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An in-situ experiment identifying flow effects on temperature measurements using a pumped CTD in weakly stratified waters

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ABSTRACT

A simple experiment shows that the tubing leading to and from the pumped duct of temperature T and conductivity C-sensors of a Sea-Bird Electronics 911plus CTD can cause artificial T-effects as a function of the instrument package vertical velocity. This artifact is due to a pressure difference between inlet and exhaust tubes of the pump-system, even when they are mounted at precisely the same height (pressure level). The vertical velocity dependent pressure difference causes an estimated internal flow speed variation of $\pm 0.5\ \mathrm{m\,s^{-1}}$ inside the pumped duct that generates artificial temperature variations of ± 0.5 mK due to sensor frictional heating. First, this effect is demonstrated in weakly stratified waters by precise but horizontal mounting of the two tubes (at the same height), which leads to similar amplitudes of erroneous T and opposite sign as erroneous T observed using the standard vertical mounting. Secondly, the use of identical surface area tubes, mounted (at the same height) in the vertical downward direction, successfully removes the unwanted pressure gradient and hence the temperature dependence. This second mounting, acting as a hardware filter, can effectively replace a recently proposed software filter.

1. Introduction

Ship's and/or instrument's motions affect high-precision temperature (T) measurements using a shipborne Sea-Bird Electronics SBE911plus Conductivity-Temperature-Depth (CTD) profiler in very weakly stratified waters where the buoyancy frequency N is only a few cycles per day, cpd (van Haren, 2015; Uchida et al., 2015). Artificial temperature variations (ΔT) were found in data from deep Puerto Rico Trench (PRT) waters (van Haren, 2015), as well as, in retrospect, in historic data from deep NE-Atlantic waters (Fig. 1), to be correlated with the instrument package vertical velocity, under zero phase-lag, like,

$$\Delta \mathrm{T} = \gamma_{\mathrm{T}} \mathrm{d}p/\mathrm{d}t, \quad \gamma_{\mathrm{T}} = -3 \pm 1 \times 10^{-4}\,{}^{\circ}\mathrm{C\,s\,dbar^{-1}}, \tag{1}$$

where p denotes pressure and t time. Here ‘instrument package vertical velocity’ refers to the vertical velocity of the instrument as it is lowered or hoisted. This velocity is modulated by the motion of the sheave over which the cable attaching the instrument package to the ship lays, that motion being induced by the action of surface gravity waves on the ship. Conductivity was not correlated with the instrument package vertical velocity.

Following (1), at about $1\ \mathrm{m\,s^{-1}}$ downcast velocity, average T was cooler by about $6 \times 10^{-4}\,{}^{\circ}$C compared with that of upcast data. The data underlying the empirical relation (1) were measured using a standard vertical mounting of the pumped TC-duct with tubing of different inner diameters (ID's) as per instructions from the manufacturer (Sea-Bird, 2012). Uchida et al. (2015) reported data obtained by using a standard horizontal mounting of the pumped TC-duct were not affected by such instrument velocities.

Although the cause of the erroneous T-data was not found, the relation (1) suggested unwanted flow-induced pressure variations across the pumped TC-duct. It could not be attributed to the dragging of warmer/cooler waters by the CTD-frame, as this would give erroneous T in variable phase difference with pressure (Trump, 1983), but not strictly in phase with pressure tendency (first derivative of pressure with respect to time) as in (1). To remedy this artifact, a software post-processing low-pass filter was proposed (van Haren, 2015) to remove the variations due to surface wave effects. Naturally, this filter could not remedy the ‘constant’ difference between down- and upcast or any other mechanical variation in instrument package vertical velocity varying at intervals of 20 s or more.

