C-PROOF GPCTD Processing Report

Lauryn Talbot

January 2026

Preamble

This document describes the conductivity, temperature, and pressure processing procedures applied to delayed-mode data collected by the Canadian Pacific Ocean Observing Facility (C-PROOF) using the Glider Payload CTD (GPCTD) by Sea-Bird Scientific.

C-PROOF gliders are equipped with either a pumped Sea-Bird GPCTD or an unpumped RBRlegato CTD, each requiring different correction methods. Delayed-mode corrections for RBRlegato CTDs are not yet implemented. This report demonstrates the GPCTD correction procedures using the Line P dfo-rosie713-20230810 as an example. Mission specific reports can be found on the C-PROOF website on the "deployments" page.

Contents

1 Quality Flags

C-PROOF applies quality flags to delayed-mode data following Argo standards. Each data point is assigned a quality flag, summarized in Table 1. The interpretation of these flags within this workflow is described in subsequent sections.

Quality Flag	Description
QC 1	Good data. Measurements pass all quality tests.
QC 3	Potentially correctable bad data. Often caused by partial clogging of the conductivity cell.
QC 4	Bad data that fail quality-control tests. Typically caused by air bubbles or severe clogging.

Table 1: Quality flag definitions used for C-PROOF delayed-mode CTD data. Information adapted from `https://argo.ucsd.edu/data/how-to-use-argo-files/`.

2 Identify and flag anomalous conductivity data

2.1 Automated process

We first identify any conductivity values that are clearly unphysical, typically caused by air entering the conductivity cell. Data points more than five standard deviations from the mean (within profile–depth bins) are temporarily excluded so that the mean and standard deviation can be recomputed without their influence. This criterion is applied using 50-profile bins and 5-m depth bins, chosen to accommodate variability in time and depth while isolating unphysical outliers. Points still differing from the mean by more than 3 standard deviations are flagged as **QC 4** (red, Figure 1). Values that differ from the mean by less than the GPCTD accuracy (0.0003 S/m) are not flagged. Measurements passing this criterion receive **QC 1**.

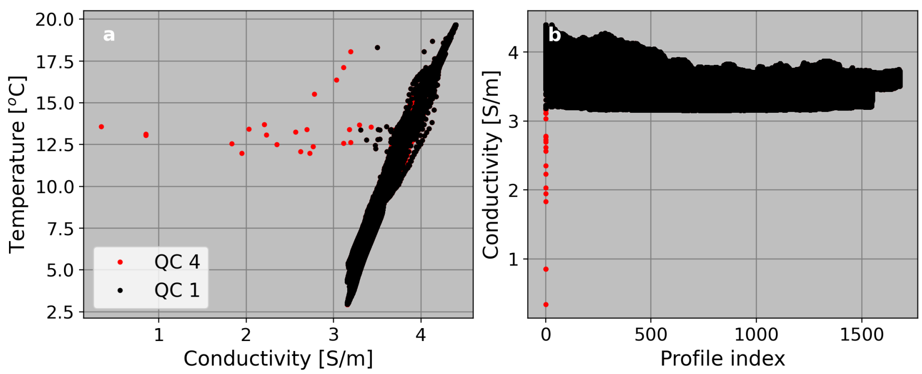


Figure 1: (a) Delayed-mode temperature vs. conductivity from dfo-rosie713-2023081 with conductivity data flagged as QC 4 plotted in red. (b) Delayed-mode conductivity vs. profile index with data flagged as QC 4 plotted in red.

2.2 Manual process

The conductivity field is analyzed to identify remaining outliers caused by clogged pumps.

To better visualize variations from the mean, we remap data onto a vertical coordinate based on the mean isopycnal depth then remove the mean conductivity along the isopycnal (Figure 2a) and normalize by the standard deviation of conductivity along that isopycnal (Figure 2b). Sections that are red (blue) are more (less) conductive than the mean along that isopycnal (Figure 2c). The mixed layer, shallower than approximately 75 m in this mission, has a lot of asymmetry in the up-cast and down-cast signal, contributed to isopycnal heaving (Figure 2).

