Thermal mass correction for the evaluation of salinity

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ABSTRACT

This paper revisits the thermal mass inertia correction of Sea Bird Electronics 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* (1994), is proposed to determine optimal values from selected datasets. Values valid for the general case are then proposed yielding significant improvements in the reduction of salinity errors which occur during the upcasts and downcasts of CTD profilers in sharp thermoclines areas. The sources of the differences found between 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 as salinity is not obtained through direct measurement, but instead, calculated from measurement of electrical conductivity. However conductivity only slightly depends on salinity and mainly on temperature, whose effect 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 (SBE) Conductivity-Temperature-Depth (CTD) profilers are widely used in oceanographic cruises. The SBE4 conductivity cells is known to be affected by a phenomenon of thermal inertia, as 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 there exists quick temperature changes. Solutions to this problem have been proposed and the first work on this 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 then been lead in order to test this thermal model (Lueck and Picklo 1990; Morison *et al.* 1994), which was adopted by Sea-bird Electronics with recommendations for their instruments, in particular, vertical velocity is limited to 1 m s^{-1}, in order to avoid too rapid temperature variations. Recently, a paper (G. C. Johnson, 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 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 opposite sign errors which are typical of thermal inertia problems. This has lead us to revisit the thermal correction and the aim of this paper is thus to determine the corrections giving the best results on average for our CTD data collection, independently of the thermocline sharpness.

In section 2, evidences are given for the persistence of a salinity error associated with the temperature gradient, when the recommended cell thermal mass correction is applied. In section 3 a method, inspired from Morison *et al.* (1994), is described for computing optimum coefficients for the correction algorithm, given a dataset, and the results are compared to previous studies. New values for corrections in the general case are proposed in section 4, and evidence of their efficiency are showed on yo-yo CTD data. A summary and final comments are given in the last section.

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 but also 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 2 sensors with a pump. With the constant flow rate it generates, it enables 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 which 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 τ, or its inverse β, and the value of the initial, volume-weighted, fluid temperature error for a step of 1 °C temperature variation α. The conductivity correction relation is given by:

$$C_T(n) = -bC_T(n-1) + \gamma a[T(n) - T(n-1)] \qquad (1)$$

where T is the temperature, n the sample index and γ the sensitivity of conductivity to temperature. The coefficients a and b only depend on α and τ and are given by:

$$a = 4 f_n \alpha \beta^{-1} (1 + 4 f_n \beta^{-1})^{-1} \qquad (2)$$

and

$$b = 1 - 2a\alpha^{-1} \qquad (3)$$

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

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:

$$T_T(n) = -bT_T(n-1) + a[T(n) - T(n-1)]. \qquad (4)$$

This produces the same effects than (1), but using a more direct approach, and with the advantage of not using γ, resulting in faster calculation times. In the following, however, the study focus on (1), in order to match the correction method adopted by Seabird.

The correction algorithm (1) was approved by Sea-bird who recommends the use of the values 0.03 and 0.14 for α and β^{-1} respectively. However different studies have lead to propose a different set of values (Lueck and Picklo 1990; Morison *et al.* 1994), which obviously shows that there is no consensus on the choice of (α, β). In particular, one study has indeed shown that different couples yielded results that were very similar (see Morison *et al*. 1994).

Notice that, rather than vertical gradients, time variations of temperature is the important parameter for thermal inertia errors, so that in the following temperature gradient, evaluations will be calculated as a function of time, and will take into account the vertical speed of the probe (usually at most 1 m s^{-1}).

In the 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 Seabird. 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, while the corresponding temperature profiles overlay. All CTD data are acquired with different SBE 911^+ profilers, 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 it has been the standard configuration recommended by Seabird for many years. The pump rate was always the same (3000 rpm) and acquisition frequency of data was always 24 Hz. Then, difference of setting or dysfunctions of the SBE4 conductivity sensor due to poor maintaining can be set aside. Finally notice that our CTD profilers were fitted with a single SBE32 carousel, installed above the horizontally positioned profiler.

