Pressure dependence of reference deep-ocean thermometers

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Abstract
In this work, the pressure dependence of the temperature readings of reference deep-ocean thermometers (i.e. SBE 35, Sea-Bird Electronics) was investigated in a thermostatically controlled and pressurized environment. To this end, a deep-ocean environment emulator was constructed to reproduce the extremely stable temperature and high-pressure nature of the deep ocean; it consisted of a pressure vessel, a pressure controller and a thermostatic water bath. With the aid of this emulator, the pressure effect on three SBE 35 thermometers was investigated at various hydrostatic pressures from atmospheric pressure to 68 MPa, equivalent to the pressure at a depth of 6,800 m. In addition, the effect of external thermal disturbances was corrected by measuring the real-time temperature variation around the SBE 35 thermometer in order to achieve the highest possible accuracy. From extensive testing of the pressure dependence of the temperature readings of the three SBE 35 thermometers, it was found that two of the three thermometers exhibited clear and repeatable pressure dependences, although the respective tendencies were different from each other. The third thermometer showed no repeatable pressure dependence. All the measured pressure dependences of the three thermometers amounted to changes which were within ±1 mK. The results indicated that the pressure dependence of these reference deep-ocean thermometers is significant, and the pressure dependence is not the same for all SBE 35 devices but specific to each individual device. It was concluded that the pressure dependence of the individual reference deep-ocean thermometers needs to be accounted for during calibration.

KEYWORDS
deep-ocean environment emulator, deep-ocean temperature, external thermal disturbances, pressure dependence, reference deep-ocean thermometer, SBE 35

INTRODUCTION

Deep-ocean temperature is a clear indicator of long-term climate change. Due to the large volume of the deep ocean, about 40% of the total ocean heat content, which serves as the largest heat reservoir in the Earth's climate system (IPCC, 2013), is stored in the depths below 700 m (Church et al., 2011). In addition, because of the large...
thermal inertia of such a volume of sea water, the oceans clean up the climate signal, eliminating the effect of short-term variations due to weather conditions. Furthermore, as a small change in the deep-ocean temperature also serves as an indicator of a change in the ocean currents, which is observed by a comparison between the decadal hydrographic measurements (Fukasawa et al., 2004; Uchida et al., 2007; 2015), observation of the deep-ocean temperature can be an effective way of monitoring the long-term evolution of global climate change and of tracking the changes in the ocean circulation.

The typical temperature change in the deep ocean is estimated to be about 1 mK per decade (Wunsch, 2016), and because of this small change in temperature very sensitive thermistor-based thermometers are generally used to monitor it. Two types of thermometer are widely used in deep-ocean thermometry: working thermometers (SBE 3, Sea-Bird Electronics), having a drift rate of about 2 mK per year, are calibrated in situ by comparison with a reference-grade thermometer (SBE 35, Sea-Bird Electronics) having a stability of about 0.14 mK per year. Notably, as the measurement uncertainty of the deep-ocean temperature for tracking the ocean currents needs to be less than about 2 mK (Fukasawa et al., 2004; Uchida et al., 2007; 2015), it is very important to guarantee that the measurement uncertainties of the deep-ocean thermometers (i.e. the SBE 3 and SBE 35 thermometers) do not increase during deployment over and above the calibration uncertainties; alternatively, the calibration of these thermometers should include all possible factors affecting the temperature measurements encountered during deployment down to the deepest (rated) depth. However, due to the possible pressure dependence of the temperature readings of these deep-ocean thermometers, which has already been reported in some literature (Uchida et al., 2007; 2015; Peruzzi et al., 2017), there is a strong need to understand the pressure dependence of the deep-ocean thermometers in a thermostatically controlled and pressurized environment.

In particular, despite the well characterized pressure dependence of the working thermometers (i.e. SBE 3), the reference deep-ocean thermometer (i.e. SBE 35) still lacks a reliable characterization of its pressure dependence (Uchida et al., 2007; 2015). In addition, since the working thermometers are calibrated in situ by comparison with the reference thermometers, the pressure dependence of the reference deep-ocean thermometer is of paramount importance for accurate calibration and subsequent measurement of the deep-ocean temperature. A recent examination of the pressure dependence of the SBE 35 thermometer showed a significant pressure dependence implying that the in situ calibration of the SBE 3 thermometers by comparison with the SBE 35 may not be a suitable practice (Peruzzi et al., 2017). However, as in that work the environmental temperature around the deep-ocean thermometers was not precisely controlled, and as only one reference thermometer was employed to test the pressure dependence, a more detailed investigation in a thermostatically controlled environment with several reference thermometers is still necessary for accurate characterization and generalization of the findings. This amounts to emulating an extremely stable thermal environment with a stability less than a millikelvin and very large hydrostatic pressures, up to a few tens of megapascals.