Under normal operating conditions, the temperature–salinity (TS) properties of adjacent upcasts and downcasts are nearly identical (e.g., profiles 300–400 in Figure 2). However, when the conductivity cell becomes clogged, asymmetry between upcasts and downcasts appears in several data fields, including conductivity, producing vertical "striping" in anomaly space (e.g., profiles 250–275 in Figure 2).

Before we flag regions as clogged, we look at the TS properties.we examine the TS properties. For typical up/downcast pairs, the TS curves overlap closely (e.g., Figure 3b). In contrast, when the CTD is clogged, the TS curves from upcasts and downcasts diverge (e.g., Figure 3a). Profiles exhibiting both (1) up/down asymmetry in the normalized conductivity anomalies (Figure 2) and (2) abnormal TS structure (Figure 3) are interpreted as likely clogged, and their conductivity values are flagged as**QC3**.

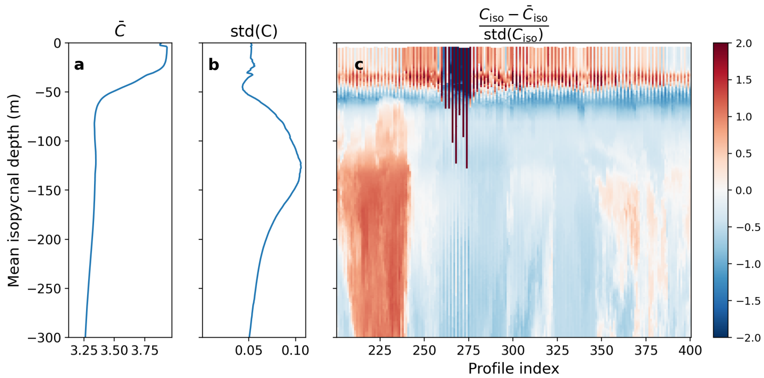


Figure 2: (a) Mean conductivity along each isopycnal (b) Standard deviation of conductivity along each isopycnal. (c) Conductivity anomalies from the mean conductivity along each isopycnal normalized by the standard deviation for profiles 200 to 400.

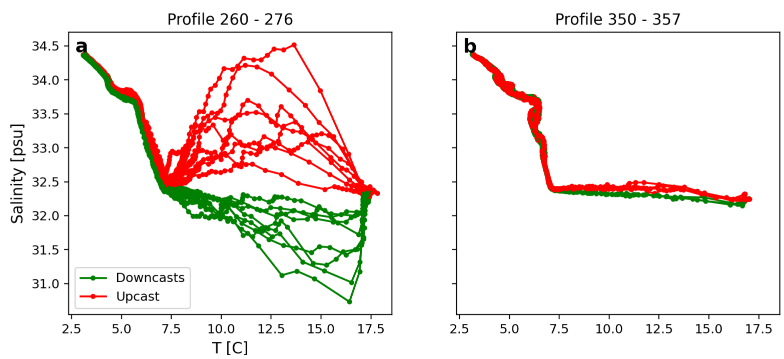


Figure 3: T–S diagrams for profile ranges: (a) 260-276 and (b) 350-357. Downcasts are in green and upcasts are in red.

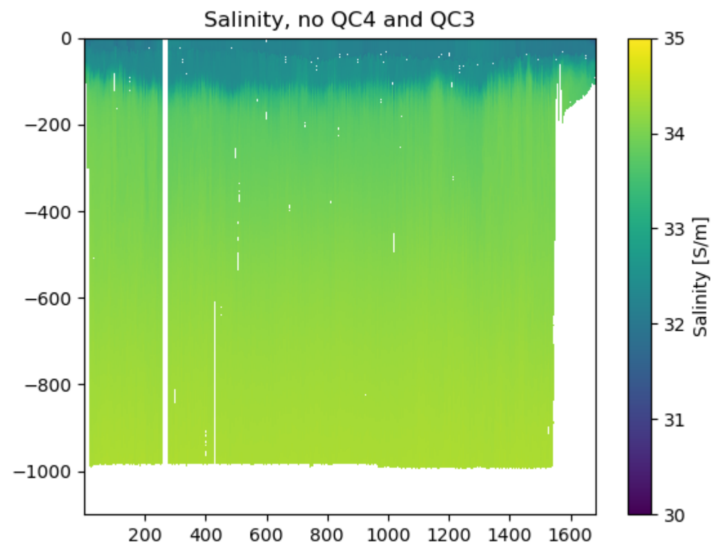
3 Identify and flag anomalous temperature profiles

Temperature data are flagged as **QC 4** when there are temperature spikes in the time series, defined here as differences greater than 0.75 °C between a measurement and the mean of its neighbouring data point in time. This mission does not have any QC4 temperature data.