In this note, a simple in-situ experiment is described to determine the cause of the artificial T-variations and to create a hardware solution for the problem outlined in (1), that is, to minimize the value of γ_{T}, for a vertically mounted SBE911plus CTD. As the T-measurement is partially dependent on flow speed

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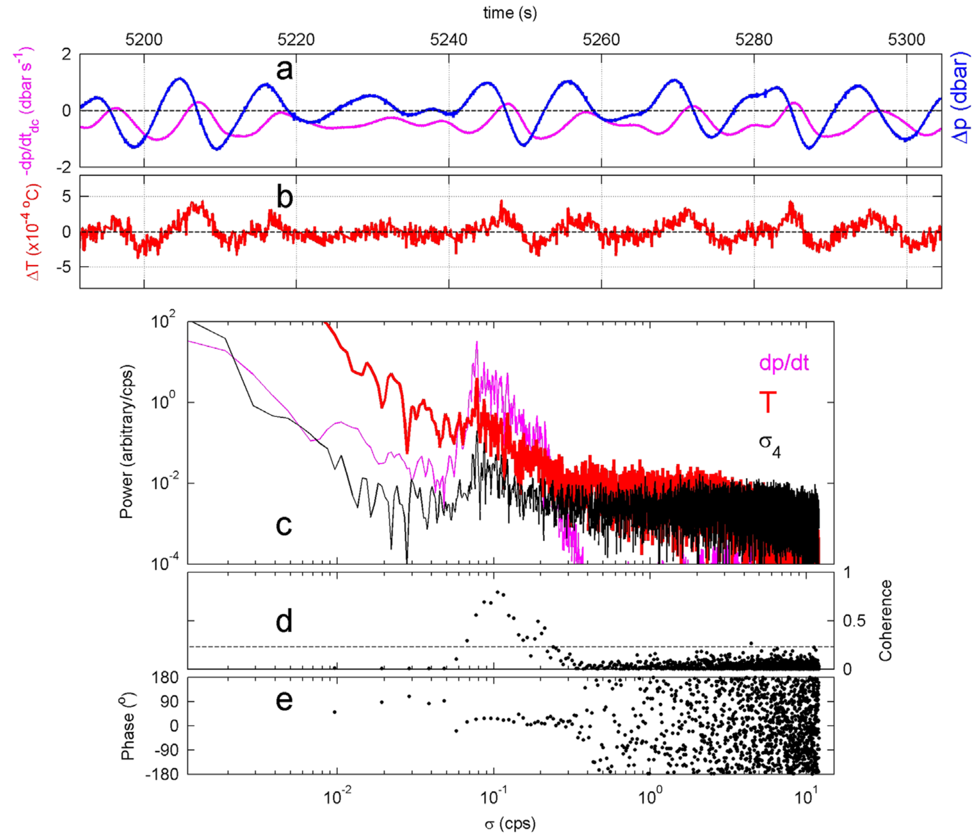

Fig. 1. Nearly raw 24 Hz sampled historic downcast data obtained from the R/V Pelagia using a standard vertical CTD-configuration at 37° 30′N, 12° 34′W in 5100 m water depth on 29 October 2012. Short example time series for the 50-m depth range [4785,4835] m. (a) Detrended pressure (blue) and its (negative signed) first time derivative −dp/dt, 2-dbar-smoothed (purple). (b) Detrended temperature. (c) Nearly unsmoothed (~3 degrees of freedom; dof) spectra of data from the 4000–5000 m depth range. (d) Moderately smoothed (40 dof) coherence between dp/dt and T from panel c., with dashed line indicating the 95% significance level. (e) Corresponding phase difference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

through sensor frictional heating, our experiment is set-up to verify the hypothesis that the 'internal' flow speed inside the TC-duct is not constant. We presume this is caused by a variable pressure tendency across the duct induced by the turbulent flow around different ID's of intake and exhaust. The null hypothesis is then a constant (pump) flow yielding no variation in internal flow speed despite any variations in instrument package vertical velocity. We speculate that the hypothesized variation of the internal flow speed as a function of the instrument package vertical velocity is reduced to zero when identical ID's are used for end-tubing of intake and exhaust. Ideally, such a solution would work for all instrument package vertical velocity variations.

