CORRESPONDENCE

Comments on “Corrections for Pumped SBE 41CP CTDs Determined from Stratified Tank Experiments”

GREGORY C. JOHNSON

NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington

(Manuscript received 10 June 2019, in final form 1 November 2019)

Conductivity–temperature–depth (CTD) instruments collect the bulk of modern ocean temperature and salinity data. CTDs are deployed from ships (Talley et al. 2016), on moorings, on the Argo network of autonomous profiling floats (Jayne et al. 2017), and even on marine mammals (Treasure et al. 2017). Sensor response corrections (Horne and Toole 1980; Johnson et al. 2007; Lueck 1990; Lueck and Picklo 1990; Morison et al. 1994) are often applied to CTD data to improve their quality, by reducing noise and removing biases. Recently sensor response correction coefficients for the Sea-Bird Scientific model SBE 41CP CTD were estimated (Martini et al. 2019) using data from three time series collected in a double-diffusive interface test tank (Schmitt et al. 2005) at 5, 10, and 15 cm s^{−1} profiling speeds typical of Argo floats. Here we show that unconventional minimization constraints applied by Martini et al. (2019) in determining the conductivity cell thermal mass (CTM) error sensor response corrections result in coefficients that would undercorrect this bias error in the data. Hence the use of these coefficients would result in a fresh bias wherever Argo floats profile up through thermoclines. Thus we redo the calculation with their dataset, but using an unbiased constraint, the conventional one of minimizing the variance between modeled and corrected temperature and salinity data.

CTDs measure conductivity, temperature, and pressure, from which salinity, density, depth, and other physical water properties can be calculated (Feistel 2012).

Generally, there are three sensor response corrections applied to the data from Sea-Bird Scientific CTDs. First, the lag time for the thermistor measurements to approach the actual temperature is corrected. This thermistor lag is usually modeled as an exponential with a time constant of about 0.5 s for the SBE 41CP (Johnson et al. 2007; Martini et al. 2019), and often corrected by applying a simple sharpening filter modeling an exponential response. Next, the time for the water at the thermistor to reach the conductivity cell in the Sea-Bird CTD plumbed system is corrected. This time shift is typically found to be about 0.1 s for the SBE 41CP (Johnson et al. 2007; Martini et al. 2019) and is often accounted for by shifting the time series from each to align them. With the 1 Hz sampling rate of the SBE 41CP, accomplishing this small time shift even on the raw data requires care. Since conductivity is a strong function of temperature, both of these steps are useful in reducing salinity noise levels. The third and final step is to account for the fact that the conductivity cell and even its protective jacket (made of polyurethane in the case of the SBE 41CP) store heat and transfer that heat between the cell and the jacket, between the cell and the water transiting inside the cell, and between the jacket and the water surrounding it. This is the CTM error and is customarily modeled as an exponential adjustment to a change in temperature, but with a time constant of several seconds, and an initial amplitude smaller than unity (Johnson et al. 2007; Lueck 1990; Lueck and Picklo 1990; Martini et al. 2019; Morison et al. 1994).

We reanalyze the double-diffusive interface test tank data from Martini et al. (2019). They analyzed data from a Sea-Bird Scientific SBE 41CP CTD modified to sample at 16 Hz that they lowered three times (each time at a different profiling speed R) in a test tank with a sharp double-diffusive interface. Initially following their

Denotes content that is immediately available upon publication as open access.

Corresponding author: Gregory C. Johnson, gregory.c.johnson@noaa.gov

DOI: 10.1175/JTECH-D-19-0098.1

For information regarding reuse of this content and general copyright information, consult the [AMS Copyright Policy \(www.ametsoc.org/PUBSReuseLicenses\)](http://www.ametsoc.org/PUBSReuseLicenses).

