An Expanded Batch-to-Batch Correction for IAPSO Standard Seawater

HIROSHI UCHIDA AND TAKESHI KAWANO
Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Kanagawa, Japan

TOSHIYA NAKANO
Nagasaki Meteorological Office, Japan Meteorological Agency, Nagasaki, Japan

MASAHIDE WAKITA
Mutsu Institute for Oceanography, Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Mutsu, Aomori, Japan

TATSUYA TANAKA AND SONOKA TANIHARA
Marine Works Japan, Ltd., Yokosuka, Kanagawa, Japan

(Manuscript received 6 November 2019, in final form 18 May 2020)

ABSTRACT

We expanded the batch-to-batch offsets of The International Association for the Physical Sciences of the Oceans (IAPSO) Standard Seawater (SSW) batches P145–P163 by intercomparison measurements using salinometers. On the basis of our results, we recommend using the correction factors instead of the offsets to correct the batch-to-batch differences, especially for salinity data outside the range of 30–40 g kg$^{-1}$. We evaluated the expanded batch-to-batch correction factors by applying them to time series salinity data collected in the northwestern North Pacific Ocean and found that they are effective for detecting recent freshening ($-0.6 \pm 0.1 \times 10^{-3}$ g kg$^{-1}$ decade$^{-1}$) in the deep North Pacific, which might be related to a reduction of the formation rate of Antarctic Bottom Water. We also evaluated the SSW linearity pack by applying the batch-to-batch correction factors. Linearity errors of the salinometers estimated from decade resistance substituters were consistent with the results of the linearity pack measurements. To correct the linearity errors of a salinometer, it might be suitable to use the more detailed distribution of those estimated from the decade resistance substituter than the linearity pack measurements. Since the cause of large batch-to-batch differences is still unclear, a reference seawater that is more robust and stable than SSW might be necessary to establish a high-level of international comparability of salinity measurements; the Multiparametric Standard Seawater (MSSW) currently under development might be a candidate for such reference seawater, because MSSW is expected to be more stable than SSW not only in practical salinity but also in absolute salinity.

1. Introduction

The salinity of the ocean is an important indicator of Earth’s climate change. For example, the Southern Ocean has freshened and warmed over the past several decades primarily as a result of human-induced greenhouse gas increases (Swart et al. 2018). Swart et al. (2018) concluded that the primary changes of the freshening result from changes in precipitation and the northward advection of freshwater by sea ice. The freshening substantially increases the buoyancy of the seawater and perhaps reduces the formation rate of Antarctic Bottom Water (Purkey et al. 2019). Purkey et al. (2019) also observed an infusion of freshwater propagating along the pathway of the bottom water as
it moves northward from Antarctica. Monitoring long-term changes in the deep-sea environment, such as freshening of abyssal waters, requires salinity measurements of the highest possible quality (Levin et al. 2019).

To establish comparability of salinity data, a bottled standard reference material called The International Association for the Physical Sciences of the Oceans (IAPSO) Standard Seawater (SSW) has been used worldwide for more than 40 years (Culkin and Ridout 1998). However, there is a fundamental problem with seawater salinity measurements: a lack of traceability to the International System of Units (SI) (Seitz et al. 2011; Pawlowicz et al. 2016). Seawater salinity is derived from electrical conductivity, temperature, and pressure in the current oceanographic practice [the Practical Salinity Scale of 1978 (PSS-78); IOC and SCOR and IAPSO 2010]. At present, it is possible to certify the electrical conductivity of SSW with traceability to the SI within an uncertainty of about 0.02% at the highest level (Seitz et al. 2019) and corresponding uncertainty of 0.008 in practical salinity. This level of uncertainty is too large to use in climate studies in the deep ocean (e.g., Levin et al. 2019; Purkey et al. 2019). Meanwhile, it is possible to measure salinity with traceability to the $K_{15}$ value of SSW defined by the PSS-78 within a relative uncertainty of 0.002 in practical salinity (Guildline Instruments 2004), where the $K_{15}$ is electrical conductivity ratio relative to a potassium chloride (KCl) solution (32.4356 g kg$^{-1}$) at a temperature of 15°C [International Practical Temperature Scale of 1968 (IPTS-68)] and a pressure of one standard atmosphere. However, SSW is a metrological artifact and is subject to variations over time or between independent realizations (Seitz et al. 2011).

Several studies have reported systematic batch-to-batch differences for SSW (e.g., Aoyama et al. 2002; Kawano et al. 2006). For example, Kawano et al. (2006) reported batch-to-batch salinity offsets ranging from $-0.9 \times 10^{-3}$ to $2.5 \times 10^{-3}$ on the practical salinity scale for SSW batches P91–P145. Kawano et al. (2005) concluded that the batch-to-batch offsets could result from inconsistency in the conductivity of the KCl standard solution defined by the PSS-78. Meanwhile, Bacon et al. (2007) reported recalibrated batch-to-batch offsets in reference to carefully prepared solutions of KCl and concluded that SSW batches P130–P144 had offsets effectively equal to zero within the expanded uncertainty ($0.4 \times 10^{-3}$ in practical salinity). Bacon et al. (2007) suggested that batch-to-batch offsets resulted from handling effects (motion and temperature changes during global shipping), especially for older batches contained in soda-glass ampoules (produced before 2000), and that recent batches in borosilicate-glass bottles might hold the labeled conductivity ratio over longer periods, including transportation.

In this study, we expanded the batch-to-batch salinity offset table proposed by Kawano et al. (2006) for recent batches P145–P163 to check the magnitude of the offsets, which is expected to be small for recent batches (Bacon et al. 2007). We evaluated the expanded batch-to-batch correction table by applying it to time series of salinity data obtained in the deep ocean in recent decades. We also evaluated the SSW linearity pack (practical salinities of 10, 30 and 38) by applying the batch-to-batch correction.

2. Materials and methods

We used the P series (practical salinity of about 35) of SSW to estimate batch-to-batch offsets from batch P145 to P163. We also used the SSW linearity pack (Ocean Scientific International, Ltd.). In the linearity pack, SSW with practical salinities of 10 (10L series), 30 (30L series), and 38 (38H series) are available in addition to the P series for evaluating the linearity of salinometers. The linearity pack is produced from the same source seawater (northeastern Atlantic Ocean surface water) as that of the P series, with dilution by deionized water or concentration by evaporation.

The practical salinity of SSW was measured with a salinometer (Autosal model 8400B; Guildline Instruments, Ltd.). This salinometer has a practical salinity measurement range from 0.005 to 42 and a resolution of 0.0002 and is used to determine the label value of SSW as the de facto standard laboratory salinometer for high-quality salinity measurements. The salinometers were calibrated using the P-series SSW, and the salinities of test samples were measured at 24°C, following the method of Kawano (2010).

The salinity measurements were conducted by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), except for the measurements to estimate the batch-to-batch offset for batch P153, which were conducted by the Japan Meteorological Agency (JMA).

