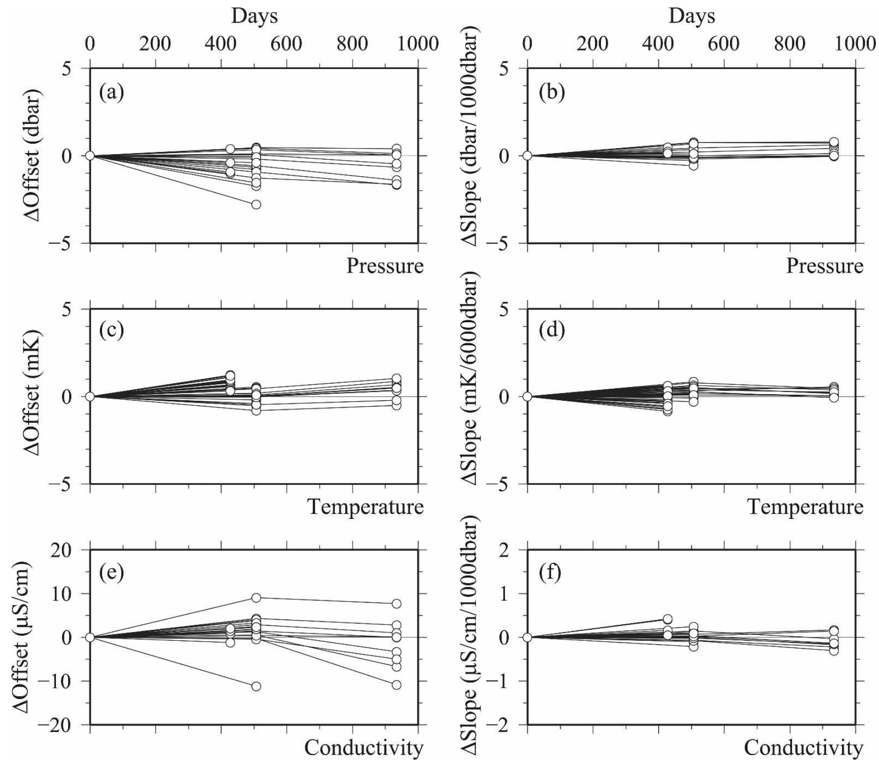

FIG. 5. Accumulated drift after the first in situ calibration of the SBE-37s. Offset is defined here as the difference between the SBE-37 and shipboard CTD data at 4500 dbar estimated from the in situ calibration coefficients. The slope is the same as that in Fig. 3.

temperature error, and 0.0009 from the conductivity error). Therefore the initial expanded uncertainties (k = 2) of the in situ calibration for the deep ocean (≥3000 dbar) were estimated to be 0.6 dbar, 0.6 mK, and 0.0026 for pressure, temperature and salinity, respectively, relative to the shipboard CTD data.

4. Long-term stabilities

The long-term stability of data from the SBE-37s was examined using results of the in situ calibrations obtained before and after the first mooring observation period (17 months), or before and after the second mooring observation period (14 months), or both. Nine SBE-37s were calibrated in situ 3 times, with an additional one SBE-37 calibrated 3 times for the temperature sensor only. Thirteen SBE-37s were calibrated twice, with an additional 20 calibrated twice for the temperature sensor only. To minimize the influence of the estimation error of the slope on the time drift of the offset, the difference between the SBE-37 and shipboard CTD at 4500 dbar estimated from the offset and slope of the in situ calibration was used as the offset for pressure, temperature, and conductivity data. Time drifts of the offsets were more stable (maximum drift of 2 dbar, 1 mK, and 8 μS cm^{-1} yr^{-1} for pressure, temperature, and conductivity, respectively; Fig. 5) than typical stability (Table 1) for these sensors in the deep ocean, although time drifts of the pressure sensors tended to be negative. The slopes were also stable over time. The average time drift per year for the offset of all SBE-37s was −0.4 dbar (SD 0.6), 0.4 mK (SD 0.4), and 0.6 μS cm^{-1} (SD 2.5) for pressure, temperature, and conductivity, respectively. The average time drift per year for the slope was 0.1 dbar (SD 0.2), 0.01 mK (SD 0.3), and 0.05 μS cm^{-1} (SD 0.1) for pressure, temperature, and conductivity, respectively.