TABLE 1. Thermistor time lag time scales (τ_T), conductivity cell thermal mass (CTM) sensor correction coefficients for amplitudes (α) and time scales (τ_{CTM}), and plumbing alignment corrections (t_p), from analysis of 16 Hz CTD data from [Martini et al. \(2019\)](#) for three different profiling speeds (R) in a double-diffusive interface test tank.

R (m s ⁻¹)	τ_T (s)	α	τ_{CTM} (s)	t_p (s)
0.05	0.54	0.0958	11.0	+0.06
0.10	0.59	0.241	3.99	+0.02
0.15	0.60	0.292	3.60	+0.01

lead, we filter the noisy 16 Hz temperature data with a 3–4 Hz first-order Butterworth stop filter but apply a 7-point Hanning window rather than their 7-point boxcar window to reduce noise further. Rather than invoking symmetry to find the lag time for the thermistor (τ_T), we elect to find the values that result in the best fits of an error function (the integral of a Gaussian, and the expected shape for a double-diffusive interface) to the temperature profile in the vicinity of the interface. We set the initial and final values of temperature on either side of the interface, and then minimize variance between the corrected data and the modeled double-diffusive interface (which is optimized to best fit the corrected data in a least squares sense by the minimization) within 5 times the interface length scale (which the CTD sees as a time scale, dependent on its profiling speed). We solve for the time at which the center of interface is sampled, the time scale to cross the interface, and the thermistor time lag. This procedure results in thermistor time lags of order 0.6 s ([Table 1](#)), very similar to those found by [Martini et al. \(2019\)](#). The corrected data ([Fig. 1a](#); red line) very closely track the modeled double-diffusive interface values ([Fig. 1a](#); black line), whereas the uncorrected data ([Fig. 1a](#); blue line) are clearly biased by the thermistor lag.

As demonstrated below, the 16 Hz tank test CTD data do not appear to require an alignment correction. Hence that step, while not neglected, is not applied in this case. Thus we proceed to estimating the CTM coefficients. When determining the CTM correction coefficients [Martini et al. \(2019, p. 738\)](#) state “There is a slight asymmetry to the salinity gradient caused by other mixing processes which are larger than the change in shape caused by the cell thermal mass.” They then elect to prohibit overshoot of salinity corrected for CTM in the lower layer by introducing a “curviness” constraint when estimating the CTM sensor response correction coefficients. We reject the notion that the temperature gradient is Gaussian but the salinity gradient is not, for some unspecified reason. We assert instead that modeling the complicated fluid and thermal dynamics of the CTM error with a single exponential leaves a substantial

residual between the overly simple CTM model and the more complex actual CTM response, so overshoot must be tolerated for an unbiased fit. After all, the cell itself is cylindrical but of varying diameter and encased in a substantial jacket of polyurethane. Fluid inside the cell is pumped whereas that on the outside of the polyurethane jacket is not. A single exponential amplitude and time scale cannot adequately model the transfer of heat between the cell and the jacket, between the jacket and the surrounding seawater, and between the cell and the seawater flowing inside it as well as the boundary layers within the cell and outside the jacket, each with its own time scale and amplitude.

Nonetheless, we proceed with a simple exponential model for the CTM error (which can remove most of the error in a statistical sense, even it does not reproduce double-diffusive interfaces perfectly) and fit an Error function to the salinity data to model the double-diffusive interface. We specify the initial and final salinity. We solve for values of the time at which the CTD samples the center of the interface, the time scale to cross the interface, the CTM lag amplitude (α), and the CTM lag time scale (τ_{CTM}) that together minimize the variance of the model–data residual for each profile ([Table 1](#)). Thus, in contrast to [Martini et al. \(2019, 2020\)](#), we allow the modeled salinity interface location and width to differ from those of the temperature. This allowance is warranted because the molecular diffusivity of heat is much larger than that of salt, so the temperature interfaces may be thicker than the salinity interfaces, although their centers should be coincident (e.g., [Shibley and Timmermans 2019](#)). In addition, rather than using the statistically unorthodox “curviness” constraint of [Martini et al. \(2019\)](#), we employ the standard, and unbiased, constraint of minimizing variance between model and observations. We minimize this variance within 5 times the double-diffusive interface length scale (which the CTD sees as a time scale related to its profiling velocity) before crossing the center of the interface, and 5 times the much longer CTM time scale after crossing the center of the interface.