We used the High-Accuracy Resistance Substituter (HARS) series of decade resistance substituter (model HARS-X-7-0.001-K from IET Laboratories, Inc.) to estimate linearity errors of the salinometers. The maximum resistance of this instrument is 11111.11 Ω and zero resistance is less than 1 mΩ per decade, with a resolution of 1 mΩ. The decade resistance substituter can be used with a four-wire Kelvin lead connection to replace the conductivity cell in the salinometer, as described in the user’s manual (Guildline Instruments 2004). The double
conductivity ratio $2K$ can be determined by the decade resistance substituter as

$$2K = 2R_{2.0}/R,$$ (1)

where $R_{2.0}$ is the resistance of the decade resistance substituter at a salinometer reading of 2.0 and $R$ is the resistance of the decade resistance substituter for obtaining a chosen $2K$ value. For example, if it is desired to obtain 1.0 as the $2K$ value, the $R$ should be set to the value of $2R_{2.0}$.

3. Evaluation of P-series SSW

We evaluated the certified double conductivity ratios of the P-series SSW (practical salinity of about 35) using measurements of double conductivity ratios by the salinometer. Since we can only evaluate the batch-to-batch offset of a target batch relative to a known estimated “true value,” we referred to the batch-to-batch offset-corrected salinities proposed by Kawano et al. (2006) with reference to the average of the batch-to-batch offsets for batches P130–P145, taking the comparability into consideration.

Several consecutive batches of SSW, including a target batch for which the batch-to-batch offset was to be determined, were measured simultaneously every time that a new batch of SSW was produced. Figure 1 is a schematic of the method for estimating the batch-to-batch offset. The manufacturer claims a 3-yr shelf life for SSW based on their stability tests (Culkin and Ridout 1998). However, because of the uncertainty of measurements, it is desirable to use as many batches as possible for reference to estimate the batch-to-batch offset of the target batch. In principle, therefore, at the time of measurement we used five consecutive batches, including the target batch as the most recent (see appendix A for more details), because SSW is stable for 5 years after calibration (Bacon et al. 2007) (see also Fig. A1).

The expanded batch-to-batch offsets in practical salinity relative to the new reference proposed by Kawano et al. (2006) up to P163 are listed in Table 1 and shown in Fig. 2. The batch-to-batch offset for P145 was reevaluated because the difference between the value proposed by Kawano et al. (2006) and the value in this study was quite large ($1.1 \times 10^{-3}$ in practical salinity) and no values consistent with that proposed by Kawano et al. (2006) have been obtained since those measurements (see Table A1 for more details). The average of the expanded batch-to-batch offsets (from P145 to P163) was close to zero ($-0.19 \times 10^{-3}$ in practical salinity), but sometimes the magnitude of the offset was larger than the expanded uncertainty ($0.4 \times 10^{-3}$ in practical salinity; Bacon et al. 2007); for example, the estimated offset for P146 was 3 times the expanded uncertainty.

Standardization of the salinometer involves changing the span of the slope of the salinometer by adjusting it to the labeled conductivity ratio of the SSW. Time drift of the salinometer is also a change in the span of the
slope (see appendix B). Strictly speaking, the batch-to-batch offset correction does not reflect this nature of standardization. Therefore, there could be an error in case of applying a large batch-to-batch offset. Nonetheless, the offset correction is usually adequate for real seawater samples, as demonstrated by previous studies (e.g., Kawano et al. 2006), because the salinity range for 99% of the world’s ocean waters (33–37 g kg\(^{-1}\); Millero 2006) is close to the salinity of SSW (about 35 g kg\(^{-1}\)). However, for salinities much lower or higher than 35 g kg\(^{-1}\), the offset correction introduces an artificial error.

If the batch-to-batch offset is 0.0015 in practical salinity (maximum in Table 1), the artificial error becomes detectable (greater than the resolution of the salinometer) for practical salinity higher than 40 or lower than 30. Considering the measurement range of the salinometer (0.005–42 in practical salinity), this becomes a significant issue for measurements in low salinity regions affected by river runoff or meltwater [e.g., surface water of the Arctic Ocean (Millero et al. 2010) and Baltic Sea (Feistel et al. 2010)]. It is therefore recommended that the correction factors (Table 1) be used instead of using the offsets to correct the batch-to-batch differences of SSW by multiplying the salinity by the correction factor, as there is a linear relationship between the conductivity ratio and salinity.

4. Evaluation of the batch-to-batch correction table

We evaluated the expanded batch-to-batch correction factors (Table 1) by applying them to the conductivity–temperature–depth (CTD) salinity data collected in the northwestern North Pacific Ocean. Bottom water in the northern North Pacific originates from the Circumpolar Deep Water that flows northward from the Southern Ocean, and its water properties [such as the temperature–salinity (\(T–S\)) relationship] is expected to be relatively uniform for a long time as bottom water is not formed in the North Pacific.

We collected full-depth CTD data obtained from R/V Mirai at time series station K2 [47°N, 160°E; water depth 5215 m; see Wakita et al. (2017) for more detail]. The CTD data are available online (http://www.godac.jamstec.go.jp/k2/ and https://ebcrpa.jamstec.go.jp/k2/en/). Station K2 is one of the CTD stations along WOCE Hydrographic Program (WHP) line P01; high-accuracy hydrographic observations were conducted along line P01 in 1985 (https://cchdo.ucsd.edu/cruise/31TTTPS47), 1999 (Uchida et al. 2002), 2007 (Kawano et al. 2009) and 2014 (Uchida and Doi 2017). Station K2 is also one of the CTD stations of the repeat hydrographic section maintained by the JMA. Full-depth CTD observations have been conducted at station K2 by R/Vs Ryofu-maru and Keifu-maru once per year since 2011, except for 2012; the CTD data are available online (https://www.data.jma.go.jp/gmd/kaiyou/db/vessel_obs/data-report/html/ship_e.php). Station K2 bottom water is therefore a good choice for applying the batch-to-batch corrections.