Figure 1 shows examples of temperature (left) and salinity (right) upcast and downcast profiles for 3 different temperature gradient levels.

Fig. 1a shows a CTD station acquired in the Channel in May 2007, when the seasonal thermocline is not yet formed. Here, the vertical temperature gradient (function of time) is about 0.01 °C s^{-1} with a maximum of 0.025 °C s^{-1} between 18 and 25m. This variation is modest 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 is efficient enough.

Fig. 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, are the same and superimpose quite well. However, salinity profiles show important discrepancies, accompanied by a smoothing of the halocline. This suggests that the thermal inertia has not been adequately corrected for this profile.

This problem is confirmed in Fig. 1c, showing a summer thermocline situation. This data has been acquired in August 2005, off the Ushant front. In this area, strong atmosphere heating and weak currents lead to the formation of a very strong summer thermocline with temperature variation of nearly 8 °C within 5 to 10 meters. 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 cannot be exploited from 20 to 40 meters 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 have been analysed. For each pair of profiles, the mean temperature gradient and salinity error (salinity difference between upcast and downcast) have been computed on the seasonal thermocline area. In order 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 interval along the profile are underlined. To make the comparison reliable, all the pairs of profiles influenced by internal waves have been eliminated by discarding profiles where there exist differences of more than 2 meters between upcast and downcast thermoclines. Eventually, 134 profiles are retained for the tests. Figure 2 displays the results of these tests. For each profile, the maximum salinity error is represented as a function of the temperature gradient.

Obviously there is a tendency for the salinity error to increase with the temperature gradient, with a generally weak error for weak temperature gradients and errors of nearly 0.05 psu 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 supposed to be due to profiles showing strong 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, we have differentiated the profiles presenting strong salinity gradients (superior to 0.10 s^{-1}, figured by empty squares in Fig. 2), and weak to moderate salinity gradients (plain triangles in Fig. 2).

The latter exhibits weak dispersion, leaving a clear dependence of the salinity error on the temperature gradient.

To conclude, we believe these preliminary tests prove that thermal inertia problems have not been entirely corrected and that there is a need to re-evaluate the (α, β) parameters, at least for the profiles presented here.

3. Calculation of optimal parameters for given profiles

a. Method and results

Keeping the Lueck thermal correction model, it is possible to find a couple of (α, β) coefficients minimizing 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 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 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 dbars 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, β) coefficients providing the minimum error is then retained. Finally, the mean value and standard deviation for the whole set is computed for α and τ or β, as well as for the salinity error.

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

Table 2 displays the results for the second data set (strong thermocline). Here, the mean values for α is similar to the one of the previous set, while the value for β is a bit 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 three. This indicates that the discrepancies in the position of the halocline between the upcast and downcast have been strongly reduced, if not eliminated. This is illustrated in Fig. 3 which presents the same data as in Fig. 1b but in Theta-S space (thin lines), and compares them to 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 0.001psu instead of 0.003 psu).

It thus seems possible to improve the salinity determination by a proper choice of α and β values. Before trying to generalize these results and evaluating if a unique couple of coefficients could be found for all gradient situations, it is useful to compare our study to the previous ones.