The corrected salinity profile ([Fig. 1b](#); red line) is initially fresh of the modeled double-diffusive salinity profile ([Figs. 1b,c](#); black lines), but overshoots the final salinity value shortly thereafter, becoming salty of the modeled profile, and then asymptotically approaches that final salinity value near the end of the portion of the record used for the fit. An appropriate metric for the Argo dataset might be the average difference between the reported salinity values and the values of the modeled salinity profile over the fitting area. The cumulative average salinity bias over the fitted region for the corrected value ([Fig. 1c](#); red line) is initially fresh, later

FIG. 1. Profiles of (a) temperature, (b) salinity, and (c) cumulative average salinity bias relative to modeled double-diffusive salinity values vs time for the 0.10 m s^{-1} double-diffusive interface test tank 16 Hz CTD data from [Martini et al. \(2019\)](#). Black lines show modeled double-diffusive interface values (optimizing the central point and double-diffusive scale to fit the corrected data with the final and initial values fixed). Blue lines show (a) temperature values smoothed with a 3–4 Hz first-order Butterworth stop filter and then a 7-point Hanning window, (b) salinity values computed using temperature values corrected only for the thermistor time lag τ_T , and (c) their cumulative average salinity bias. Red lines show (a) temperature values corrected for the thermistor lag τ_T , (b) salinity values using temperatures corrected for both the thermistor time lag τ_T and the conductivity cell thermal mass (CTM) error using coefficients α and τ_{CTM} from our [Table 1](#), and (c) their cumulative average salinity bias. Yellow lines show (b) salinity values corrected for both the thermistor time lag τ_T and the CTM error using coefficients α and τ_{CTM} from [Table 1](#) of [Martini et al. \(2019\)](#), and (c) their cumulative average salinity bias.

slightly salty, and ends up only +0.002 Practical Salinity Scale of 1978 (PSS-78) salty in the mean, essentially unbiased. This result is in contrast to the profile generated using the [Martini et al. \(2019\)](#) coefficients ([Fig. 1b](#); yellow line), which result in a physically pleasing (in that salinity overshoot and hence density inversions are avoided) but biased (in that it is everywhere fresh of the modeled double-diffusive salinity profile) solution. This solution is biased fresh on average by -0.047 PSS-78 over the fitted region ([Fig. 1c](#); yellow line). The partially

corrected salinity data ([Fig. 1b](#); blue line, using the temperature values corrected for the thermistor lag, but not adjusted for the CTM error) are -0.077 PSS-78 fresh ([Fig. 1c](#); blue line) of the modeled double-diffusive interface values ([Fig. 1b](#); black line) in the mean over the fitted region. Hence, data corrected for the CTM error using the [Martini et al. \(2019\)](#) coefficients ([Fig. 1c](#); yellow line; see their [Table 1](#)) leave about 60% of the original CTM bias. In contrast, the data corrected using the CTM correction coefficients estimated here ([Fig. 1c](#);

red line; see our Table 1) overcorrect by only about 3% of the size of the original bias. Similar results apply for the other two cases not shown here.