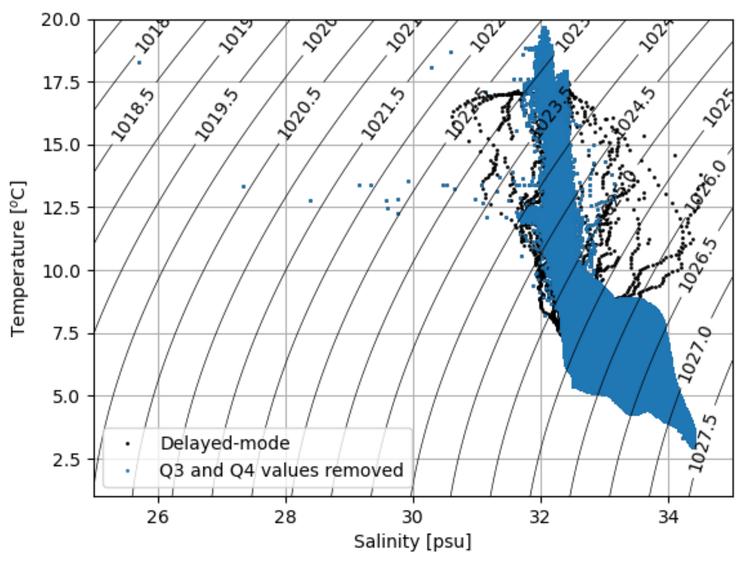
The same procedure described in Section 2.2 is applied to temperature to identify profiles affected by clogging. Profiles exhibiting up/down asymmetry in the normalized temperature anomalies, together with abnormal TS structure, are interpreted as likely clogged, and the temperature profiles are flagged as **QC3**.

4 Flagging Salinity Values

Because salinity is derived from temperature and conductivity, the worst QC flag from these variables (QC 4 > QC 3 > QC 1) is applied to salinity. Figure 4a shows the QC1 flagged salinity data. There are white speckles and lines where data has been flagged as QC3 or QC4. Figure 4b compares the TS plots for delayed-mode and QC1 salinity and temperature data, after having applied the steps above. Many outliers have been removed from processing.



(a) Delayed-mode salinity data flagged as QC1 (QC3 and QC4) data removed.



(b) Temperature-salinity plots for delayed-mode (black) and data flagged as QC1 (blue), having removed QC3 and QC4 data.

Figure 4: Flagged salinity data

5 Correct CT misalignment

This correction is often used to align the temperature and conductivity in time, relative to the pressure. This correction reduces the occurrence of salinity spikes near sharp gradients in T and S, and ensures calculations are made using the same parcel of water for all variables. The misalignment between the sensors is caused by:

- The physical separation between sensors causing a transit time delay for water being pumped through the CTD, and,
- Different sensor response times

We look at the cross-correlation of $\frac{dTemperature}{dt}$ vs $\frac{dConductivity}{dt}$ for lags from -2 to 2 seconds with 0.1 second intervals (Figure 5). For this mission, there was no apparent lag between the conductivity and temperature signals, so no correction was applied. We have yet to find a mission using a GPCTD sensor with a CT lag.