b. Discussion

The new values found above are quite 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 α are very close, around 0.012, with low standard deviation. This value is far smaller than the theoretical one (Lueck 1990), 0.043, and also from practical ones found by Lueck and Picklo (0.028) and 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 TC-duct, which leads to smaller α. But the practical values found by Lueck and Picklo (1990) or Morison *et al.* (1994) for this parameter are however also more important than ours. In fact their environmental as well as instrumental conditions were quite different from ours. 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. Contrarily to our study, these previous studies have considered situations with rather strong temperature but also strong salinity gradients. As 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 particularly strong, which should emphasize the thermal inertia error and allow a better correction. Another interesting aspect is that the situations we have chosen represent very sharp thermoclines dividing layers of homogeneous water masses. As the temperature doesn't 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 they have used a towed fish with a very slow vertical speed, which reduce the temperature step and associated errors. In addition their CTD profiler was not ducted. We can suppose that the TC-duct between the temperature and conductivity sensor makes the flow more turbulent-due to the right angle curve and temperature sensor needle- thus, decreasing the value of α. In Morison *et al.* (1994), the CTD profiler was ducted but their instrument was fitted with 2 couples of TC sensors, linked to a single pump. The flow speed inside the cells was 1.75 m s^{-1}, contrarily to 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 less turbulent. According to Lueck (1990), this could again explain why we get smaller α in our case. The sensitivity of this parameter to the flow speed has been confirmed by Seabird (N.Larson, personal communication, 2007).

The coefficient β has been determined with a low uncertainty for both of our data sets (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, 0.096 s^{-1} for MOUTON2007. The corresponding relaxation times τ are respectively 14.08 s and 10.41 s. These values are more important than the theoretical one or found in previous studies. As already discussed in Lueck and Picklo (1990), the theoretical value of τ (5.3 s) is underestimated because of the presence of epoxy around the cell. The reason for the difference between our evaluation of β and previous studies is unclear. It could be due to our particular environment, which -we believe- emphasizes the thermal inertia errors and allows 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 couple of coefficients

Given that, for two distinct datasets, the improvement brought by new α and β coefficients can be important, we seek for a single couple of newly computed coefficients, optimized for all situations, possibly improving results whatever the temperature gradient.

To determine this couple, we have done the same test than previously with 87 pairs of profiles coming from 4 different campaigns, all of them presenting strong thermocline dividing stable water masses in temperature and salinity. The optimal values found are α = 0.0132 and β = 0.0829 s^{-1} (τ = 12.03 s) with respective standard deviation 0.0056 and 0.0218 s^{-1}. Given the variability of all profiles and conditions, this variability can be considered as good.

To test the efficiency of this couple of coefficients, it has then been used on all the profiles already tested and whose results have been described in section 2, which were not taken into account to determine the optimal α and β. Each of the selected profiles has been processed the same way than 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, while Figure 5 shows the results obtained with the new couple of coefficients. The comparison of these two figures underlines the important improvement brought by the new coefficients. Indeed, the strong errors have been considerably reduced, many of the profiles now showing errors inferior to 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 against 0.050 with the standard coefficients. The values calculated for α and β seem therefore appropriate for all campaigns at sea we have performed, even though they were not taken into account for the calculation of these coefficients. It is also interesting to notice that the profiles acquired in situations of weak temperature gradients haven't been modified by the new α and β. Thus, they don't have any negative influence on weak gradients, which was expected as in this case, the correction should remain small for most (α, β) couples.

5. Summary and conclusions

Although an efficient method for correcting the thermal inertia of SBE4 conductivity cells has been developed in the 1990s, but we have found that the recommended parameters still produce some errors, in particular in case of strong temperature gradients. For our datasets, the values recommended by Sea Bird for the parameters α (0.03) and β- (0.14 s^{-1}) are overestimated, as well as other values proposed in previous studies (Lueck and Picklo 1990 or Morison *et al.* 1994): in spite of this correction, salinity errors can reach quite high values and increase with the temperature gradient.

The determination of new -optimal- coefficients adapted to each situations, allows a very important improvement of salinity data. The data tested and the optimum α and β 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, are the best conditions to determine the optimal correction coefficients. We have then determined a single couple of coefficients which allows a better correction of the data in almost all situations: α = 0.0132 and β = 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 inferior to 0.01 psu which no longer depends on the temperature gradient.

If the value of α seems stable and precisely determined for all temperature gradient situations, the parameter β seems more sensitive to environmental conditions. As the heat stored in the epoxy hasn't been modelled by the thermal model of Lueck (1990), it is probable that a filter of a different order, taking into accounts this phenomenon, would produce a better correction.