In this work, to investigate the pressure effect on the temperature readings of the reference deep-ocean thermometers (SBE 35), a pressure vessel capable of achieving pressures up to 68 MPa was constructed, and this in turn was fully immersed in a thermostatic water bath having a nominal temperature stability of about ±1 mK. Protruding into the pressure vessel was an unpressurized thermometer well located near the sensing part of the SBE 35, which was closed only at one end; the other end was open to accommodate a standard platinum resistance thermometer (SPRT). The SPRT was used to correct for the external thermal disturbances due to the finite temperature stability of the thermostatic bath, thus enabling complete separation of the pressure effect from the thermal disturbances. Three SBE 35 thermometers were tested at various pressures from atmospheric pressure to 68 MPa, which is equivalent to the hydrostatic pressure at a depth about 6,800 m. The detailed experimental set-up and the measurement procedures are described in Section 2. The measurement results are provided and discussed in Section 3 in the context of the possible implications for reliable calibration of deep-ocean thermometers and hence accurate measurement of the deep-ocean temperature. Some conclusions are drawn in Section 4.

2 TEST SET-UP AND METHODS

In this work, a deep-ocean environment emulator was constructed to thermo-hydraulically reproduce the deep-ocean environment down to 6,800 m; the emulator consisted of a pressure vessel, a pressure controller and a thermostatic water bath. The pressure vessel was made of rigid stainless steel (316 L) containers and was designed to accommodate and pressurize the whole body of the reference deep-ocean thermometer (SBE 35) up to a pressure of 68 MPa, which is the equivalent hydrostatic pressure at a depth of about 6,800 m and is also the maximum pressure allowed for the SBE 35 thermometer. Figure 1a,b shows drawings of the pressure vessel and a
The photograph of the pressure vessel immersed in the thermostatic bath. As shown in Figure 1, the pressure vessel was equipped with a closed-end thermometer well protruding into the fluid within, allowing the insertion of an SPRT from outside. The tip of the well is located near the sensing part of the SBE 35; the SPRT mount on this unpressurized but thermally linked space allowed measurement of the real-time temperature variation near the SBE 35 thermometer. This enabled an accurate temperature correction in response to environmental temperature changes.

The generation of the hydrostatic pressure was accomplished using a manual bellows-type pressure controller, which was able to generate a hydrostatic pressure up to 70 MPa with an uncertainty of about 10 kPa (with a confidence level of approximately 95%). To control the temperature, a thermostatic water bath having internal dimensions of 1 m × 0.5 m × 0.5 m (length × width × depth) was employed. The temperature range and the nominal stability of the bath were from −5°C to 50°C, and about 1 mK, respectively. Throughout the experiment, the temperature of the water was set at 25°C to avoid unnecessary cooling and heating of the medium in the laboratory environment. Figure 2 shows the temperature variations measured by the SBE 35 (in the pressure vessel) and the adjacent SPRT (in the protruding...
well) for 10 hr at atmospheric pressure (i.e. the unpressurized condition). The figure shows that both temperature readings showed a close correspondence, implying that the SPRT was able to measure the temperature variation near the sensing part of the SBE 35 reliably; a slight delay in the SPRT reading compared with the SBE 35 was attributed to the thermal resistance between the SBE 35 and the SPRT (e.g. the thermal resistance through the intervening water in the pressure vessel and the wall of the thermometer well). The measured standard deviations during the 10 hr measurement were slightly less than 0.3 mK, but as the peak-to-peak variation exceeded the stated stability of the bath (i.e. 1 mK) an additional correction, based on the SPRT measurements, for the environmental temperature changes (i.e. the external thermal disturbances) needed to be implemented.