Figure 3 shows the \(T–S\) relationship for the bottom water at station K2. Variation in the \(T–S\) relationship was reduced by applying the batch-to-batch correction

| Batch No. | Date of preparation | \(K_{15}\) | Salinity (PSS-78) | Offset \((\times 10^{-3})\) | Correction factor |
|-----------|-------------------|---------|-----------------|-----------------|-----------------|
| P145      | 15 Jul 2004       | 0.99981 | 34.9926         | −1.0            | 0.999714        |
| P146      | 12 May 2005       | 0.99979 | 34.9918         | −1.5            | 0.9999571       |
| P147      | 06 Jun 2006       | 0.99982 | 34.9930         | −0.6            | 0.9999829       |
| P148      | 01 Oct 2006       | 0.99982 | 34.9930         | 0.0             | 1.0000000       |
| P149      | 05 Oct 2007       | 0.99978 | 34.9937         | 0.7             | 1.0000200       |
| P150      | 22 May 2008       | 0.99978 | 34.9941         | 0.7             | 1.0000200       |
| P151      | 20 May 2009       | 0.99997 | 34.9988         | −0.5            | 0.9999857       |
| P152      | 05 May 2010       | 0.99981 | 34.9926         | −0.1            | 0.9999714       |
| P153      | 08 Mar 2011       | 0.99979 | 34.9918         | 0.4             | 1.0000114       |
| P154      | 20 Oct 2011       | 0.99990 | 34.9961         | 0.5             | 1.0000143       |
| P155      | 19 Sep 2012       | 0.99981 | 34.9926         | 0.1             | 1.0000029       |
| P156      | 23 Jul 2013       | 0.99984 | 34.9937         | 0.4             | 1.0000114       |
| P157      | 15 May 2014       | 0.99985 | 34.9941         | −0.8            | 0.9999711       |
| P158      | 25 Mar 2015       | 0.99970 | 34.9883         | −0.2            | 0.999943        |
| P159      | 15 Dec 2015       | 0.99988 | 34.9953         | −0.4            | 0.999886        |
| P160      | 20 Jul 2016       | 0.99983 | 34.9933         | 0.0             | 1.0000000       |
| P161      | 03 May 2017       | 0.99987 | 34.9949         | −0.2            | 0.999943        |
| P162      | 16 Apr 2018       | 0.99983 | 34.9933         | −0.5            | 0.9999857       |
| P163      | 10 Apr 2019       | 0.99985 | 34.9941         | −0.6            | 0.9999829       |
to the CTD salinity data (Fig. 3b), especially for the WHP data in 1985, as also shown by Kawano et al. (2006). The $T$–$S$ relationship is almost linear for the range plotted in Fig. 3; we therefore examined the temporal variation of the $T$–$S$ relationship by extracting salinity at a potential temperature of 1.09°C from the regression line between 1.08°C and 1.10°C for each CTD profile (Fig. 4). The original salinity data showed a decadal time-scale undulation [high (34.8544 g kg$^{-1}$) around 2006, low (34.8514 g kg$^{-1}$) around 2014, and relatively high (34.8526 g kg$^{-1}$) around 2019]. However, this undulation disappeared after applying the batch-to-batch correction factors to the salinity data, and a linear trend of slight freshening ($-0.6 \pm 0.1 \times 10^{-3}$ g kg$^{-1}$ per decade$^{-1}$) was observed, and the standard deviation from the regression line is $0.7 \times 10^{-3}$ and $0.3 \times 10^{-3}$ g kg$^{-1}$ for the original salinity data and the corrected salinity data, respectively. There were no CTD data calibrated with batches 134–138, 140, 143, 147, 149, 150, or 158.

5. Evaluation of the SSW linearity pack

Unlike the P-series salinity standards, the label salinities of the linearity pack (series 10L, 30L, and 38H) were certified by using a salinometer (Autosal model 8400B; Guildline Instruments, Ltd.) calibrated by using the P-series SSW. Therefore, for precise evaluation of the linearity pack, the batch-to-batch offset correction should be applied to the label salinity in addition to the batch-to-batch correction for the measured salinity of the linearity pack.

We measured several batches of the linearity pack. The label salinity was calibrated by using P-series SSW (P150 for 38H10, P149 for 30L14 and 30L11, and P158 for 10L15; R. Williams, Ocean Scientific International, Ltd., 2019, personal communication). The batch-to-batch correction factors were applied to the label salinity and the measured salinity (Table 2). The measured salinity agreed well with the label salinity (within ±0.0001 in practical salinity) for batches 30L14 and 38H10. However, for batches 10L11 and 10L15, the difference between the label value and measured value was relatively large (0.0007–0.0011 in practical salinity). We then estimated the linearity errors of the salinometers by using decade resistance substituters and compared these results with those of the linearity pack measurements.

The double conductivity ratio $2K$ was determined at each step of the suppression dial, which changes the number of the resistors in series (23 steps for the full range of double conductivity ratios from 0 to 2.2) by adjusting the resistance $R$ of the decade resistance substituter from Eq. (1) and then measuring the ratio with the salinometer. Differences in salinity calculated from the measured $2K$ values and those determined from the decade resistance substituters were plotted for six
salinometers (Fig. 5). For the three salinometers used in the linearity pack measurements (serial numbers 62827, 62556, and 71758), the salinity errors estimated from the decade resistance substituters were consistent with the salinity differences seen in the linearity pack measurements. This suggests that most of the relatively large salinity differences (0.0007–0.0011 in practical salinity) for the 10L series can be explained by the linearity error of the salinometers, excluding a contribution from the conductivity cell. Any linearity error in the salinometer used by the manufacturer for the calibration of the linearity pack could also contribute to the rest (about 0.0005 in practical salinity) of the relatively large salinity differences. The repeatability of the decade resistance substituter measurements is discussed in appendix C.

6. Discussion

Kawano et al. (2006) reported the batch-to-batch offsets of IAPSO SSW up to batch P145 by conducting intercomparisons of IAPSO SSW measurements, as in this study: they concluded that the standard deviation of batch-to-batch differences of recent (at that time) batches (P130 to P145) had been reduced (0.3 $\times$ 10$^{-3}$ in practical salinity) and was comparable to the resolution of the salinometer (0.2 $\times$ 10$^{-3}$ in practical salinity). Bacon et al. (2007) also reported batch-to-batch...
differences of IAPSO SSW by recalibrating in reference to carefully prepared solutions of KCl for recent (at that time) batches (P130–P144), and batch-to-batch offsets estimated from newly calibrated data obtained within the shelf life (3 years from the original calibration date) are shown in Fig. 2. Bacon et al. (2007) found no significant change in label salinity outside the expanded uncertainty (0.4 × 10⁻³ in practical salinity). The standard deviation (0.3 × 10⁻³ in practical salinity) of batch-to-batch offsets from Bacon et al. (2007) was also comparable to the resolution of the salinometer.

Six batches (P138, P139, P141, P142, P143, and P144) overlapping between Kawano et al. (2006) and this study were measured totally 16 times to check consistency between the two studies, although ages of these batches were older than 5 years at the time of measurements [identifier (ID) “N” in Table A1]. Mean with the standard error of the differences from the batch-to-batch offset-corrected values for the above 16 measurements was 0.0003 ± 0.0001 in practical salinity. The mean value was not different from the resolution of the salinometer (0.0002 in practical salinity), although the mean value might include the effect of evaporation of water due to long-term storage. These results suggest that Kawano et al. (2006) and this study are consistent with each other, except for P145.

In Kawano et al. (2006), the batch P145 was measured at JAMSTEC and the Woods Hole Oceanographic Institution in 2005, and these two results were consistent with each other. In this study, the batch P145 was measured at JAMSTEC, in 2006, 2007, 2009, and 2010 and at JMA in 2011, and these five results were consistent with each other. Although the reason of the inconsistency for the batch P145 between Kawano et al. (2006) and this study is unknown, the estimated offset in this study is reasonable judging from the tendency of the freshening in the deep North Pacific (Fig. 4).