5. Discussion

a. Salinity offset correction

The moored SBE-37 data were calibrated as follows. The moored SBE-37 data were first corrected using the calibration coefficients obtained from the in situ calibration before mooring deployment. Time drift rates at the mean depth of the moored SBE-37s were estimated from the in situ calibrations for pressure, temperature, and conductivity before mooring deployment and after mooring recovery. Since time drifts of the slopes for pressure, temperature, and conductivity data were small (Figs. 5b,d,f), the time drifts of the moored SBE-37 data were corrected using the time drift rates and assuming that the drifts were linear over time.

The reliability of the calibrated moored SBE-37 data was examined by comparing the potential temperature (θ)–salinity relationships obtained from 1-day mean SBE-37 data just after mooring deployment and just before mooring recovery with those extracted from shipboard CTD data at the same θ of the same mooring station. The shipboard CTD station for the in situ calibration of the SBE-37 was not necessarily at the same location as the station where the in situ–calibrated SBE-37 was moored. Data from conductivity sensors calibrated in situ agreed well with the shipboard CTD data, whereas data from uncalibrated sensors did not. However, there was a slight bias in the in situ–calibrated salinity data compared to the shipboard CTD salinity data (mean difference of +0.0014, SD of 0.0013; Fig. 6). The salinity bias may have been caused by disequilibrium of the SBE-37 conductivity sensors during the in situ calibration (Kanzow et al. 2006). Variability of the salinity differences can be explained by the estimated error (0.0013) of the SBE-37 salinity data (see section 3). In practice, the bias in the salinity data from the SBE-37s must also be corrected for the θ–salinity relationship to match salinity data from the shipboard CTD data.

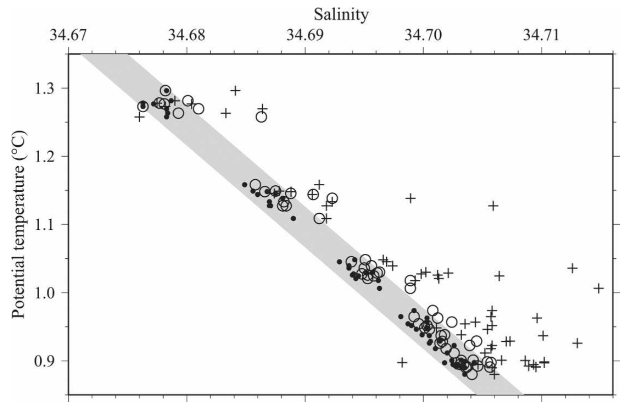

FIG. 6. Potential temperature (θ) plotted against salinity for 1-day mean SBE-37 data just after mooring deployment and just before mooring recovery. Dots indicate shipboard CTD data extracted at the same θ of the same mooring station obtained during the mooring deployment and recovery cruises. Crosses and circles indicate data from the moored SBE-37s without and with the in situ calibration of conductivity, respectively. The shipboard CTD data were naturally found on the straight line with a width of 0.004 in salinity (gray shaded area).

b. *Estimation of Argo temperature and pressure data quality*

Most present-day autonomous profiling floats (Argo floats) use a pumped CTD (model SBE-41CP or SBE-41; Sea-Bird Electronics, Inc.; Johnson et al. 2007b) and the CTD module uses the SBE-37 temperature, conductivity sensors, and the Druck pressure sensors (full-scale range of 2000 dbar). Salinity measurements may drift significantly with time, so the salinity data is corrected using climatological θ–salinity relationships, based on measured temperature and pressure data calibrated in the laboratory before deployment (Wong et al. 2003; Böhme and Send 2005). However, few studies have investigated the reliability of the Argo pressure and temperature data in situ. The results of this study can provide information about the quality of temperature and pressure data from the Argo floats. For our SBE-37 temperature data, the initial uncertainty at the surface was estimated to be -1.2 ± 1.2 mK (see Fig. 3c), the pressure dependency was smaller than +1 mK at 2000 dbar (see Fig. 3d), and the time drift was smaller than 1 mK yr^{-1} (see Fig. 5c). Therefore, the accuracy goal of 5 mK for Argo temperature data can be achieved over a 4-yr float life (Kobayashi and Minato 2005). The SBE-37 pressure data tended to have a negative bias at least deeper than 1000 dbar and the time drift of the pressure sensors tended to be negative (see the appendix for details).