2. Data

We had brief opportunity to make experimental observations from the Dutch R/V Pelagia above a NE-Atlantic abyssal plain off Portugal. Using freshly calibrated T-C sensors (calibration date: April 2015), SBE911plus CTD-profiles were obtained at 36° 56′N, 12° 58′W in 5100 m water depth on 17 August 2015. The sensor housings were mounted vertically next to the main electronics housing (Fig. 2) in a frame which can be used independently, or inside a 1.5 m high Rosette-carousel holding 24 water sampling bottles. For the present experiment the CTD-frame was lowered, without Rosette-carousel, via a heave compensator. This compensator reduces the effects of the ship's vertical motions by no more than 50% from the surface to 2000 m depth. Below 2000 m, the heave compensator does not function because of the weight of the cable and instrument package.

The standard CTD configuration has T- and C-sensors vertically mounted in a 'TC-duct' attached to a 3000 rpm pump, realizing an internal flow speed of 2.3 m s^{-1} near the sensors, just behind the intake. The sensors are near the bottom of the electronics frame, with an unobstructed flow exposure when moving downward. The exhaust of the pumped duct is at the same (pressure) level as the intake, so as to in principle eliminate the ram effect of dynamic pressure to maintain a constant flow passing the sensors (Sea-Bird, 2012).

However, the cross-section area of the downcast directed inlet and exhaust perpendicular to the mean down- and upward velocity direction is not identical in the standard configuration. This is, as per instructions from the manufacturer (Figs. 1-2 in Sea-Bird, 2012), because no tube is used over the inlet of the TC-duct and a soft long tube is used over the pump outlet to bring the exhaust down to the same height as the inlet. The intake has a 0.004 m ID while the exhaust 0.012 m. This gives a one order of magnitude difference between intake and exhaust internal speeds for a given flow-rate. In addition, a more complex pressure and flow difference is expected between the different tubes of intake and exhaust, because of the strongly turbulent character of the flow. We modify the end-tubing of both inlet and exhaust for the present in-situ experiments.

Due to time limitations, we could not make a cast with standard CTD-configuration. As a reference we use an R/V Pelagia standard CTD-cast obtained in the same deep-sea basin 60 km NNE of the above position in 2012. When these historic data were taken, the surface wave heights were half of those when PRT observations were made reported in van Haren (2015) and about two-thirds of those when the present observations were made.