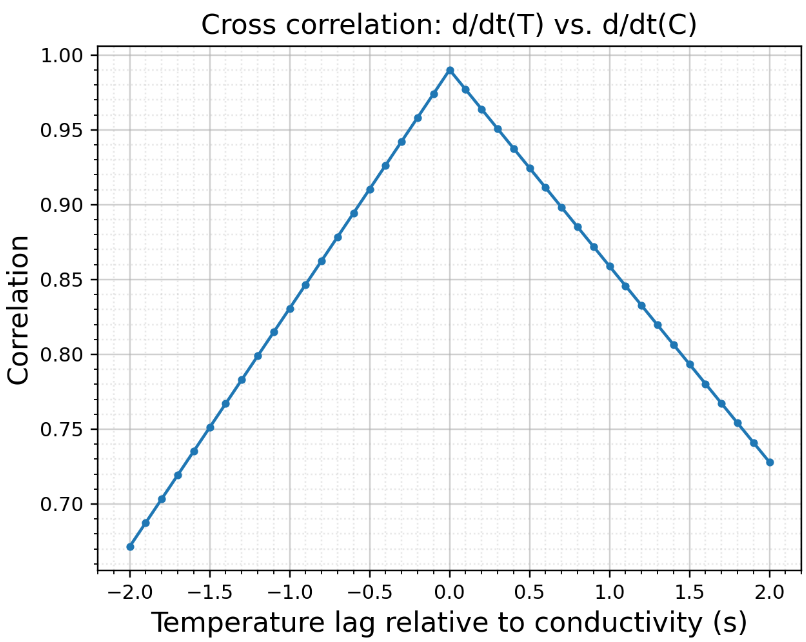


Figure 5: Cross correlation between dT/dt and dC/dt for the entire mission. The best correlation is when no lag is applied (0 seconds).

6 Thermal Lag correction

Thermal lag arises from the thermal mass of the conductivity cell altering the temperature of water passing through it. Optimal thermal-lag parameters (α, τ) can be robustly chosen for a given sensor. **Constants may drift if the sensor has been out of use for a few months requiring new constants to be calculated.** For example, ctd 0256 shifted constants after being out of use for 1.5 years (mission dfo-eva035-20231019 to dfo-eva035-20250411).

We use the method of Garau et al. [2011], building upon Morison et al. [1994]. Because gliders sample continuously at a nearly constant rate, thermal lag can be treated as constant throughout a mission. A thermal lag appears in the data as vertical striping in collected properties, with a pattern of high-low-high-low values, where values are consistent for upcasts and downcasts alike. Correcting for a thermal lag makes properties consistent across both upcasts and downcasts.

A recursive filter estimates the temperature inside the conductivity cell:

$$T_T(n) = -b\,T_T(n-1) + a\,T(n) - a\,T(n-1), \tag{1}$$

where

$$a = \frac{4f_n\alpha\tau}{1+4f_n\tau}, \qquad b = 1 - \frac{2a}{\alpha},$$

and f_n is the mean sampling frequency. The parameter α represents the strength of thermal coupling between the water and conductivity cell, and τ is the associated time constant; both are strictly positive physical parameters. *Salinity_adjusted* is found by recalculating salinity using equations from *Thermodynamic Equation Of Seawater - 2010* (TEOS-10) and the cell's temperature.

Previous C-PROOF processing used fixed values $\alpha = 0.06$ and $\tau = 10$ s [Janzen and Creed, 2011]. However, optimal values can vary by sensor.

6.1 'First' mission processed with a given GPCTD

We interpolate the salinity data onto isotherms (Figure 6). There is asymmetry visible from the normalized salinity anomalies where alternate profiles are higher or lower than the profiles beside it.

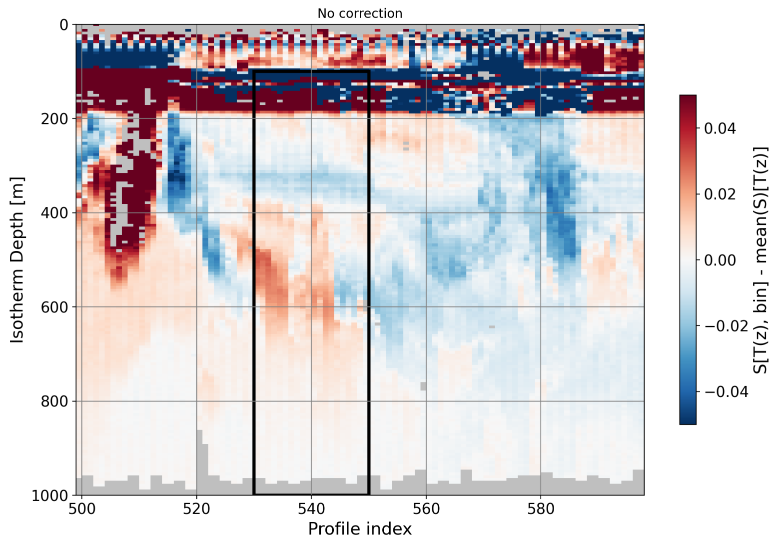


Figure 6: Salinity anomalies on isotherms for profiles 500 - 560.