As suggested in these previous studies, the batch-to-batch differences are small for recent batches, but the difference sometimes deviates beyond the expanded uncertainty (e.g., −0.0015 in practical salinity for batch P146). The standard deviation of the batch-to-batch differences proposed by this study (P145–P163) was 0.0006 in practical salinity. Therefore, uncertainty of salinity changes in the recent decade is statistically expected to be reduced by 0.0006 in practical salinity by applying the batch-to-batch correction. In fact, the standard deviation from the decadal trend of the deep North Pacific freshening (Fig. 4) was reduced from 0.0007 to 0.0003 g kg⁻¹ by applying the batch-to-batch correction. Magnitude of the reduction was estimated to be 0.0006 g kg⁻¹ [√(0.0007² − 0.0003²)] and agreed well with the standard deviation of the batch-to-batch differences.

Howell et al. (2010) presented large shift (about +0.0013 in practical salinity) of measured salinity values for their in-house standard seawater when they began using SSW P151 instead of using P150 for the calibration of their salinometer. This large shift can be completely explained by the batch-to-batch offsets proposed by this study (+0.0007 and −0.0005 in practical salinity for P150 and P151, respectively).

The batch-to-batch correction was also successfully applied to recent international hydrographic data to detect freshening of bottom water in the South Pacific Ocean (Purkey et al. 2019), although additional ad hoc offsets were sometimes required for older data from the 1990s to improve internal consistency of the salinity dataset (Purkey et al. 2019). The standard deviation of the batch-to-batch differences proposed by Kawano et al. (2006) and this study since 1980 (P91–P163) was 0.0009 in practical salinity. Therefore, uncertainty of salinity difference due to the batch-to-batch differences is comparable to the basin mean deep freshening (0.0013 in practical salinity per decade) observed in the South Pacific Ocean (Purkey et al. 2019). These results suggest that the batch-to-batch correction is effective for deep-ocean salinity data to evaluate and to monitor deep ocean salinity changes.

Older SSWs (batches before P140) were sealed in soda-glass ampoules. The soda glass of the ampoules had a lower quality than the borosilicate glass of the bottles used for more recent SSWs (batches after P140), and the ampoules had a larger air space than the bottles. The larger air space allows more “sloshing” inside the ampoules with any motion (Bacon et al. 2007). Bacon et al. (2007) hypothesized that motion and temperature changes are important agents causing batch-to-batch differences of SSW. If this is true, then a reference seawater more robust and stable than SSW is necessary to allow SSW users worldwide to estimate batch-to-batch differences of the SSWs used in their laboratories and on ships.

Such reference seawater must have long-term stability at least in terms of practical salinity, especially against motion and temperature changes. The Chinese Primary Standard Seawater for practical salinity measurement is distributed in borosilicate glass bottles with air space in the bottle (Li et al. 2016), similar to IAPSO SSW, and therefore will have the same problems. On the other hand, the Multiparametric Standard Seawater (MSSW) currently under development jointly by KANSO Co., Ltd., Osaka, Japan, and JAMSTEC might be a candidate for such reference seawater.
MSSW uses 500-ml aluminum beverage bottles (New Bottle Can; Daiwa Can Company) with highly functional plastic inner caps and is produced by a method similar to that used for the Reference Material for Nutrients in Seawater (RMNS) (KANSO Co., Ltd.), with no air space in the bottle. MSSW is intended for use as a reference for the Multiparametric Standard Seawater (lot Pre16, produced on 6 Sep 2012). Open circles indicate original salinity data, and closed circles indicate salinity data after applying the batch-to-batch correction for IAPSO SSW. From two to five bottles of Pre16 were measured at each measurement, and the measured salinity data were averaged to evaluate stability in practical salinity. The solid and dashed lines indicate mean and ±standard deviation (SD) of the salinity data after applying the batch-to-batch correction.

Although the batch-to-batch correction for IAPSO SSW is practically efficient for establishing comparability for salinity measurements in oceanography and climatology, as shown in Figs. 3 and 4, the lack of traceability to the SI with sufficiently small uncertainty in salinity measurements (at a level of $10^{-3}$ g kg$^{-1}$) is a fundamental problem (Seitz et al. 2011, 2019). Therefore, Pawłowicz et al. (2016) recommended measuring the density of IAPSO SSW to establish traceability of absolute salinity to the SI with an uncertainty of $5 \times 10^{-3}$ g kg$^{-1}$. However, the resolution of the density (or absolute salinity) measurement for the de facto standard oscillation-type density meter ($1 \times 10^{-3}$ kg m$^{-3}$; DMA 5000M, Anton-Paar GmbH) is an order of magnitude larger than that of the conductivity salinometer (0.15 $\times 10^{-3}$ kg m$^{-3}$), and the density meter may have a linearity error ($-6 \times 10^{-3}$ kg m$^{-3}$) in the seawater density measurements (Uchida et al. 2011). The interference method, on the other hand, is one of the most sensitive methods for measuring the refractive index (or density) of seawater. There is now an ultrahigh-resolution (0.1 $\times 10^{-3}$ kg m$^{-3}$) density sensor based on measuring the refractive index by the interference method (Uchida et al. 2019). This density sensor will contribute substantially toward establishing the traceability of salinity measurements, and it will be suitably calibrated by using MSSW, because density-related parameters (practical salinity, nutrient concentrations, and carbonate system parameters; Pawłowicz et al. 2011) and thus density of MSSW are expected to be more stable than SSW whose density increases with time by dissolution of silicate from the glass bottles (Uchida et al. 2011).
7. Conclusions

We expanded the batch-to-batch salinity offset table of the IAPSO SSW proposed by Kawano et al. (2006) for recent batches P145–P163 by intercomparison measurements using salinometers (Autosal model 8400B). Several consecutive batches (within five years from production), including the target batch for which the batch-to-batch offset was to be determined, were measured simultaneously every time that a new batch of SSW was produced. Also, six batches overlapping between Kawano et al. (2006) and this study were measured, although ages of these batches were older than five years at the time of measurements. We confirmed that the batch-to-batch offset tables proposed by Kawano et al. (2006) and this study are consistent with each other, except for P145. As suggested in the previous studies, the batch-to-batch differences are small for recent batches (the standard deviation for P145–P163 was 0.0006 in practical salinity), but the difference sometimes deviates beyond the expanded uncertainty (e.g., −0.0015 in practical salinity for P146).

We recommend using the correction factors instead of the offsets to correct the batch-to-batch differences, especially for salinity data much lower or higher than 35 g kg$^{-2}$, because standardization of the salinometer involves changing the span of the slope of the salinometer. Time drift of the salinometer is also a change of the span of the slope. The offset correction introduces an artificial error for salinities much lower or higher than 35 g kg$^{-2}$. If the batch-to-batch offset is 0.0015 in practical salinity, the artificial error become detectable for practical salinity higher than 40 or lower than 30.