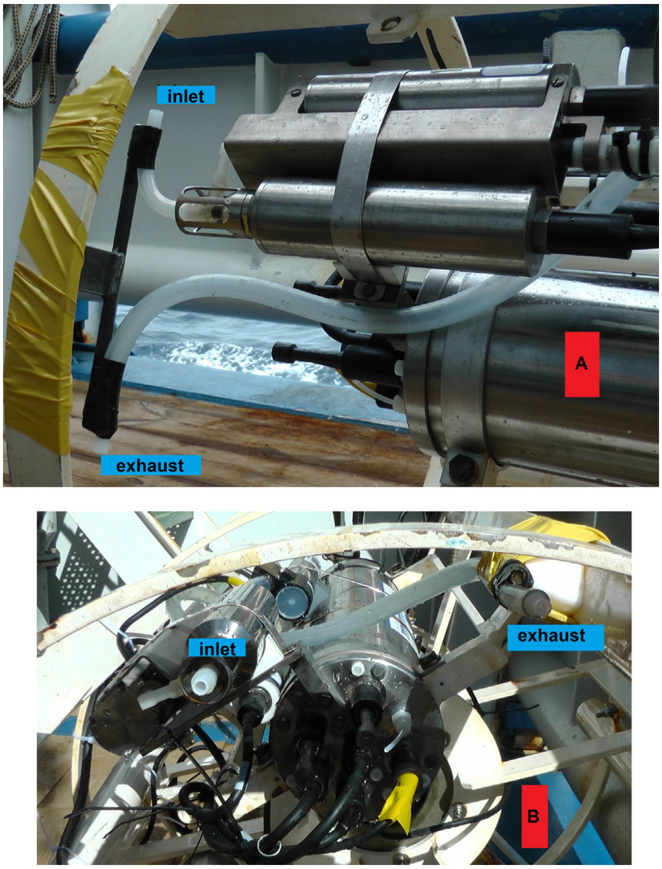

Fig. 2. Two experimental set-ups of TC-sensor pump end-tubing of the same flow-obstructive area with 0.006 m inner diameter. (a) Experiment A: horizontally directed inlet and exhaust. Side-view of part of the CTD-electronics frame that is lying on its side on deck; the direction of lowering in the water would be to the left. (b) Experiment B: downward directed inlet and exhaust. Plan-view from below of (part of the) CTD-electronics frame; the direction of lowering in the water would be out of the page, nearly towards the viewer.

Also, the mean downward instrument package vertical velocity was reduced to 0.4–0.5 m s^{-1} (Fig. 1a) in the lower 300 m, while in other casts the normal vertical velocity of about 1 m s^{-1} was maintained except in the lower 10–20 m above the bottom (not considered here).

3. Results

We performed two experiments with different mounting of inlet and exhaust tubing. In both experiments, we used identical end-tubing of 0.006 m ID for inlet and exhaust so as to have the same surface area across their opening. We took care that inlet and exhaust were at the same height.

In experiment A (Fig. 2a), we used a custom-made T-bar to mount the inlet and exhaust tubes horizontally, so that in- and outflow surface-normal vectors were perpendicular to the instrument package vertical velocity. The bar prevented direct attachment to the frame and multiple layers of tape applied to the bar before attachment afforded some thermal isolation of the tubes from the bar. Erroneous temperature data due to bulk heating from the tubing or frame are not the issue here. They are even expected to be negligible (below detection limit) in the weakly stratified waters under investigation where T-variations are typically 1 mK. We recall that the present hypothesis associates erroneous T-data with vertical velocity (pressure-tendency) variations, not with pressure variations as the above potential errors due to bulk and frictional tube heating would imply. This is provided the null hypothesis is valid of a constant pump flow dominating the internal flow. In retrospect, this experiment set a reference for potential pressure difference effects by variable turbulent flow across inlet and exhaust.

In experiment B (Fig. 2b), we mounted the tubes vertically, as in Sea-Bird (2012) but with identical cross-sectional areas for inlet and exhaust (including in particular a small set-up tube over the TC-duct inlet). In this experiment, the exhaust is held away from the frame by taping it to a custom-made Teflon separator. Note that the horizontal distance between inlet and exhaust is about the same in both experiments.

For each experiment, we lowered the CTD to great depths >4000 m, where the stratification is very weak with N between 0 and 4 cpd. For comparison, the data examined from the PRT were in waters with N = 1.9 cpd (van Haren, 2015) and the data in Fig. 1 in homogeneous waters $N \approx 0$. In such waters, natural temperature variations are in the 1 mK range with a Conservative ($\sim$potential) temperature gradient of typically $d\Theta/dz = 2-3 \times 10^{-5}$°C m^{-1}. Thus, the adiabatic lapse rate, $\Gamma = -1.5 \times 10^{-4}$ °C $dbar^{-1}$, is dominantly visible in temperature increasing with depth due to compressibility effects. Nonetheless, in such waters slow internal waves and large-scale overturning can be observed (van Haren and Gostiaux, 2011). From the present CTD-measurements in this depth range, all main variables show a dominant oscillation with time having relatively short periods from 8 to 10 s (Fig. 3). As before (Fig. 1), this oscillation is associated with ship's motion due to surface waves. Although sea conditions were favorable (2 m surface wave height; 6 m s^{-1} wind speeds), considerable variation is found in the (here downcast-) instrument package vertical velocity, as may be inferred from the pressure variations (Fig. 3a).