We determine the optimal thermal-lag correction parameters, α and τ, by minimizing the area between paired up/downcast salinity profiles across 20 representative profile pairs. The mismatch is normalized by the standard deviation within each temperature bin (Figure 7). The analysis is restricted to depths below the mixed layer (defined here as 100 m), where temperature bins contain more observations and variability from surface forcing and internal waves is reduced.

The resulting error exhibits a distinct low-error valley in α-τ space (Figure 7, blue line). Error is minimized for combinations of relatively small τ and larger α with the error increasing approximately exponentially as τ increases. Rather than selecting the absolute minimum, we choose the inflection point along this trough as the representative 'best' parameter pair for this sensor.

The precise location of the minimum depends somewhat on the bin resolution used in the search. However, the orientation and position of the low-error valley remain stable across different resolutions, indicating that the solution reflects a robust tradeoff between α and τ, rather than a finely tuned minimum. When the parameter search is repeated over a narrower range surrounding the selected values using finer resolution, the same low-error valley structure emerges (Figure 8), further confirming the robustness of the method.

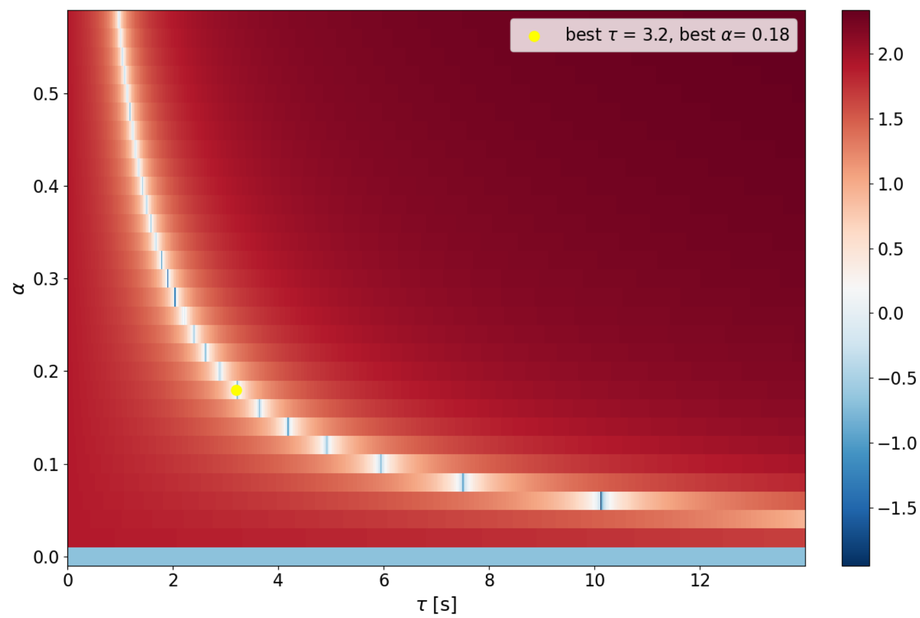


Figure 7: Example of brute-force search for optimal thermal-lag parameters of Line P mission dfo-rosie713-20230810. Colours show $\log_{10}$ error; the darkest region indicates parameter combinations minimizing up/downcast mismatch. The 'best' α and τ were selected to be on the inflection point of the low trough: α= 0.18, τ = 3.2.