Instrumental conditions are also particularly important, as 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 α and β values that we have found drastically improve the salinity evaluation in every situations. By using the method that we have proposed here, it is also possible to refine the parameters value, in function of a particular environmental or instrumental condition.

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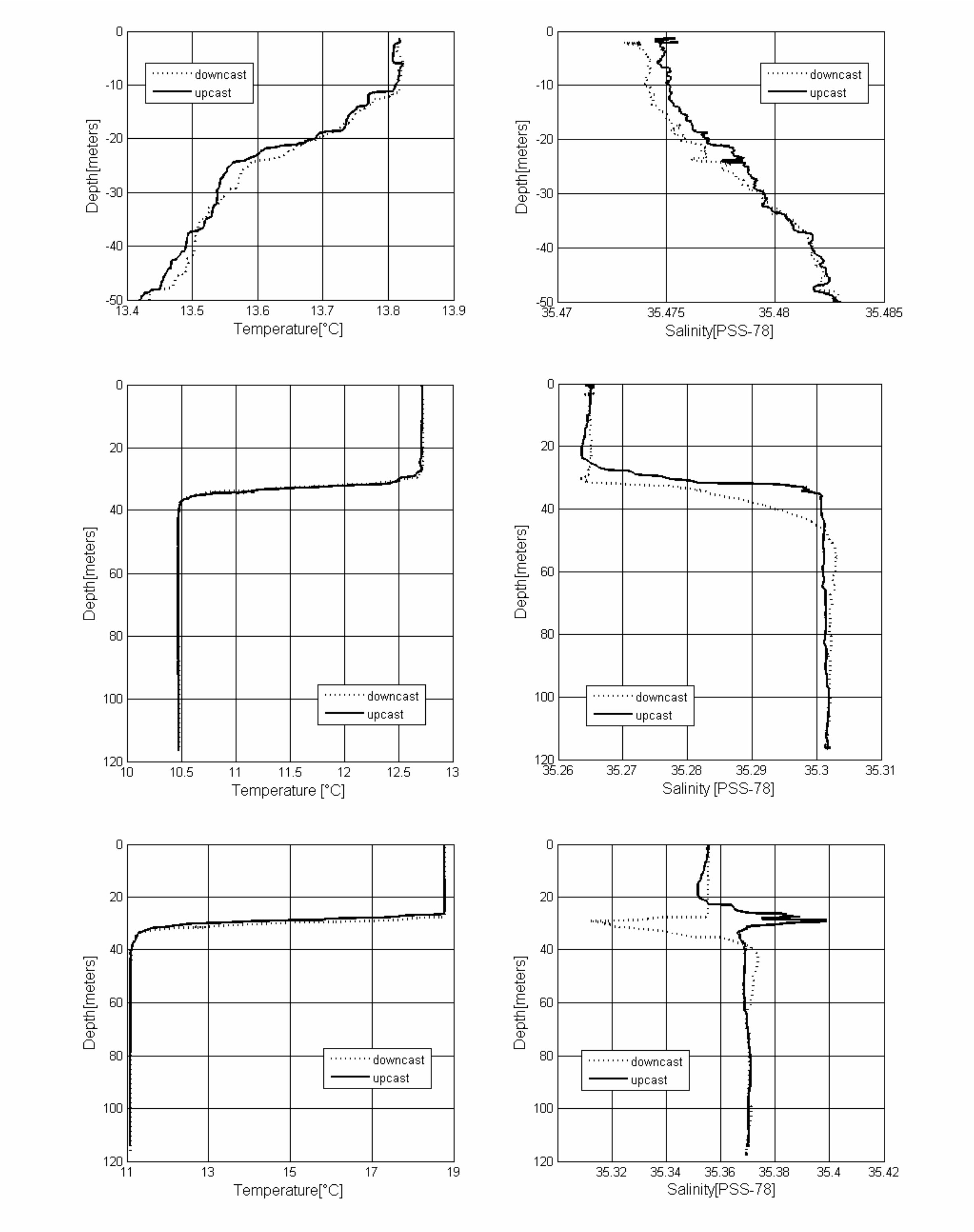
FIG. 1. Temperature and salinity upcast and downcast profiles for 3 different temperature gradient conditions. (a) Weak (0.01 °C s^{-1}) temperature gradient. (b) Strong (0.2 °C s^{-1}). (c) Extreme (0.7 °C s^{-1}).