Finally, we can use the difference of the centers of the modeled double-diffusive temperature and salinity interfaces to check the alignment correction (t_p) for the time elapsed between the temperature and conductivity measurements that occurs because the temperature is in front of the conductivity cell in the flow path. These values of t_p (Table 1) imply a 0–1 scan (at 16 Hz) alignment correction of the conductivity relative to the temperature measurement. Given that the choice of τ_T strongly influences the location of the center of the modeled double-diffusive temperature interface, and that the choices of α and τ_{CTM} influence the location of the center of the modeled double-diffusive salinity interface, the determination of t_p from this analysis may be somewhat uncertain. However, the close proximity of the modeled temperature and salinity interface centers does suggest that the modeled profiles (Figs. 1a,b; black lines), which are optimized to fit the corrected data, are well approximating the actual profiles. It is because of this result that we do not apply a value of t_p . If we apply the 2-scan alignment correction t_p recommended for two of the three test tank profiles by Martini et al. (2019; their Table 1), the interfaces end up being about 2 scans apart, instead of nearly overlying, suggesting that t_p is close to zero for the 16 Hz CTD data from the tank experiment. We recognize that the alignment correction, t_p , may be different, and quite important for 1 Hz CTD sampling in some profiles. The example from Martini et al. (2020), using 1 Hz data from profile 86 of Argo float WMO number 4902354, illustrates that need clearly.

Finally, the fact that the length scales of the modeled temperature double-diffusive interfaces are about 1.3–1.4 times larger than those of the modeled salinity interfaces for all three profiles in our analysis is consistent with the fact that the molecular diffusivity of heat is much larger than that of salt (e.g., Shibley and Timmermans 2019).

Argo floats do not typically sample sharp thermohaline staircases, but on almost every profile they rise through thermoclines with large, relatively constant, temperature gradients, reporting 2-dbar average values of 1 Hz data. Applying CTM error correction coefficients that use an overly reductive single exponential model that is constrained to avoid salinity overshoot after step changes in temperature (Martini et al. 2019) will result in an overall fresh bias in the corrected data through every thermocline that an Argo float samples. The product of the CTM amplitude and time-scale coefficients, $\alpha \times \tau_{CTM}$, when multiplied by the time rate of change of temperature, gives the magnitude of the CTM

error correction when that time rate of change is a constant. The values of $\alpha \times \tau_{CTM}$ estimated here, 1.05, 0.96, and 1.05 s, for R of 0.05, 0.10, and 0.15 ms^{-1} , respectively, are all quite similar. They are also very similar to 0.94 s, which is the product of median values of α and τ_{CTM} estimates from an analysis of CTM correction coefficients using 1-Hz data from 309 CTD profiles collected in the Arctic from ice-tethered profilers (Johnson et al. 2007). Each of those profiles sampled a few dozen steps within sharp, well defined, diffusive thermohaline staircases. In contrast, Martini et al. (2019) CTM correction coefficients using the full 16 Hz data result in $\alpha \times \tau_{CTM}$ values of 0.63, 0.38, and 0.32 s, which are suspiciously internally inconsistent, given the small difference in profiling speeds relative to the 0.85 ms^{-1} flow rate in the pumped cell interior. In a thermocline, using the Martini et al. (2019) CTM sensor response correction coefficients would leave between 1/3 and 2/3 of the fresh bias error in the data, depending on the values chosen. Values of α and τ_{CTM} determined by minimization can be quite variable from profile to profile, but their product is more robust (e.g., Johnson et al. 2007; their Fig. 7). Given that variability, and the fact that thousands of times more steps than three were used for estimating the values of $\alpha = 0.141$ and $\tau_{CTM} = 6.68 \text{ s}$ for CTM sensor correction coefficients in Johnson et al. (2007), those values should continue to be used for correcting SBE 41CP data from Argo floats until further work is done on this issue.

Acknowledgments. G.C.J. is supported by the NOAA Global Ocean Monitoring and Observation Program, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce and NOAA Research. Conversations with John Toole and John Lyman were helpful. PMEL Contribution Number 4984.