The Argo pressure sensors should be more accurate (nominal initial accuracy of 2.0 dbar and typical stability of 1.0 dbar yr^{-1} for full-scale range of 2000 dbar) than the SBE-37 pressure sensors (full-scale range of 7000 dbar). Furthermore, the Argo pressure sensor drift might be different from that of the SBE-37 deployed at great depth for a full year, since it might be subjected to less overall pressure and cycles regularly to the surface. However, if the initial bias and time drift also tend to be negative for the Argo pressure sensors, the pressure data from these sensors may have systematic errors of about −3 dbar after deployment within 3 yr. A pressure error of −3 dbar for a CTD profile causes an artificial temperature bias of about −0.075°C at 400 dbar, and about −0.025°C at 700 dbar in the subtropical North Pacific (24°N) where the mean vertical temperature gradient was 0.025°C $dbar^{-1}$ at 400 dbar, and 0.010°C $dbar^{-1}$ at 700 dbar. The magnitude of this temperature bias corresponds to estimates of recent cooling of the upper ocean (Lyman et al. 2006), although the systematic biases in a subset of Argo float profiles and expendable bathythermograph (XBT) data appear to have contributed to the rapid cooling (Willis et al. 2007). Some portion of the discrepancy in recent steric sea level trends between estimates from satellite altimetry combined with gravity data, and those from in situ hydrographic data (Lombard et al. 2007) may be explained by the artificial temperature bias resulting from such a systematic pressure error in Argo floats. Although characteristics of vertical distribution of initial bias and time drift of the Argo pressure sensors should be investigated, the present results suggest that in situ offset correction of the Argo pressure data by using the measured sea surface pressure will reduce such a systematic error. For a more accurate estimation of the offset, the atmospheric pressure deviation from a standard atmospheric pressure (1013.5 hPa) should be subtracted from the measured sea surface pressure.

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APPENDIX

Full-Depth Characteristics of the Druck Pressure Sensors

Most present Argo floats use the Druck pressure sensor (full-scale range of 2000 dbar), which is the same pressure sensor in the SBE-37s used in the present study, except with a different full-scale range. Since few studies have investigated the Argo pressure sensor characteristics in situ, we investigated the characteristics of the Druck pressure sensors not only for depths greater than 3000 dbar but also for shallower depths. Shipboard CTD data from the in situ calibrations before mooring deployment were not available for shallow depths for 8 of the 50 SBE-37s, so the characteristics of 42 pressure sensors were investigated. For investigation of the time drift, only 22 pressure sensors were available because of failure or leakage of the Druck pressure sensors during mooring observations.

First, the differences between up- and downcasts were examined, and although the differences between data from the up- and downcasts for the shipboard CTD pressure sensor were small (about 0.2 dbar from laboratory calibrations against a deadweight piston gauge), the differences for the Druck pressure sensors exceeded 1 dbar for depths shallower than 2500 dbar (see Fig. 2a). The mean difference between up- and downcasts for the 42 Druck pressure sensors from the in situ calibration before mooring deployment exceeded 3 dbar for depths from 100 to 400 dbar (Fig. A1). Most of the discrepancies between up- and downcasts pressure data from the SBE-37s were caused by the SBE-37's dynamic response to temperature changes. Profiling CTDs are typically subjected to large temperature changes over short time scales. Pressure sensors of the SBE 9*plus* and the SBE-41/41CP for Argo floats are well insulated inside the pressure housing to achieve the required dynamic accuracy. This effort carefully controls heat flow between the environment and the pressure sensor and reduces the dynamic temperature error. On the other hand, the SBE-37 moored CTDs are manufactured with the pressure sensor in immediate contact with the end cap of the pressure housing and the pressure sensors are not insulated because the dynamic range of temperature is expected to be low. Therefore a large temperature change over short time scales causes a large change in pressure signal (Sea-Bird Electronics, Inc., 2007, personal communication). Temperature at the CTD casts for the in situ calibration of the SBE-37s was about 30°C at surface, 4°C at 1000 dbar, 2°C at 2000 dbar, and 1.3°C at the bottom (5500 dbar). Pressure difference between the up- and downcasts of the in situ calibrations of the SBE-37s was small for depths deeper than 2500 dbar (Fig. A1). The result suggests that the pressure error caused by large temperature change at shallower depths is quite small for depths deeper than 3000 dbar. Also pressure difference between the SBE-37 and the SBE 9*plus* at the upcast was almost linear against pressure for depths deeper than 1000 dbar (Fig. 2a). The result also suggests that the pressure error is small for depths deeper than 1000 dbar for the upcast since temperature change was small for the depths.