In the CTD-cast of experiment A, temperature variations (Fig. 3b) are approximately in-phase with pressure tendency (purple line in Fig. 3a; $\sim$velocity), not with pressure variations. The correspondence between instrument package vertical velocity and T-variations is found to be close to (1), with similar value (by chance) well within error for γ_T except for the sign. The latter implies an 'overcompensation' with respect to the Sea-Bird (2012) standard configuration used in similar weakly stratified waters in van Haren (2015) and in Fig. 1. Both data sets yield a coherent relationship between dp/dt and T in the frequency range around 0.1 cps (Figs. 1d, 3d), but with corresponding phase difference near zero ($25 \pm 15°$) in Fig. 1e and oppositely near π ($155 \pm 15°$) in Fig. 3e. It is confirmed by quasi-steady mean temperatures in the homogeneous near-bottom waters around 4900 m where downcast-T is found warmer by 2×10^{-4}°C than upcast-T (and opposite in sign to those for Fig. 1 and reported in van Haren, 2015 and Uchida et al., 2015). These observations indicate that pressure differences are induced in the TC-duct tubing, so that the internal flow passing the sensors is not a constant (solely due to the pumping) but highly variable with time and a function of the instrument package vertical velocity. The overcompensation sign-change may be, as a constant with time for a given flow rate, due to the longer tube used before intake because of viscous heating at the tube walls. However, this would equally increase upcast-T and cannot explain the sign-change that is variable with time. The overcompensation is most likely either due to the effects of rotation as suggested by Uchida et al. (2015), or due to the complex turbulent oblique flow causing further/reverse pressure gradient differences inside the tubing.

The variable internal flow speed imposes artificial T-measurement variations due to sensor frictional heating ($\approx +1 \times 10^{-3}$ °C for a 1 m s^{-1} flow speed; Larson and Pedersen, 1996), but does not affect the C-measurements, as was confirmed by van Haren (2015) and in the present data (not shown). This also results in an