We evaluated the expanded batch-to-batch correction factors by applying them to time series CTD salinity data collected in the northwestern North Pacific Ocean in recent decades. We examined the temporal variation of the $T$–$S$ relationship by extracting salinity at a potential temperature of 1.09°C. Although the original salinity data showed a decadal time-scale undulation, the undulation disappeared after applying the batch-to-batch correction factors to the salinity data, and a linear trend of slight freshening ($-0.6 \pm 0.1 \times 10^{-3}$ g kg$^{-1}$ decade$^{-1}$) was detected. The slight freshening might be related to a reduction of the formation rate of Antarctic Bottom Water. We suggest that the batch-to-batch correction is extremely important for detecting salinity changes in the deep ocean for climate studies.

We also evaluated the SSW linearity pack (practical salinities of 10, 30, and 38) by applying the batch-to-batch correction factors. Linearity errors of the salinometers estimated from decade resistance substituters were within the manufacturer’s specification ($\pm 0.002$ in practical salinity) in six Autosal 8400B salinometers, the linearity error distributions did not allow any clear pattern and rarely spiked. Therefore, to correct the linearity error of a salinometer, it might be suitable to use the detailed distribution estimated from the decade resistance substituter rather than using linear trends estimated from the linearity pack measurements.

Although the reasons for the batch-to-batch differences beyond the expanded uncertainty are unknown, motion and temperature changes might be important agents causing batch-to-batch differences of SSW, then a reference seawater more robust and stable than SSW is necessary to allow SSW users worldwide to estimate batch-to-batch differences of the SSWs used in their laboratories and on ships. Moreover, the lack of traceability to the SI with sufficiently small uncertainty in salinity measurements is a fundamental problem and measuring the density of SSW is recommended to establish traceability of absolute salinity to the SI. MSSW currently under development might be a candidate for such reference seawater, because MSSW is expected to be more stable than SSW not only in practical salinity but also in absolute salinity. The ultrahigh-resolution density sensor based on measuring refractive index by the interference method will contribute substantially toward establishing the traceability of salinity measurements to the SI, and it will be suitably calibrated by using MSSW.

Acknowledgments. Part of this work was supported by the Japan Society for the Promotion of Science KAKENHI Grants 26610154 and 18K03752. We thank the marine technicians of Marine Works Japan, Ltd., who analyzed salinity for some of the standard seawaters. We also thank Richard Williams of Ocean Scientific International, Ltd., for providing calibration information for the SSW linearity pack. The Multiparametric Standard Seawater was developed through cooperative research by KANSO Co., Ltd. (Hitoshi Mitsuda) and JAMSTEC (author Uchida), and its salinity was evaluated through cooperative research by Marine Works Japan, Ltd. (author Tanaka), and JAMSTEC (Uchida). This work contributes to the tasks of the Joint SCOR/IAPSO/IAPWS Committee on the Properties of Seawater (JCS).

APPENDIX A

Details of Batch-to-Batch Offset Measurements

Details of measurements for determining the batch-to-batch offsets shown in Table 1 are presented in Table A1 and...
Table A1. Results of measurements to determine the batch-to-batch offsets shown in Table 1. In the “identification label” (ID) column, D indicates batches whose offsets were determined, R indicates batches used as a reference, and N indicates batches that were not used for determination of the offsets. The number of bottles measured (Num), and the difference in practical salinity from the label value for bottles with ID D or from the batch-to-batch offset-corrected values (see Table 1) for R and N bottles are also shown.

| ID | Batch No. | Salinity ± SD (PSS-78) | Num | Calibrated salinity (PSS-78) | Diff (×10^{-3}) | Correction factor |
|----|-----------|------------------------|-----|------------------------------|-----------------|------------------|
| N  | P138      | 34.9989 ± 0.0004       | 5   | 34.9984                      | 0.8             |                  |
| N  | P141      | 34.9980 ± 0.0002       | 5   | 34.9975                      | 0.5             |                  |
| R  | P142      | 34.9974 ± 0.0003       | 5   | 34.9969                      | 0.2             |                  |
| R  | P144      | 34.9948 ± 0.0004       | 5   | 34.9943                      | -0.1            |                  |
| D  | P145      | 34.9921 ± 0.0001       | 5   | 34.9916                      | 0.999           | 971              |
| D  | P146      | 34.9908 ± 0.0002       | 5   | 34.9903                      | -1.5            | 0.999           |
| D  | P147      | 34.9929 ± 0.0002       | 7   | 34.9924                      | -0.6            | 0.999           |

Determination of P145, P146, and P147 (date of measurements: 6 Jul 2006)

| N  | P138      | 34.9989 ± 0.0004       | 5   | 34.9989                      | 1.3             |                  |
| N  | P139      | 34.9978 ± 0.0002       | 5   | 34.9978                      | 0.1             |                  |
| N  | P141      | 34.9973 ± 0.0003       | 5   | 34.9973                      | 0.3             |                  |
| N  | P142      | 34.9974 ± 0.0001       | 5   | 34.9974                      | 0.7             |                  |
| R  | P144      | 34.9943 ± 0.0004       | 7   | 34.9943                      | -0.1            |                  |
| R  | P145      | 34.9915 ± 0.0005       | 7   | 34.9915                      | -0.1            |                  |
| R  | P146      | 34.9905 ± 0.0001       | 7   | 34.9905                      | 0.2             |                  |
| R  | P147      | 34.9923 ± 0.0002       | 9   | 34.9923                      | -0.1            |                  |
| D  | P148      | 34.9930 ± 0.0001       | 9   | 34.9930                      | 0.0             | 1.000           |

Determination of P148 (date of measurements: 30 May 2007)

| N  | P144      | 34.9952 ± 0.0001       | 3   | 34.9945                      | 0.1             |                  |
| N  | P145      | 34.9924 ± 0.0005       | 3   | 34.9917                      | 0.1             |                  |
| R  | P146      | 34.9911 ± 0.0002       | 3   | 34.9904                      | 0.1             |                  |
| R  | P147      | 34.9928 ± 0.0002       | 4   | 34.9921                      | -0.3            |                  |
| R  | P148      | 34.9938 ± 0.0001       | 7   | 34.9931                      | 0.1             |                  |
| D  | P149      | 34.9951 ± 0.0002       | 9   | 34.9944                      | 0.7             | 1.000           |
| D  | P150      | 34.9928 ± 0.0002       | 9   | 34.9921                      | 0.7             | 1.000           |

