Thermal Mass Correction for the Evaluation of Salinity

VIGAN MENSAH* AND MARC LE MENN
French Hydrographic and Oceanographic Service (SHOM), Brest, France

YVES MOREL
French Hydrographic and Oceanographic Service (SHOM), Brest, and Météo-France, Toulouse, France

(Manuscript received 30 November 2007, in final form 19 August 2008)

ABSTRACT

This paper revisits the thermal mass inertia correction of Sea-Bird Electronics, Inc., (SBE4) conductivity probes for the calculation of salinity. In particular, it is shown that the standard parameters recommended for the correction method are not satisfactory for the data collected during recent campaigns at sea. A method, based on Morison et al., is proposed to determine optimal values for the correction parameters from selected datasets. Values valid for general cases are then proposed that yield significant improvements in the reduction of salinity errors that occur during the upcasts and downcasts of CTD profilers in areas with sharp thermoclines. The sources of the differences found between the recommended coefficient values and the ones proposed here are also discussed.

1. Introduction

The measurement of absolute salinity in the ocean during campaigns at sea is problematic because salinity is not obtained through direct measurement but instead is calculated from measurement of electrical conductivity. However, conductivity only slightly depends on salinity and mainly depends on temperature, the effect of which must then be filtered out very precisely. It is thus extremely important that the conductivity sensors respond perfectly to the quick temperature changes that often occur in the ocean.

The Sea-Bird Electronics, Inc., (SBE) conductivity–temperature–depth (CTD) profilers are widely used in oceanographic cruises. The SBE4 conductivity cells are known to be affected by a phenomenon of thermal inertia because the cell walls, made of glass, have a relatively important heat capacity. This causes the sample temperature, and then its conductivity, to be modified inside the cell. Thus, salinity profiles present important anomalies when quick temperature changes exist. Investigations into this problem have been published, and the first work on the subject has indeed emphasized the effects of the heat stored in the cell on the computed salinity and density (Lueck 1990). The outcome of this work has been the development of a thermal model for the correction of the data. Additional studies have attempted to test this thermal model (e.g., Lueck and Picklo 1990; Morison et al. 1994). It was adopted by Sea-Bird Electronics with recommendations for the use of their instruments; in particular, vertical velocity is limited to 1 m s\(^{-1}\) to avoid too-rapid temperature variations. Recently, a paper (Johnson et al. 2007) described sensor corrections for SBE-41 CTDs and showed the importance of the thermal mass effect even for Argo floats, for which the vertical velocity is low. Another study (Schmitt et al. 2005) deals with the thermal mass correction for Falmouth Scientific, Inc. (FSI) Excell profilers, using a double-diffusive tank to evaluate accurate corrections.

The French Hydrographic and Oceanographic Service (SHOM) regularly leads oceanographic campaigns with CTD measurements. Hundreds of profiles, acquired with different SBE911+ CTD profilers and corrected with the recommended coefficients, show persistent errors in the computed salinity in areas where seasonal thermoclines are present. Upcast and downcast salinity profiles exhibit
2. Thermal inertia errors

Several sources of errors lead to inaccuracy in the CTD profiles acquired with SBE3 temperature and SBE4 conductivity sensors. We can quote the mismatch in the time response of these two sensors and the contamination of the samples of water by the temperature of the wall of the sensors. This has been studied in Horne and Toole (1980), Gregg et al. (1982), Gregg and Hess (1985), Bray (1987), Ochoa (1989), and Lueck and Picklo (1990), who all propose different corrections, based on filtering, to correct this kind of error.

A relative improvement to the time response problem can be obtained by associating the two sensors with a pump. The constant flow rates generated enable the sensors’ time responses to be fixed and thus independent of the profiling speed.

The other major cause of inaccuracy is the thermal inertia of the SBE4 conductivity cell. This phenomenon is primarily due to the heat stored in the wall of the cell and in the epoxy layer that protects it. As mentioned in the introduction, a thermal correction model is necessary and has been developed by Lueck (1990). It is based on two main parameters: the surface temperature anomaly relaxation time \( \tau \) or its inverse \( \beta \) and the value of the initial, volume-weighted, fluid temperature error of a step of 1°C temperature variation \( \alpha \). The conductivity correction relation is given by

\[
C_T(n) = -bC_T(n-1) + ya[T(n) - T(n-1)],
\]

where \( T \) is the temperature, \( n \) is the sample index, and \( y \) is the sensitivity of conductivity to temperature. The coefficients \( a \) and \( b \) only depend on \( \alpha \) and \( \tau \) and are given by

\[
a = 4f_n\alpha\beta^{-1}(1 + 4f_n\beta^{-1})^{-1}
\]

and

\[
b = 1 - 2\alpha\beta^{-1}.
\]

Here \( f_n \) is the Nyquist frequency (12 Hz for an SBE911+ acquiring at 24 Hz).