FIG. 2. Mean salinity errors calculated with PSS-78 formulas, as a function of the temperature gradient. Empty squares represent the profiles with strong salinity gradients (superior to 0.01 s^{-1}), plain triangle shows profiles with weak salinity gradients (less than 0.01 s^{-1}).

FIG. 3. Theta-S plot of a profile with strong temperature gradient (see Fig 1b). Thick lines represent the results with optimal coefficients, while thin lines show the results for standard coefficients.

FIG. 4. Salinity error as a function of temperature gradient, for standard parameters (zoom of Fig.2, retaining only profiles with weak salinity gradients).

FIG. 5. Same as Fig. 4 but with the new parameters. The maximum salinity error is 0.017 against 0.050 in Fig. 4.



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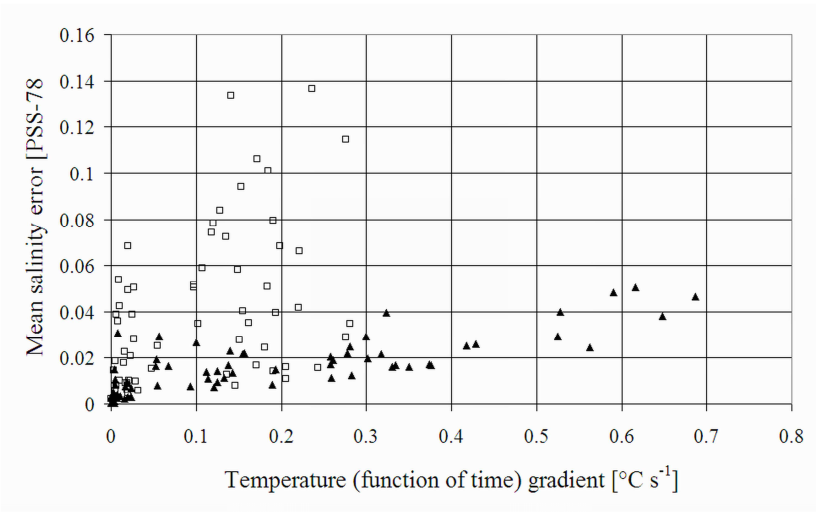

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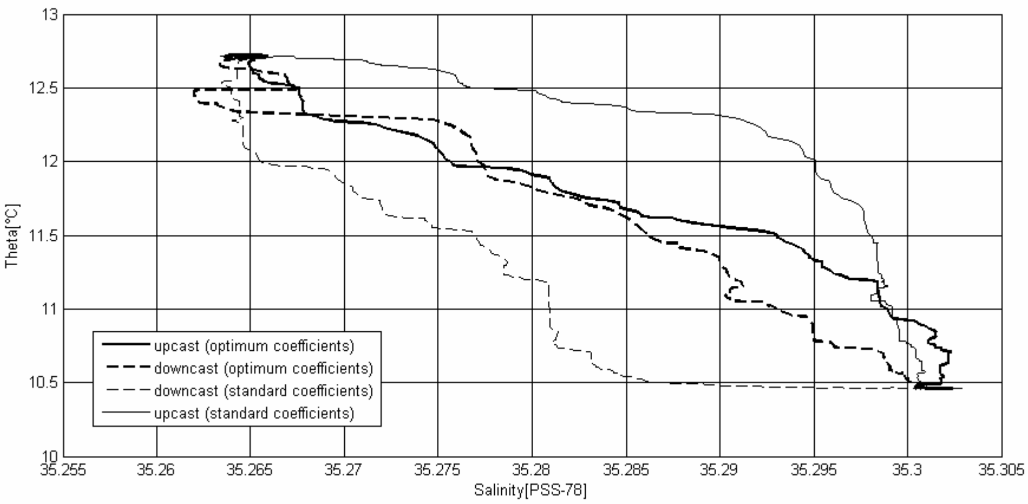