Determination of P149 and P150 (date of measurements: 19 Jan 2009)

| N  | P144      | 34.9940 ± 0.0001       | 5   | 34.9939                      | -0.5            |                  |
| N  | P145      | 34.9913 ± 0.0002       | 3   | 34.9912                      | -0.4            |                  |
| N  | P146      | 34.9898 ± 0.0006       | 3   | 34.9897                      | -0.6            |                  |
| N  | P147      | 34.9914 ± 0.0003       | 5   | 34.9913                      | -1.1            |                  |
| R  | P148      | 34.9932 ± 0.0003       | 4   | 34.9931                      | 0.1             |                  |
| R  | P149      | 34.9945 ± 0.0002       | 4   | 34.9944                      | 0.0             |                  |
| R  | P150      | 34.9920 ± 0.0002       | 5   | 34.9919                      | -0.2            |                  |
| D  | P151      | 34.9984 ± 0.0002       | 4   | 34.9983                      | -0.5            | 0.999           |
| D  | P152      | 34.9926 ± 0.0002       | 6   | 34.9925                      | -0.1            | 0.999           |

Determination of P151 and P152 (date of measurements: 25 Aug 2010)

| N  | P141      | 34.9972 ± 0.0004       | 5   | 34.9976                      | 0.6             |                  |
| N  | P143      | 34.9961 ± 0.0002       | 5   | 34.9965                      | 1.0             |                  |
| N  | P144      | 34.9942 ± 0.0003       | 4   | 34.9946                      | 0.2             |                  |
| N  | P145      | 34.9911 ± 0.0002       | 5   | 34.9915                      | -0.1            |                  |
| N  | P146      | 34.9897 ± 0.0001       | 5   | 34.9901                      | -0.2            |                  |
| N  | P147      | 34.9914 ± 0.0004       | 5   | 34.9918                      | -0.6            |                  |
| N  | P148      | 34.9928 ± 0.0003       | 5   | 34.9932                      | 0.2             |                  |
| R  | P149      | 34.9942 ± 0.0002       | 5   | 34.9946                      | 0.2             |                  |
| R  | P150      | 34.9917 ± 0.0002       | 5   | 34.9921                      | 0.0             |                  |
| R  | P151      | 34.9978 ± 0.0002       | 5   | 34.9982                      | -0.1            |                  |
| R  | P152      | 34.9922 ± 0.0002       | 6   | 34.9926                      | 0.1             |                  |
| D  | P153      | 34.9918 ± 0.0003       | 20  | 34.9922                      | 0.4             | 1.000           |

Determination of P153 (date of measurements: 17 Aug 2011)

| R  | P151      | 34.9980 ± 0.0003       | 5   | 34.9983                      | 0.0             |                  |
| R  | P152      | 34.9922 ± 0.0002       | 5   | 34.9925                      | 0.0             |                  |
| R  | P153      | 34.9918 ± 0.0003       | 11  | 34.9921                      | -0.1            |                  |
| D  | P154      | 34.9963 ± 0.0001       | 5   | 34.9966                      | 0.5             | 1.000           |

Determination of P154 (date of measurements: 16 Apr 2012)
| ID | Batch No. | Salinity ± SD (PSS-78) | Num | Calibrated salinity (PSS-78) | Diff (×10⁻³) | Correction factor |
|----|-----------|------------------------|-----|------------------------------|--------------|------------------|
| R  | P151      | 34.9981 ± 0.0001       | 5   | 34.9984                      | 0.1          |                  |
| R  | P152      | 34.9922 ± 0.0002       | 5   | 34.9925                      | 0.0          |                  |
| R  | P153      | 34.9919 ± 0.0001       | 5   | 34.9922                      | 0.0          |                  |
| R  | P154      | 34.9964 ± 0.0002       | 5   | 34.9967                      | 0.1          |                  |
| D  | P155      | 34.9924 ± 0.0002       | 9   | 34.9927                      | 0.1          | 1.0000029        |

Determination of P155 (date of measurements: 15 May 2013)

| R  | P152      | 34.9925 ± 0.0002       | 5   | 34.9929                      | 0.4          |                  |
| R  | P153      | 34.9917 ± 0.0001       | 5   | 34.9921                      | -0.1         |                  |
| R  | P154      | 34.9959 ± 0.0002       | 5   | 34.9963                      | -0.3         |                  |
| R  | P155      | 34.9923 ± 0.0001       | 5   | 34.9927                      | 0.0          |                  |
| D  | P156      | 34.9937 ± 0.0002       | 8   | 34.9941                      | 0.4          | 1.000114         |

Determination of P156 (date of measurements: 6 Jun 2014)

| N  | P152      | 34.9922 ± 0.0002       | 5   | 34.9924                      | -0.1         |                  |
| R  | P153      | 34.9971 ± 0.0003       | 5   | 34.9962                      | -0.1         |                  |
| R  | P154      | 34.9963 ± 0.0003       | 5   | 34.9965                      | -0.1         |                  |
| R  | P155      | 34.9928 ± 0.0003       | 5   | 34.9930                      | 0.3          |                  |
| R  | P156      | 34.9938 ± 0.0003       | 5   | 34.9940                      | -0.1         |                  |
| D  | P157      | 34.9931 ± 0.0003       | 5   | 34.9933                      | -0.8         | 0.9999771        |

Determination of P157 (date of measurements: 19 Nov 2014)

| N  | P153      | 34.9932 ± 0.0004       | 5   | 34.9923                      | 0.1          |                  |
| R  | P154      | 34.9971 ± 0.0001       | 5   | 34.9962                      | -0.4         |                  |
| R  | P155      | 34.9940 ± 0.0002       | 5   | 34.9931                      | 0.4          |                  |
| R  | P156      | 34.9950 ± 0.0001       | 5   | 34.9941                      | 0.0          |                  |
| R  | P157      | 34.9941 ± 0.0003       | 5   | 34.9932                      | -0.1         |                  |
| D  | P158      | 34.9890 ± 0.0004       | 5   | 34.9881                      | -0.2         | 0.9999943        |

Determination of P158 (date of measurements: 27 Dec 2015)

| N  | P141      | 34.9977 ± 0.0001       | 2   | 34.9971                      | 0.1          |                  |
| N  | P144      | 34.9945 ± 0.0006       | 2   | 34.9939                      | -0.5         |                  |
| N  | P148      | 34.9934 ± 0.0004       | 2   | 34.9928                      | -0.2         |                  |
| R  | P155      | 34.9934 ± 0.0002       | 5   | 34.9928                      | 0.1          |                  |
| R  | P156      | 34.9946 ± 0.0002       | 5   | 34.9940                      | -0.1         |                  |
| R  | P157      | 34.9939 ± 0.0001       | 5   | 34.9933                      | 0.0          |                  |
| R  | P158      | 34.9885 ± 0.0002       | 5   | 34.9879                      | -0.2         |                  |
| D  | P159      | 34.9955 ± 0.0003       | 5   | 34.9949                      | -0.4         | 0.9999886        |