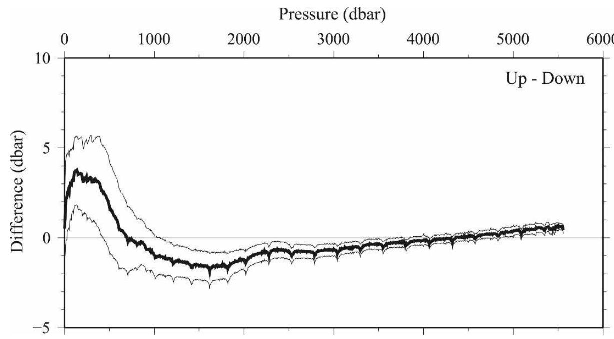

FIG. A1. Mean pressure difference (thick line) between the up- and downcasts of the in situ calibrations for 42 SBE-37s before mooring deployment. Thin lines represent one standard deviation from the mean.

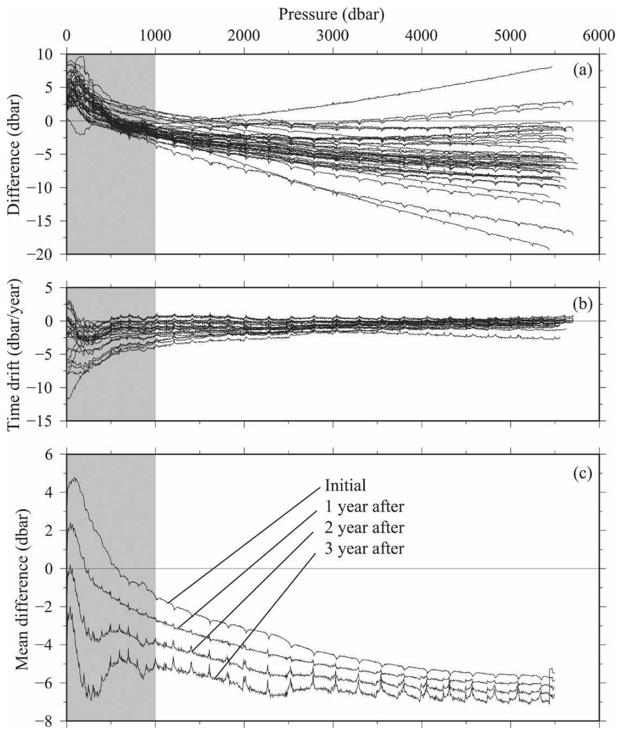

FIG. A2. Characteristics of the SBE-37 pressure sensors for the upcasts of the in situ calibration. (a) Initial differences between 42 SBE-37s and the shipboard CTD from in situ calibrations before mooring deployment, (b) time drifts per year for 22 SBE-37s estimated from in situ calibrations before mooring deployment and after mooring recovery, and (c) mean initial difference and mean differences after 1, 2, and 3 yr from the initial comparison as estimated using the mean time drift rate. Pressure error was large at depths shallower than 1000 dbar (shaded) because of the SBE-37's dynamic response to temperature changes.

Next, characteristics of the Druck pressure sensors from only the upcast of the in situ calibrations were examined, since the Argo floats take measurements during an ascending profile. Differences between data from the Druck pressure sensors and the shipboard CTDs were initially large and varied widely for depths greater than 2000 dbar (Fig. A2a). The mean of the initial differences was within 5 dbar for depths shallower than 4000 dbar (Fig. A2c). The time drifts of the Druck pressure sensors were large and varied widely for depths shallower than 2000 dbar (Fig. A2b). The mean of the time drifts tended to be negative for all depths; its magnitude was about -1 dbar yr^{-1} between 1000 and 2000 dbar. When the mean initial difference and time drift rate are used to estimate the error of the Druck pressure sensors, the error exceeds 5 dbar three years after deployment for depths deeper than 1000 dbar (see Fig. A2c).

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