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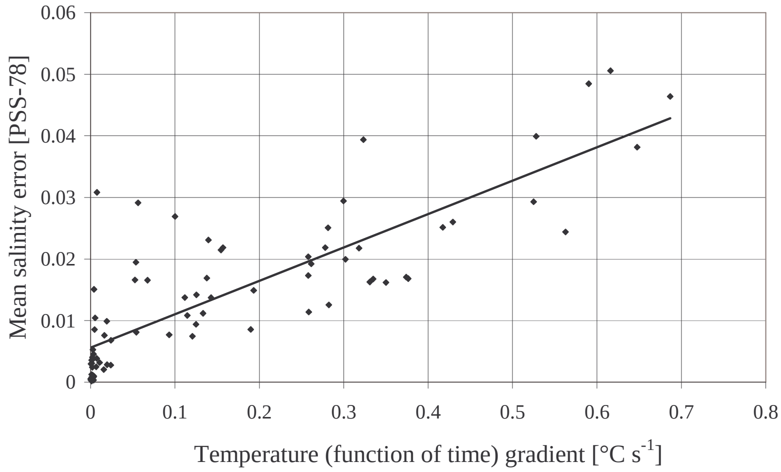

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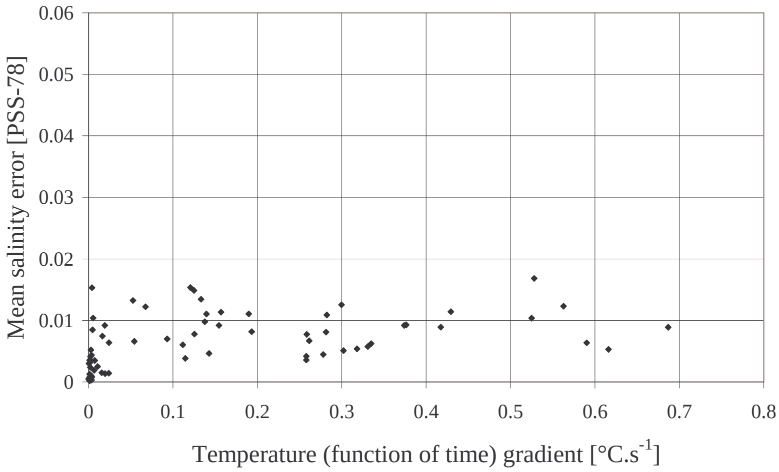

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TABLE 1. Results of *α*, *β* and *τ* calculations for the 22 profiles of the campaign MOUTON2007.

	Optimum values		Default Sea-bird values	
Variable	Mean	Standard deviation	Mean	Standard deviation
α	0.012	0.004	0.03	
β (s^{-1})	0.096	0.026	1/7	
τ (s)	10.42		7	
Salinity error	0.0010	0.0004	0.0030	0.0008

TABLE 2. Results of α, β and τ calculations for the 23 profiles of the campaign MOUTON2005.

	Optimum values		Default Sea-bird values	
Variable	Mean	Standard deviation	Mean	Standard deviation
α	0.012	0.001	0.03	
β (s^{-1})	0.071	0.010	1/7	
τ (s)	14.08		7	
Salinity error	0.0024	0.0013	0.0064	0.0013