Determination of P159 (date of measurements: 14 Feb 2017)

| R  | P156      | 34.9938 ± 0.0003       | 5   | 34.9941                      | 0.0          |                  |
| P157 | 34.9931 ± 0.0002 | 5 | 34.9934 | 0.1 |                  |
| R  | P158      | 34.9876 ± 0.0001       | 5   | 34.9879                      | -0.2         |                  |
| R  | P159      | 34.9949 ± 0.0001       | 5   | 34.9952                      | 0.3          |                  |
| D  | P160      | 34.9930 ± 0.0003       | 5   | 34.9933                      | 0.0          | 1.0000000        |

Determination of P160 (date of measurements: 14 Jul 2017)

| R  | P157      | 34.9935 ± 0.0003       | 5   | 34.9934                      | 0.1          |                  |
| R  | P158      | 34.9882 ± 0.0002       | 5   | 34.9881                      | 0.0          |                  |
| R  | P159      | 34.9950 ± 0.0003       | 5   | 34.9949                      | 0.0          |                  |
| R  | P160      | 34.9933 ± 0.0002       | 5   | 34.9932                      | -0.1         |                  |
| D  | P161      | 34.9948 ± 0.0002       | 4   | 34.9947                      | -0.2         | 0.9999943        |

Determination of P161 (date of measurements: 23 Jul 2018)

| R  | P158      | 34.9887 ± 0.0001       | 5   | 34.9882                      | 0.1          |                  |
| R  | P159      | 34.9955 ± 0.0001       | 5   | 34.9950                      | 0.1          |                  |
| R  | P160      | 34.9936 ± 0.0001       | 4   | 34.9931                      | -0.2         |                  |
| R  | P161      | 34.9953 ± 0.0001       | 5   | 34.9948                      | 0.1          |                  |
| D  | P162      | 34.9933 ± 0.0002       | 5   | 34.9928                      | -0.5         | 0.9999857        |
are also available online (http://www.jamstec.go.jp/datadoi/doi/10.17596/0001983.html). The correction factor was calculated for ID “D” bottles. Relatively older batches of standard seawater were sometimes simultaneously measured in addition to several consecutive batches to determine the batch-to-batch offset (Fig. 1). Differences in practical salinity from the batch-to-batch corrected values are shown in Fig. A1. The differences used for the calibration were mostly within the expanded uncertainty (0.4 $\times$ $10^{-3}$ in practical salinity), although the differences for the older batches sometimes deviated outside the expanded uncertainty.

**APPENDIX B**

**Time Drift of the Salinometer**

Time drift of the salinometer was estimated from ultrapure water (Milli-Q water from MilliporeSigma) and the IAPSO SSW measurements at the beginning and the end of the seawater sample measurements for each day during the R/V Mirai cruise MR19-04 (Fig. B1). The salinometer drifted in time probably because of the contribution from the conductivity cell, because the salinometer was electrically stable during the cruise; the standard deviation of the readings with the FUNCTION switch on both of ZERO and STANDBY was smaller than one last digit (see the technical manual for the salinometer; Guildline Instruments 2004). The salinometer was stable for the first half of the cruise but drifted (about $-0.0012$ in practical salinity per 22 days for SSW measurements) for the second half of the cruise by changing the span of the slope (Fig. B1).

The measurement of a batch-to-batch offset estimation for five consecutive batches (a total of 25 bottles) takes 3 h or less. Therefore, the effect of time drift of the salinometer on the batch-to-batch offset estimation is generally small and is negligible by calibrating the salinometer as shown in Fig. 1.

**APPENDIX C**

**Repeatability of the Decade Resistance Substituter Measurements**

The uncertainty of the HARS decade resistance substituter is claimed by the manufacturer to be $\pm (0.01% + 2\text{ m}\Omega)$. If there is no correlation between the uncertainty of $R_{2,0}$ and $R$ in the calculation of Eq. (1), then the uncertainty of $2R_{2,0}/R$ can be estimated from

![Fig. A1. Differences in practical salinity from the batch-to-batch offset-corrected value (see Table A1). Closed circles show the differences that were used for the calibrations (bottle ID “R” in Table A1), and open circles show the differences that were simultaneously measured at the determination of the batch-to-batch offset of a target batch but not used for the calibration (ID “N” in Table A1). Dashed lines show the expanded uncertainty of the label salinity (Bacon et al. 2007).](unauthenticated-unavailable)

![Fig. B1. Time series of the measured double conductivity ratios $2K$ for (a) the ultrapure water and (b) the IAPSO SSW (batch P162). Dashed lines indicate the average for the ultrapure water and double the label conductivity ratio for the IAPSO SSW. The regression line for the IAPSO SSW measurements (days from 27 to 51) is also shown.](unauthenticated-unavailable)
where $r_{R,2.0}$ is the uncertainty of $R_{2.0}$ and $r$ is the uncertainty of $R$. $U$ is about 0.0003 (0.006 in practical salinity) and 0.000015 (0.00015 in practical salinity) for $2R_{2.0}/R$ of 2 and 0.1, respectively. However, $r_{R,2.0}$ and $r$ are correlated. For example, $U$ must be zero when $R$ is equal to $R_{2.0}$. Therefore, $U$ must be smaller than these estimates, although the resistance of the decade resistance substituter might drift over time. In fact, the results of the decade resistance substituter measurements repeated over two or four years agree well with each other, and the variability is nearly within the resolution of the salinometer ($\pm 0.2 \times 10^{-3}$ in practical salinity) (Fig. C1).

**REFERENCES**

Aoyama, M., T. M. Joyce, T. Kawano, and Y. Takatsuki, 2002: Standard Seawater comparison up to P129. *Deep-Sea Res. I*, 49, 1103–1114, [https://doi.org/10.1016/S0967-0637(02)00018-3](https://doi.org/10.1016/S0967-0637(02)00018-3).

Bacon, S., F. Culkin, N. Higgs, and P. Ridout, 2007: IAPSO Standard Seawater: Definition of the uncertainty in the calibration procedure, and stability of recent batches. *J. Atmos. Oceanic Technol.*, 24, 1785–1799, [https://doi.org/10.1175/JTECH2081.1](https://doi.org/10.1175/JTECH2081.1).

Culkin, F., and P. S. Ridout, 1998: Stability of IAPSO Standard Seawater. *J. Atmos. Oceanic Technol.*, 15, 1072–1075, [https://doi.org/10.1175/1520-0426(1998)015<1072:SOISS>2.0.CO;2](https://doi.org/10.1175/1520-0426(1998)015<1072:SOISS>2.0.CO;2).

Feistel, R., and Coauthors, 2010: Density and absolute salinity of the Baltic Sea 2006–2009. *Ocean Sci.*, 6, 3–24, [https://doi.org/10.5194/os-6-3-2010](https://doi.org/10.5194/os-6-3-2010).

Guildline Instruments, 2004: Technical manual for model 8400B “Autosal.” Guildline Instruments Rep. TM8400B-L-00, 71 pp., [http://www.guildline.com/media/k2/attachments/TM8400B-L-00.pdf](http://www.guildline.com/media/k2/attachments/TM8400B-L-00.pdf).