The pressure effect on the temperature readings of the SBE 35 thermometer was assessed by measuring the temperature difference read by the SBE 35 between an elevated test pressure (i.e. \( p_{\text{test}} \)) and atmospheric pressure (i.e. \( p_{\text{atm}} \)). The tested pressures were 10, 20, 30, 40, 50, 60 and 68 MPa. The measurements of the temperature readings of the SBE 35 and the SPRT at the tested pressures were made only after complete stabilization of the readings from both thermometers, and afterwards the pressure vessel was relieved to measure the temperatures at atmospheric pressure. In this work, three SBE 35 thermometers were tested to determine the pressure dependence (i.e. those with serial numbers [SN] 0040, 0089 and 0098). A fully annealed SPRT connected to an AC resistance ratio bridge (F900, Automatic System Laboratories) was used to measure the actual temperature change near the sensing part of the SBE 35 during the pressure change tests.

### RESULTS AND DISCUSSION

In this work, at each pressure the measured temperature change of the SBE 35 due to the elevated pressure (i.e. \( \Delta t_{\text{SBE 35}}(p_{\text{test}} - p_{\text{atm}}) \)) was corrected for the external thermal disturbance (i.e. \( \Delta t_{\text{SPRT}}(p_{\text{test}} - p_{\text{atm}}) \)). The corrected temperature change (i.e. \( \Delta t(p_{\text{test}} - p_{\text{atm}}) \)) and the corresponding uncertainty of the corrected temperature change (i.e. \( U(\Delta t(p_{\text{test}} - p_{\text{atm}})) \)) were obtained using:

\[
\Delta t(p_{\text{test}} - p_{\text{atm}}) = \Delta t_{\text{SBE 35}}(p_{\text{test}} - p_{\text{atm}}) - \Delta t_{\text{SPRT}}(p_{\text{test}} - p_{\text{atm}})
\]

(1)

\[
U^2(\Delta t(p_{\text{test}} - p_{\text{atm}})) = U^2(\Delta t_{\text{SBE 35}}(p_{\text{test}} - p_{\text{atm}})) + U^2(\Delta t_{\text{SPRT}}(p_{\text{test}} - p_{\text{atm}}))
\]

(2)

In the estimation of the uncertainties in the temperature difference of each thermometer, non-repeatability was assumed to be the major source of uncertainty as errors arising from the other components were cancelled out due to correlation.

Figure 3a,b shows the temperature changes measured by the same SBE 35 thermometer for various pressure differences before and after applying the correction for the external thermal disturbances (i.e. the environmental temperature changes). Figure 3 shows that the correction gives a big reduction in the scatter of the measured temperature differences, demonstrating the effectiveness of the correction technique.

Based on this finding, the temperature differences for each pressure were measured three times for each of the three SBE 35 thermometers. The results are shown in Figure 4. As shown in Figure 4a–c, clear repeatable pressure dependences of the temperature readings were
observed for two of the tested SBE 35 thermometers (SN 0040 and 0089). One of the SBE 35 thermometers (SN 0040) showed continuously increasing temperature readings with increasing hydrostatic pressure except at the highest extreme (i.e. at 68 MPa), and another (SN 0089) showed an increase and then a decrease with increasing pressure, while SN 0098 showed no systematic pressure dependence. Figure 5 shows the averaged temperature differences of the SBE 35 thermometers with expanded uncertainties evaluated at approximately 95% level of confidence. Table 1 shows the numerical values of the temperature differences and the corresponding expanded uncertainties. As shown in Figure 5 and Table 1, the observed temperature differences measured by the SBE 35 SN 0040 were beyond the expanded uncertainties for most of the tested pressure range, while SN 0089 showed temperature differences outside the claimed uncertainties only at low and high pressures, and SN 0098 showed temperature differences within the measurement uncertainties for most of the tested pressure range. All the measured pressure dependences of the three tested thermometers (i.e. $\Delta t(p_{\text{test}} - p_{\text{atm}})$) manifested themselves as errors within a range of 1 mK.

FIGURE 3 Change in the temperature difference between atmospheric pressure and the pressure indicated (a) before and (b) after applying the correction for the external thermal disturbances (i.e. the environmental temperature changes); the temperature difference was measured by one of the reference deep-ocean thermometers (serial number SN 0040)

FIGURE 4 Variation of the temperature difference between atmospheric pressure and the indicated pressure for the three reference deep-ocean thermometers; the depicted temperature differences are here corrected for the effect of the external thermal disturbances: (a) serial number SN 0040; (b) SN 0089; (c) SN 0098
From these results, it was found that the pressure dependence of the reference deep-ocean thermometers (SBE 35) was significant, and the pressure dependence was not a general effect but specific to each individual thermometer. As the pressure effect of the deep-ocean thermometers is known to be caused by pressure transfer through the stainless steel needle containing the thermistor in a glass bead (Peruzzi et al., 2017), the effect would not be expected to be identical for different thermometers. Hence, the observed responses of the tested SBE 35 thermometers (i.e. the specific nature of the pressure dependence) are to be expected. Therefore, in accordance with previous work (Peruzzi et al., 2017), the in situ calibration of working deep-ocean thermometers (e.g. SBE 3) by comparison with the reference thermometer (SBE 35) is not recommended unless the pressure dependence of the individual reference thermometers is accounted for.