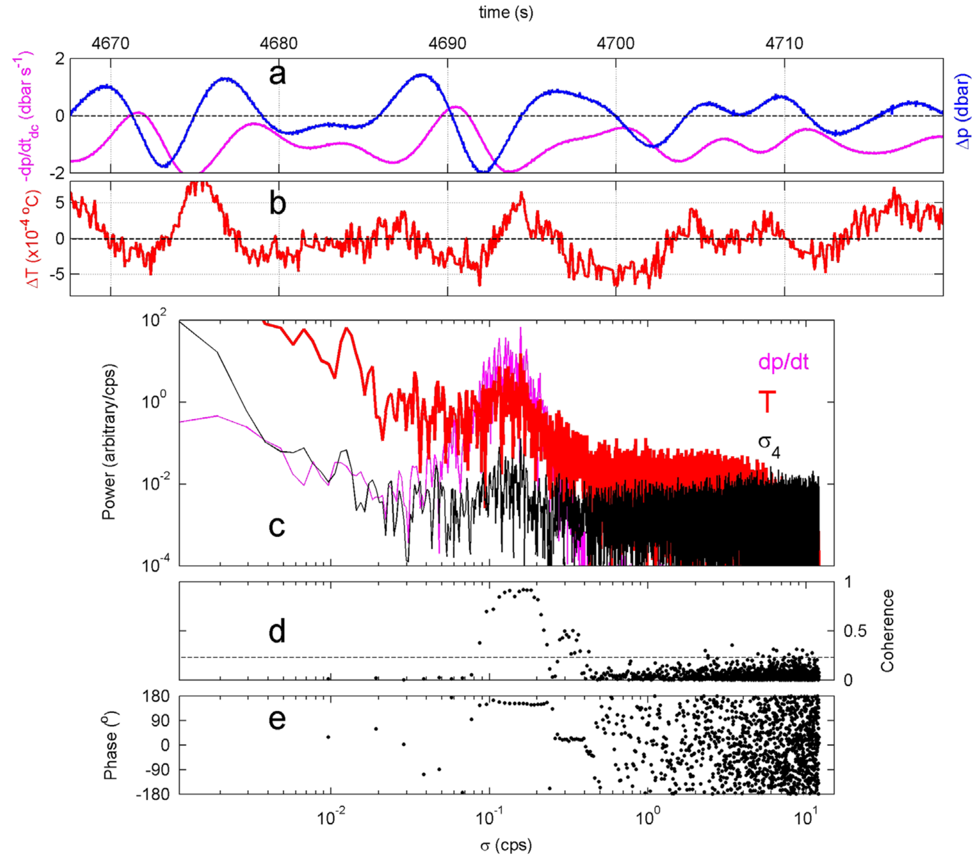

Fig. 3. As Fig. 1, but for the depth range [4660, 4710] m of the horizontally directed inlet/exhaust of experiment A in August 2015 (Fig. 2a). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

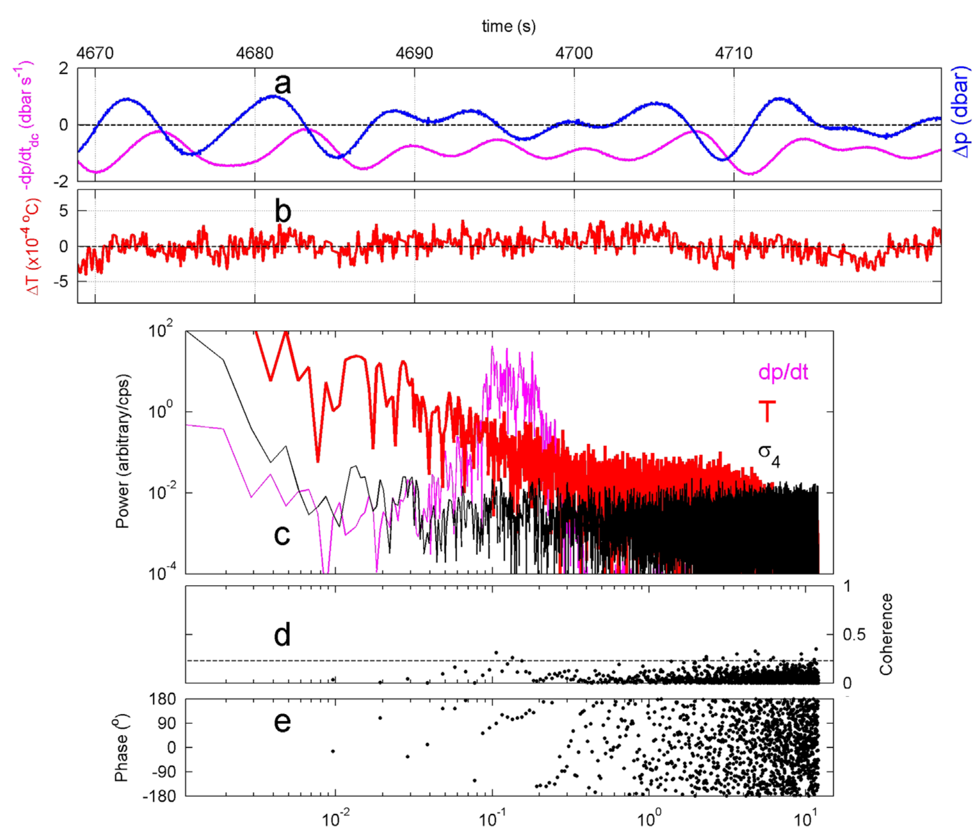

Fig. 4. As Fig. 3, but for the straight downward inlet/exhaust of experiment B (Fig. 2b).

artificial peak in salinity and hence density. Here, the density anomaly σ_4 is given with reference to 4000 dbar, see Figs. 1c, 3c.