Howell, G. H., R. Guenther, C. D. Janzen and N. G. Larson, 2010: On the use of a secondary standard to improve Autosal calibration. *Ocean Sciences Meeting*, Portland, Oregon, Amer. Geophys. Union, Abstract 751348, [https://www.seabird.com/cms-portals/seabird_com/cms/documents/SecStandardToImproveAutosalCalHandout-3Pages.pdf](https://www.seabird.com/cms-portals/seabird_com/cms/documents/SecStandardToImproveAutosalCalHandout-3Pages.pdf).

IOC, SCOR, and IAPSO, 2010: The International Thermodynamic Equation of Seawater—2010: Calculation and use of thermodynamic properties. Intergovernmental Oceanographic Commission, Manuals and Guides 56, 220 pp., [http://www.teos-10.org/pubs/TEOS-10_Manual.pdf](http://www.teos-10.org/pubs/TEOS-10_Manual.pdf).

Kawano, T., 2010: Method for salinity (conductivity ratio) measurement. The GO-SHIP repeat hydrography manual: A collection of expert reports and guidelines version 1. IOC/CO Rep. 14, ICPO Publ. Series 134, 13 pp., [http://www.go-ship.org/HydroMan.html](http://www.go-ship.org/HydroMan.html).

——, M. Aoyama, and Y. Takatsuki, 2005: Inconsistency in the conductivity of standard potassium chloride solutions made from different high-quality reagents. *Deep-Sea Res. I*, 52, 389–396, [https://doi.org/10.1016/j.dsr.2004.11.002](https://doi.org/10.1016/j.dsr.2004.11.002).

——, T. Joyce, H. Uchida, Y. Takatsuki, and M. Fukasawa, 2006: The latest batch-to-batch difference table of Standard Seawater and its application to the WOCE onetime sections. *J. Oceanogr.*, 62, 777–792, [https://doi.org/10.1007/s10872-006-0097-8](https://doi.org/10.1007/s10872-006-0097-8).

——, H. Uchida, and T. Doi, Eds., 2009: WHP P01, P14 revisit data book. JAMSTEC, accessed 24 September 2009, [https://doi.org/10.17596/0000033](https://doi.org/10.17596/0000033).

Le Menn, M., 2011: About uncertainties in practical salinity calculations. *Ocean Sci.*, 7, 651–659, [https://doi.org/10.5194/os-7-651-2011](https://doi.org/10.5194/os-7-651-2011).

Levin, L. A., and Coauthors, 2019: Global observing needs in the deep ocean. *Front. Mar. Sci.*, 6, 241, [https://doi.org/10.3389/fmars.2019.00241](https://doi.org/10.3389/fmars.2019.00241).

Li, Y., Y. Luo, Y. Kang, T. Yu, A. Wang, and C. Zhang, 2016: Chinese Primary Standard Seawater: Stability checks and comparisons with IAPSO Standard Seawater. *Deep-Sea Res. I*, 113, 101–106, [https://doi.org/10.1016/j.dsr.2016.04.005](https://doi.org/10.1016/j.dsr.2016.04.005).

——, Y. Kang, H. Yu, and Y. Pang, 2018: Linearity corrections for laboratory salinometer measurements: IAPSO Standard Salinity Curve linearly pack vs weight diluted samples. *Deep-Sea Res. I*, 137, 13–19, [https://doi.org/10.1016/j.dsr.2018.04.011](https://doi.org/10.1016/j.dsr.2018.04.011).

Millero, F. J., 2006: *Chemical Oceanography*. 3rd ed. CRC Press, 496 pp.

——, F. Huang, R. J. Woosley, R. T. Letscher, and D. A. Hansell, 2010: Effect of dissolved organic carbon and alkalinity on the density of Arctic Ocean waters. *Aquat. Geochem.*, 17, 311–326, [https://doi.org/10.1007/S10498-010-9111-2](https://doi.org/10.1007/S10498-010-9111-2).

Pawlowski, R., D. G. Wright, and F. J. Millero, 2011: The effects of biogeochemical processes on oceanic conductivity/salinity/ density relationships and the characterization of real seawater. *Ocean Sci.*, 7, 363–387, [https://doi.org/10.5194/os-7-363-2011](https://doi.org/10.5194/os-7-363-2011).

——, R. Feistel, T. J. McDougall, P. Ridout, S. Seitz, and H. Wolf, 2016: Metrological challenges for measurements of key climatological observables Part II: Oceanic salinity.
Purkey, S. G., G. C. Johnson, L. D. Talley, B. M. Sloyan, S. E. Wijffels, W. Smethie, S. Mecking, and K. Katsumata, 2019: Unabated bottom water warming and freshening in the South Pacific Ocean. *J. Geophys. Res. Oceans*, 124, 1778–1794, https://doi.org/10.1029/2018JC014775.

Seitz, S., R. Feistel, D. G. Wright, S. Weinreben, P. Spitzer, and P. De Bievre, 2011: Metrological traceability of oceanographic salinity measurement results. *Ocean Sci.*, 7, 45–62, https://doi.org/10.5194/os-7-45-2011.

——, P. T. Jakobsen, and M. Mariassy, 2019: Metrological advances in reference measurement procedures for electrolytic conductivity. *Metrologia*, 56, 034003, https://doi.org/10.1088/1681-7575/ab1527.

Swart, N. C., S. T. Gille, J. C. Fyfe, and N. P. Gillett, 2018: Recent Southern Ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. *Nat. Geosci.*, 11, 836–841, https://doi.org/10.1038/s41561-018-0226-1.

Uchida, H., and T. Doi, Eds., 2017: WHP P01 revisit in 2014 data book. JAMSTEC, accessed 24 March 2017, https://doi.org/10.17596/00000029.

——, M. Fukasawa, and H. J. Freeland, Eds., 2002: WHP P01 revisit data book. JAMSTEC, accessed 3 April 2007, http://www.jamstec.go.jp/iorgc/ocorp/data/p01rev_1999/.

——, T. Kawano, M. Aoyama, and A. Murata, 2011: Absolute salinity measurements of standard seawaters for conductivity and nutrients. *Mer*, 49, 119–126, http://www.sfjo-lamer.org/la_mer/49-3_4/49-3-4-5.pdf.

——, Y. Kayukawa, and Y. Maeda, 2019: Ultra high-resolution seawater density sensor based on a refractive index measurement using the spectroscopic interference method. *Sci. Rep.*, 9, 15482, https://doi.org/10.1038/s41598-019-52020-z.

Wakita, M., A. Nagano, T. Fujiki, and S. Watanabe, 2017: Slow acidification of the winter mixed layer in the subarctic western North Pacific. *J. Geophys. Res. Oceans*, 122, 6923–6935, https://doi.org/10.1002/2017JC013002.