An alternative to this method has been proposed and tested by Morison et al. (1994). Instead of correcting the conductivity of the sample, its temperature is corrected using the following temperature correction relation:

\[
T_T(n) = -bT_T(n-1) + a[T(n) - T(n-1)].
\]

This produces similar results as (1) does but using a more direct approach, and with the advantage of not using \( y \), allowing faster calculation times. The present study, however, focuses on (1) so as to match the correction method adopted by Sea-Bird.

The correction algorithm (1) was approved by Sea-Bird, which recommends the use of the values 0.03 and 0.14 for \( \alpha \) and \( \beta^{-1} \), respectively. However, different studies have proposed different sets of values (Lueck and Picklo 1990; Morison et al. 1994), which obviously shows that there is no general consensus on the choice of \( \alpha \) and \( \beta \). One study has indeed shown that different couples yielded results that were very similar (see Morison et al. 1994).

Note that, rather than vertical gradients, time variation of temperature is the important parameter for thermal inertia errors. Hence, the following temperature gradient evaluations are calculated as a function of time, and take into account the vertical speed of the probe (usually at most 1 m s\(^{-1}\)).

In past years, many CTD profiles using SBE 911+ have been acquired during SHOM oceanographic campaigns at sea. These data have been processed with the thermal mass conductivity correction proposed by Lueck (1990) and with the coefficients recommended by Sea-Bird. Most of the data acquired in spring or summer still show anomalies in salinity profiles across the seasonal thermocline. This phenomenon is generally highlighted by important differences between upcast and downcast salinity profiles, whereas the corresponding temperature profiles overlay. Several different SBE 911+ profilers were used to collect the data, all of them ducted, and with pressure, temperature, and conductivity sensors regularly calibrated and carefully maintained during the campaigns. The temperature and conductivity sensors were oriented horizontally, as has been the standard configuration recommended by Sea-Bird for many years. The pump rate was set at 3000 revolutions per minute (rpm), and the acquisition frequency of data was 24 Hz for all surveys. Then, differences of setting or dysfunctions of the SBE4 conductivity sensor due to poor
maintenance can be set aside. Note that the CTD profilers were fitted with a single SBE32 carousel, installed above the horizontally positioned profiler.

Figure 1 shows examples of temperature (left panels) and salinity (right panels) upcast and downcast profiles for three different temperature gradient levels. Figure 1a shows a CTD station acquired in the English Channel in May 2007, when the seasonal thermocline is not yet formed. Here, the vertical temperature gradient (function of time) is approximately 0.01°C s⁻¹, with a maximum of 0.025°C s⁻¹ between 18 and 25 m. This variation is gradual and leads to good agreement between the upcast and downcast salinity profiles (the maximum difference between the casts is about 0.002 psu); for this station the recommended correction can be considered as providing accurate results.

Figure 1b shows profiles typical of the northern part of the Biscay shelf in early spring (May 2007). The thermocline has started to form and the maximum temperature gradient for this measurement has increased to 0.2°C s⁻¹. The upcast and downcast temperature profiles, on the left, compare well. However, salinity profiles show significant discrepancies, accompanied by a relative smoothing of the halocline. This suggests that the thermal inertia has not been adequately corrected for these casts.

This problem is confirmed in Fig. 1c, showing a summer thermocline situation. These data were acquired in August 2005, off the Ushant front. In this area, strong atmospheric heating and weak currents lead to the formation of a very strong summer thermocline with temperature variations of nearly 8°C within 5–10 m. For this particular station, the temperature gradient is about 0.7 m s⁻¹ and the salinity profiles show strong opposite spikes. In this case, a symmetry is clearly visible, with a strong and nearly exponential decrease following the spike and some overshoot of the correction after this primary decrease. In this case, data are unreliable between 20- and 40-m depth. Again, this suggests that the thermal inertia has not been adequately corrected for this profile.