REFERENCES

- Feistel, R., 2012: TEOS-10: A new international oceanographic standard for seawater, ice, fluid water, and humid air. *Int. J. Thermophys.*, **33**, 1335–1351, <https://doi.org/10.1007/s10765-010-0901-y>.
- Horne, E. P. W., and J. M. Toole, 1980: Sensor response mismatches and lag correction techniques for temperature-salinity profilers. *J. Phys. Oceanogr.*, **10**, 1122–1130, [https://doi.org/10.1175/1520-0485\(1980\)010<1122:SRMALC>2.0.CO;2](https://doi.org/10.1175/1520-0485(1980)010<1122:SRMALC>2.0.CO;2).
- Jayne, S. R., D. Roemmich, N. Zilberman, S. C. Riser, K. S. Johnson, G. C. Johnson, and S. R. Piotrowicz, 2017: The Argo program: Present and future. *Oceanography*, **30**, 18–28, <https://doi.org/10.5670/oceanog.2017.213>.
- Johnson, G. C., J. M. Toole, and N. G. Larson, 2007: Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. *J. Atmos. Oceanic Technol.*, **24**, 1117–1130, <https://doi.org/10.1175/JTECH2016.1>.

- Lueck, R. G., 1990: Thermal inertia of conductivity cells: Theory. *J. Atmos. Oceanic Technol.*, **7**, 741–755, [https://doi.org/10.1175/1520-0426\(1990\)007<0741:TIOCCT>2.0.CO;2](https://doi.org/10.1175/1520-0426(1990)007<0741:TIOCCT>2.0.CO;2).
- , and J. J. Picklo, 1990: Thermal inertia of conductivity cells: Observations with a Sea-Bird cell. *J. Atmos. Oceanic Technol.*, **7**, 756–768, [https://doi.org/10.1175/1520-0426\(1990\)007<0756:TIOCCO>2.0.CO;2](https://doi.org/10.1175/1520-0426(1990)007<0756:TIOCCO>2.0.CO;2).
- Martini, K. I., D. J. Murphy, R. W. Schmitt, and N. G. Larson, 2019: Corrections for pumped SBE 41CP CTDs determined from stratified tank experiments. *J. Atmos. Oceanic Technol.*, **36**, 733–744, <https://doi.org/10.1175/JTECH-D-18-0050.1>.
- , —, —, and —, 2020: Reply to “Comments on ‘Corrections for pumped SBE 41CP CTDs determined from stratified tank experiments.’” *J. Atmos. Oceanic Technol.*, **37**, 357–363, <https://doi.org/10.1175/JTECH-D-19-0171.1>.
- Morison, J., R. Andersen, N. Larson, E. Dasaro, and T. Boyd, 1994: The correction for thermal-lag effects in Sea-Bird CTD data. *J. Atmos. Oceanic Technol.*, **11**, 1151–1164, [https://doi.org/10.1175/1520-0426\(1994\)011<1151:TCFTLE>2.0.CO;2](https://doi.org/10.1175/1520-0426(1994)011<1151:TCFTLE>2.0.CO;2).
- Schmitt, R. W., R. C. Millard, J. M. Toole, and W. D. Wellwood, 2005: A double-diffusive interface tank for dynamic-response studies. *J. Mar. Res.*, **63**, 263–289, <https://doi.org/10.1357/0022240053693842>.
- Shibley, N. C., and M.-L. Timmermans, 2019: The formation of double-diffusive layers in a weakly turbulent environment. *J. Geophys. Res. Oceans*, **124**, 1445–1458, <https://doi.org/10.1029/2018JC014625>.
- Talley, L. D., and Coauthors, 2016: Changes in ocean heat, carbon content, and ventilation: A review of the first decade of GO-SHIP global repeat hydrography. *Annu. Rev. Mar. Sci.*, **8**, 185–215, <https://doi.org/10.1146/annurev-marine-052915-100829>.
- Treasure, A. M., and Coauthors, 2017: Marine mammals exploring the oceans pole to pole: A review of the MEOP consortium. *Oceanography*, **30**, 132–138, <https://doi.org/10.5670/oceanog.2017.234>.