In the CTD-cast of experiment B taken under the same conditions at the same location within a few hours from that of experiment A, the artificial T (and hence density) 8–10 s (0.1–0.125 cps) variations are effectively removed (Fig. 4b,c). No artificial temperatures are observed that are coherent with the pressure tendency, implying that the end-tube mounting is adequate, even for a slightly tilting (not precisely vertically oriented) CTD. Apparently, the tilt is $<10\%$ in the present case, or else effects of experiment A would have become noticeable, during downcast mainly. Experiment B's results include mean T-data from the deeper homogeneous layer around 4900 m, and for which downcast-T was found negligibly cooler than upcast-T by $-3\pm5\times10^{-5}$ °C. Also, this mean upcast-T was found identical to within the same error-uncertainty as Experiment A's mean upcast-T. Although the ~0.1 cps frequency range is more or less part of white noise (a horizontal spectrum) for σ_4, the T-spectrum shows a non-white noise spectral slope before reaching white noise around 0.3 cps. As a result, a more relaxed low-pass filter may be used, if necessary, to remove artificial signals and white noise, with a cut-off around 0.3 cps rather than 0.05 cps previously proposed (van Haren, 2015).

4. Discussion

The simple in-situ experiment using hand-made ‘identical’ cross-sectional area end-tubes for inlet and exhaust of the pumped TC-duct of a SBE911plus CTD demonstrates that the internal flow speed can be highly variable passing the T (and C) sensors. From the 5×10^{-4} °C typical amplitude of artificial T-variations (Fig. 2b), the internal flow speed variations are estimated to be ±0.5 m s^{-1}, assuming entirely due to sensor frictional heating (Larson and Pedersen, 1996). This is a substantial variation to the 2.3 m s^{-1} mean speed generated by the pump. We note that this internal flow speed variation need not be identical in amplitude to the variation of the instrument package vertical velocity.

The 8–10 s period artificial T-variations can be removed during post-processing using a low-pass filter with 0.05 cps cut-off so that the remaining data are adequate for estimating turbulent overturn displacements in deep-sea weakly stratified waters (van Haren, 2015). However, this filter does not remove artificial (errors in) T due to slower variations in speed, notable especially in the differences between down- and upcast. It is thus better to apply a hardware solution. Such a solution of effectively assuring a constant internal flow passing the sensors will facilitate the dynamic response calibration (Gregg and Hess, 1985).

As suggested by our experiment B, a hardware solution should include end-tubing of identical surface area with normal vector parallel to the main flow direction for inlet and exhaust. As our ad-hoc solution worked well for downcast, but removed about 50–70% of the upcast artificial T-variations, we suggest a somewhat more sophisticated (machine- instead of hand-made) future solution. Although we acknowledge that for most oceanographic applications downcast data are more important than upcast data, we suggest some attention to improve the latter as these may be useful for some applications and, in high seas, may spuriously affect downcast data that may be difficult to repair during post-processing. For this future solution we suggest thinner walls of the end-tubes that should be hydro-dynamically smoother. As the observed remaining artificial upcast T-variations were in part in-phase with pressure and not with pressure tendency, thus evidencing heating effects by the main electronics, we also suggest to detach the pumped TC-duct from the main electronics. At least the inlet should be as far as possible away from any artificial heating sources while flow obstructions should be avoided for both inlet and exhaust. Probably, the end-tube for the inlet should not be made too long to avoid erroneous T-measurements by additional friction along the tube-walls.

Such hardware solution will also not only improve artificial T-measurements in weakly stratified waters closer to the surface, but partially also in more stratified waters there of which variable errors have been described by Trump (1983). It may thus improve turbulence parameter estimates from CTD-data using the method of overturning displacements (Thorpe, 1977) for these areas as well. However, the suggested hardware addition of end-tubing does not (yet) remove ‘salinity spiking’ caused by the mismatch between T- and C-sensors, which is still a difficult task to solve even in post-processing using (re-)alignment and correction for cell thermal mass (Mensah et al., 2009).

Larger-scale hardware implementations like a sophisticated ship's heave-compensator (Taira et al., 2005) will partially remove the latter error in T-measurements. So far, only post-processing low-pass filtering can remove such salinity spiking. Alternatively, in waters under strict tight temperature-density relationship, only T-sensor data as a tracer for density overturning are better used for turbulence parameter estimates. This is applicable for open-ocean and ocean-boundary areas, but may be difficult for, e.g., polar seas.

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