To show that the examples displayed in Fig. 1 are not isolated cases, pairs of CTD upcast and downcast profiles from 14 different oceanographic campaigns were analyzed for the present study. For each pair of profiles, the mean temperature gradient and salinity error (salinity difference between upcast and downcast) have been calculated on the seasonal thermocline area. To suppress spiking effects due to temperature and conductivity sensor short-term mismatch, all profiles are slightly corrected by replacing, for a centered window, the value at the center point by the median value of this window. Using this technique for temperature, conductivity, and salinity, spiking is effectively corrected so that errors spanning across a wide range of depth through the profile are identified. To make the comparison more robust, all pairs of profiles influenced by internal waves have been eliminated by discarding profiles where depth differences of more than 2 m between upcast and downcast thermoclines existed. In total, 134 pairs of profiles were retained for comparison and analysis. Figure 2 displays the results of these tests. For each profile, the maximum salinity error is calculated as a function of the temperature gradient.

There is a tendency for the salinity error to increase with the temperature gradient, with a generally smaller error for weak temperature gradients. Errors of nearly 0.05 psu were found for temperature gradients of 0.6°C s⁻¹ or more. Some strong scattering is, however, also visible, especially for small-to-modest temperature gradients. This dispersion is assumed to be due to profiles showing steep salinity gradients. Indeed, Lueck (1990) states that the time scale of the salt diffusion in the boundary layer is about 0.4 s and generates errors. Thus, profiles have been differentiated into profiles presenting strong salinity gradients (greater than 0.10 s⁻¹, shown as squares in Fig. 2), and weak-to-moderate salinity gradients (triangles in Fig. 2). For the latter, the dispersion is weak, showing evidence of a clear dependence of the salinity error on the temperature gradient.

These preliminary tests prove that thermal inertia problems still exist for the target datasets and that there is a need to reevaluate the α and β parameters.

3. Calculation of optimal parameters for given profiles

a. Method and results

Keeping the Lueck thermal correction model, it is possible to find a pair of α and β coefficients that minimize the upcast and downcast discrepancies, following techniques developed in previous studies (Morison et al. 1994; Johnson et al. 2007). We have thus selected two sets of profiles, both acquired during yo-yo CTD measurements, at fixed locations. The first set (22 profiles) has been acquired during spring [campaign Modelisation d’Un Theatre d’Operation Naval 2007 (MOUTON2007)] and is associated with maximum temperature gradients around 0.2°C s⁻¹. The second set of data (23 profiles) has been acquired during the campaign MOUTON2005 in a very sharp thermocline situation, such as the one presented in Fig. 1a.

For each set, we interpolate the data (temperature and salinity) every 0.2 dbar and calculate salinity profiles with different thermal inertia corrections: we vary α from 0.001 to 0.032 with a 0.001 step and τ from 6 to 16 s with a 0.5-s step. For each α–β couple, we calculate the mean salinity error (defined as the mean absolute difference between upcast and downcast profiles). For each pair of profiles, the couple of α and β coefficients...
FIG. 1. Temperature and salinity upcast and downcast profiles for three different temperature gradient conditions: (a) weak (0.01°C s⁻¹), (b) strong (0.2°C s⁻¹), and (c) extreme (0.7°C s⁻¹).
that provides the minimum error is then retained. Last, the mean value and standard deviation for the whole set is computed for $\alpha$ and $\tau$ or $\beta$, as well as for the salinity error.

Table 1 presents the results for the first dataset (early spring thermocline). For this set, the mean values of $\alpha$ and $\beta$ are 0.012 and 0.096 $s^{-1}$, respectively, with standard deviations almost one order of magnitude smaller than the mean value, thus indicating a very good determination of these coefficients.

Table 2 displays the results for the second dataset (strong thermocline). Here, the mean value for $\alpha$ is similar to the one of the previous set, and the value for $\beta$ is slightly smaller (0.071 $s^{-1}$). In this case too, the uncertainty on the determination is small, as the standard deviation values are clearly smaller than the mean values.

For the new choice of coefficients, the results also show that the salinity error has decreased by a factor of almost 3. This indicates that the discrepancies in the position of the halocline between the upcast and downcast have been significantly reduced, if not eliminated. This is illustrated in Fig. 3, which presents the same data as in Fig. 1b but in theta–salinity ($S$) space (thin lines) and compares them with results with the optimal coefficients given in Table 1 (thick lines). The overlaying of the upcast and downcast theta–$S$ profiles is far better with the new values, showing that the correction is very efficient (notice in Table 1 that the mean salinity error is only 0.001 psu instead of 0.003 psu).

It thus seems possible to improve the salinity determination by a careful selection of $\alpha$ and $\beta$ values. Before trying to generalize these results and evaluating whether a unique pair of coefficients could be found for all gradient situations, it is useful to compare our study with the previous ones.