4 | CONCLUSIONS

In this work, the pressure dependence of three Sea-Bird Electronics SBE 35 reference deep-ocean thermometers was extensively examined in a thermo-hydraulically emulated deep-ocean environment. To this end, a pressure vessel, which was able to accommodate and pressurize the whole body of an SBE 35 thermometer, was immersed in a thermostatic water bath and pressurized from atmospheric pressure up to a pressure equivalent to the hydrostatic pressure at a depth of about 6,800 m (i.e. up to about 68 MPa). Using this deep-ocean environment emulator, the changes in the temperature readings of the three SBE 35 thermometers were measured at various hydrostatic pressures in a thermostatically controlled environment having peak-to-peak temperature changes of about 1 mK and a standard deviation of less than 0.3 mK over 10 hr. During the test, to achieve the best possible accuracy the external thermal disturbances due to the instability of the thermostatic bath were also corrected for by compensating for the real-time temperature variation around the SBE 35 thermometer as measured using an unpressurized standard platinum resistance thermometer.

Results obtained from the three SBE 35 thermometers showed that at least two of the three thermometers exhibited a clear and repeatable pressure dependence, giving rise to temperature readings in excess of the

| $p_{\text{test}} - p_{\text{atm}}$ / MPa | $U$ / MPa | $\Delta t$ / mK | $U\{\Delta t\}$ / mK |
|----------------------------------------|-----------|----------------|-----------------------|
| SN 0098 | 10.21 0.19 | −0.30 0.57 | SN 0098 |
| 20.25 0.10 | −0.61 0.49 | | |
| 29.95 0.42 | −0.43 0.49 | | |
| 39.55 0.47 | −0.42 0.73 | | |
| 50.11 0.85 | −0.31 0.52 | | |
| 59.81 0.57 | −0.41 0.60 | | |
| 67.40 1.38 | −0.27 0.42 | | |
| SN 0089 | 10.54 0.13 | −0.39 0.25 | SN 0089 |
| 20.36 0.49 | 0.06 0.68 | | |
| 30.12 0.58 | 0.13 0.60 | | |
| 39.81 0.58 | 0.12 0.27 | | |
| 50.12 1.14 | −0.28 0.32 | | |
| 59.74 0.26 | −0.31 0.19 | | |
| 67.42 1.00 | −0.63 0.26 | | |
| SN 0040 | 10.41 0.52 | 0.08 0.11 | SN 0040 |
| 20.49 0.15 | 0.24 0.36 | | |
| 30.43 0.79 | 0.54 0.44 | | |
| 39.80 0.58 | 0.56 0.29 | | |
| 49.63 0.47 | 0.73 0.38 | | |
| 59.29 0.51 | 0.94 0.56 | | |
| 67.29 1.11 | 0.50 0.20 | | |

FIGURE 5 Variation of the average temperature differences between atmospheric pressure and the indicated pressure for the reference deep-ocean thermometers. The error bars indicate the measurement uncertainties of the temperature differences (vertical) and the measured hydrostatic pressures (horizontal) at approximately 95% level of confidence.

TABLE 1 The averaged temperature differences of the SBE 35 thermometers and the corresponding expanded uncertainties (at approximately 95% level of confidence)
permitted measurement uncertainties. The observed pressure dependence of the three thermometers amounted to changes in temperature readings within 1 mK. These results show that the pressure dependence of the reference deep-ocean thermometers (i.e. SBE 35) is significant, and the observed pressure dependence was not the same for all SBE 35 thermometers but specific to each individual thermometer. Therefore, it was concluded that in situ calibration of the working deep-ocean thermometers (e.g. SBE 3) by comparison with the reference thermometer is not recommended unless the reference deep-ocean thermometer is fully characterized at various temperatures and pressures. The pressure dependence of the individual reference deep-ocean thermometers needs to be accounted for during the calibration of working deep-ocean thermometers.

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