### b. Discussion

The new values found in this study are very different from the ones recommended by Sea-Bird or the ones found in previous works (Lueck and Picklo 1990; Morison et al. 1994). Indeed, for the two sets of data, our values of $\alpha$ are very close, around 0.012, with low standard deviation. This value is far smaller than the theoretical one (Lueck 1990) of 0.043 and also from practical ones found by Lueck and Picklo (0.028) and

---

**Table 1.** Results of $\alpha$, $\beta$, and $\tau$ calculations for the 22 profiles of the campaign MOUTON2007.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Optimum values</th>
<th>Default Sea-Bird values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.012</td>
<td>0.03</td>
</tr>
<tr>
<td>$\beta$ ($s^{-1}$)</td>
<td>0.096</td>
<td>1/7</td>
</tr>
<tr>
<td>$\tau$ (s)</td>
<td>10.42</td>
<td>7</td>
</tr>
<tr>
<td>Salinity error</td>
<td>0.0010</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

**Table 2.** Results of $\alpha$, $\beta$, and $\tau$ calculations for the 23 profiles of the campaign MOUTON2005.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Optimum values</th>
<th>Default Sea-Bird values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.012</td>
<td>0.03</td>
</tr>
<tr>
<td>$\beta$ ($s^{-1}$)</td>
<td>0.071</td>
<td>1/7</td>
</tr>
<tr>
<td>$\tau$ (s)</td>
<td>14.08</td>
<td>7</td>
</tr>
<tr>
<td>Salinity error</td>
<td>0.0024</td>
<td>0.0013</td>
</tr>
</tbody>
</table>
Morison et al. (0.0245). As discussed below, the difference with the theoretical value can be explained by a turbulent (and not laminar as assumed by the model) flow inside the cell, induced by the temperature–conductivity (TC) duct, which leads to smaller $\alpha$. The practical values found by Lueck and Picklo (1990) or Morison et al. (1994) for this parameter are, however, also more important than those presented here. In fact the environmental as well as instrumental conditions were very different from those of this study. First, notice that Lueck and Picklo (1990) determined the values of the parameters with a strong uncertainty. Morison et al. (1994) found that many different couples were giving almost similar results. In contrast with the work presented here, these previous studies have considered situations with strong temperature gradients but also strong salinity gradients. Because salinity gradients can also induce some errors (see Fig. 2), the choice of such environmental situations can be problematic for the determination of the coefficients associated with thermal inertia errors. In the profiles selected here, salinity gradients are weak and thermocline situations are particularly strong, which should emphasize the thermal inertia error and allow a more accurate correction of it. Another interesting aspect is that the situations selected here represent very sharp thermoclines dividing layers of homogeneous water masses. Because the temperature does not vary outside the thermocline, the effects of these thermoclines can be assimilated as a real step change, an ideal situation for determining sensor step response. Lueck and Picklo (1990) have chosen similar situations, but a towed fish with a very slow vertical speed was used, which reduced the temperature step and associated errors. In addition the Lueck and Picklo (1990) CTD profiler was not ducted. It can be assumed that the TC duct between the temperature and conductivity sensor makes the flow more turbulent because of the right-angle curve and temperature sensor needle, thus decreasing the value of $\alpha$. In Morison et al. (1994), the CTD profiler was ducted but the instrument was fitted with two pairs of TC sensors, linked to a single pump. The flow speed inside the cells was 1.75 m s$^{-1}$, in contrast with the standard case of Sea-Bird SBE 9, for which the flow speed is 2.4 m s$^{-1}$. With a smaller flow speed, the Reynolds number of Morison et al. (1994) tests is smaller and the flow is less turbulent. According to Lueck (1990), this could again explain why a smaller $\alpha$ is observed in the present study. The sensitivity of this parameter to the flow speed has been confirmed by Sea-Bird (N. Larson 2007, personal communication).

The coefficient $b$ has been determined with a low uncertainty for both of the present datasets [lower than the ones found by Lueck and Picklo (1990) and Morison et al. (1994)], but with different values: 0.071 s$^{-1}$ for MOUTON2005 and 0.096 s$^{-1}$ for MOUTON2007. The corresponding relaxation times $\tau$ are 14.08 and 10.41 s, respectively. These values are larger than the theoretical one or those found in previous studies. As already discussed in Lueck and Picklo (1990), the theoretical value of $\tau$ (5.3 s) is underestimated because of the presence of epoxy around the cell. The reason for the difference between our evaluation of $\beta$ and previous studies is unclear. It could be due to our particular environment, which is assumed to emphasize the thermal inertia errors and allow a better accuracy in the determination of the relaxation time. Indeed, with a very
stable temperature on both sides of the thermocline, the determination of the final temperature of the sensor following a step change is better.

4. Single pair of coefficients

Given that, for two distinct datasets, the improvement brought by new $\alpha$ and $\beta$ coefficients can be important, a single pair of newly computed coefficients, optimized for all situations, was investigated, with the aim of improving results whatever the temperature gradient.

To determine this couple, the same test as before was carried out with 87 pairs of profiles, coming from four different survey campaigns. All of these exhibited strong thermoclines dividing stable water masses in temperature and salinity. The optimal values found are $\alpha = 0.0132$ and $\beta = 0.0829 \text{ s}^{-1}$ ($\tau = 12.03 \text{ s}$) with standard deviations of 0.0056 and 0.0218 $\text{s}^{-1}$, respectively. Given the variability of all profiles and conditions, this variability can be considered as acceptable.

To test the efficiency of this pair of coefficients, it has then been used on all of the profiles already tested (the results of which have been described in section 2), which were not taken into account to determine the optimal $\alpha$ and $\beta$. Each of the selected profiles has been processed the same way as in the test cited above. Figure 4 presents the results of the test with the Sea-Bird coefficients, for the profiles only affected by strong temperature
gradients, and Fig. 5 shows the results obtained with the new pair of coefficients. The comparison of these two figures underlines the important improvement brought about by the new coefficients. Indeed, the strong errors have been considerably reduced, many of the profiles showing errors smaller than 0.01 between upcast and downcast. In addition, the dependence of the salinity error on the temperature gradient has disappeared and the maximum salinity error is 0.017 as compared with 0.050 with the standard coefficients. The values calculated for $\alpha$ and $\beta$ seem therefore appropriate for all the campaigns at sea we have performed, even though these were not taken into account for the calculation of those coefficients. It is also interesting to notice that the profiles acquired in situations of weak temperature gradients have not been modified by the new $\alpha$ and $\beta$. Thus, they do not have any negative influence on weak gradients, which was expected because in this case the correction should remain small for most $\alpha$–$\beta$ couples.

5. Summary and conclusions

Although an efficient method for correcting the thermal inertia of SBE4 conductivity cells was developed in the 1990s, we have found that errors are common when using the recommended parameters, in particular in cases of strong temperature gradients. For the data presented here, the values recommended by Sea-Bird for the parameters $\alpha$ (0.03) and $\beta$ (0.14 s$^{-1}$) are overestimated, as well as other values proposed in previous studies (Lueck and Picklo 1990; Morison et al. 1994): despite this correction, salinity errors can reach very high values and increase with the temperature gradient.

The determination of new—optimal—coefficients adapted to each situation allows a very important improvement of salinity data. The data tested and the optimum $\alpha$ and $\beta$ coefficients calculated here are of particular interest because their environment presents several characteristics never gathered together in previous studies: very sharp thermoclines, dividing stable temperature and salinity water masses, with reduced salinity variations. These conditions are the best to determine the optimal correction coefficients. We were then able to determine a single pair of coefficients that allows a better correction of the data in almost all situations: $\alpha = 0.0132$ and $\beta = 0.0829$ s$^{-1}$. Salinity errors have been restored to reasonable values, in particular in the cases of strong thermoclines, with a mean error generally smaller than 0.01 psu, which no longer depends on the temperature gradient.

If the value of $\alpha$ seems stable and precisely determined for all temperature gradient situations, the parameter $\beta$ seems more sensitive to environmental conditions. Because the heat stored in the epoxy has not been modeled by the thermal model of Lueck (1990), it is probable that a filter of a different order, taking this phenomenon into account, would produce a more accurate correction.

Instrumental conditions are also particularly important, because our coefficients are only adapted to horizontally oriented, ducted temperature and conductivity sensors, with a flow pumped at 3000 rpm (Sea-Bird SBE 9+ standard configuration). Errors, sometimes up to 0.017 psu on average, still persist for some measurements and are probably due to strong salinity gradients.

The new $\alpha$ and $\beta$ values that we have found drastically improve the salinity evaluation over a variety of environmental situations. By using the method proposed here, it is also possible to refine the parameters’ value in relation to a particular environmental or instrumental condition.

Acknowledgments. Helpful discussions have been held with N. Larson and D. Murphy of Sea-Bird Electronics. We specially thank N. Larson for his particularly interesting information regarding the environmental conditions and instrument configurations used for Sea-Bird testing, as well as helpful advice. The results we have found and generally all the works presented here would not have been possible without the crews and SHOM hydrographer teams who acquired or helped to acquire the numerous data used in this study.

REFERENCES