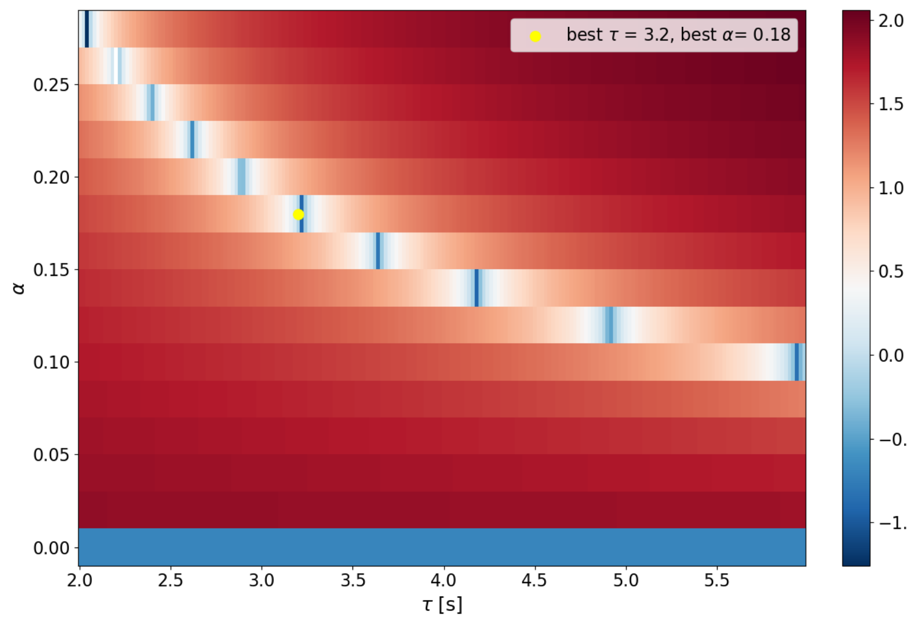


Figure 8: Example of brute-force for optimal thermal-lag parameters with a finer resolution constants. The 'best constants' are consistent with those found in Figure 7.

The salinity anomalies along isotherms are compared between the delayed-mode data (Figure 9a) and data with a thermal lag correction applied (Figure **??**b). The correction reduces the up/down asymmetry between casts, which appears as vertical striping in salinity anomalies along isotherms. To quantify this improvement, the mean normalized error along each isotherm, averaged across the selected range of profiles, is plotted as a function of isotherm depth (Figure 9c). In this example, the error approaches zero over much of the depth range, indicating improved agreement between salinity anomalies from adjacent upcasts and downcasts. Because similar improvement is observed across the mission (Figure 10a–c), the thermal-lag correction is applied to the QC1 delayed-mode dataset. The corrected variable is hereafter referred to as *salinity_adjusted*.

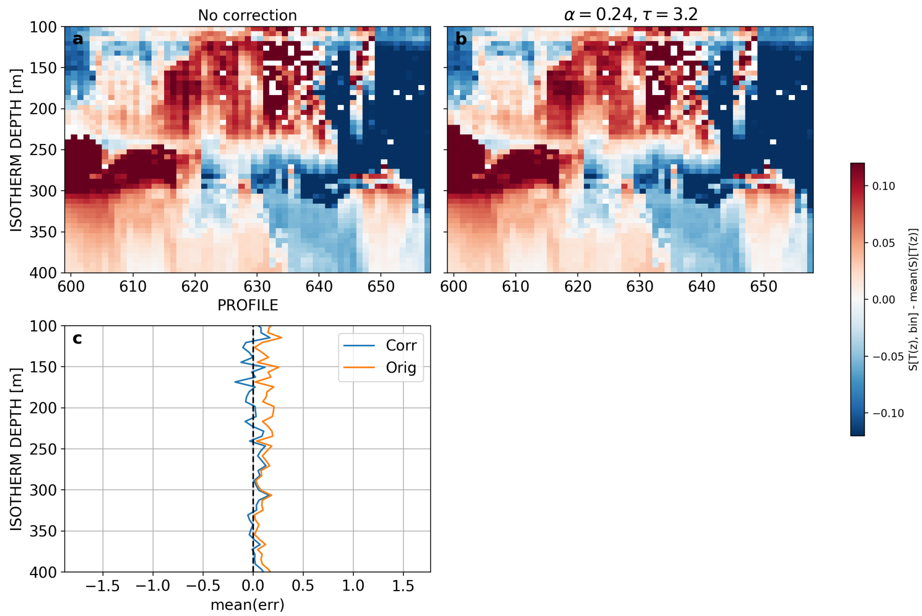


Figure 9: Salinity anomalies along isotherms from the mean salinity for profiles 600-660 from mission dfo-rosie713-20230810 using (a) delayed-mode and (b) thermally-adjusted salinity. (c) Mean normalized error along each isotherm in a and b.

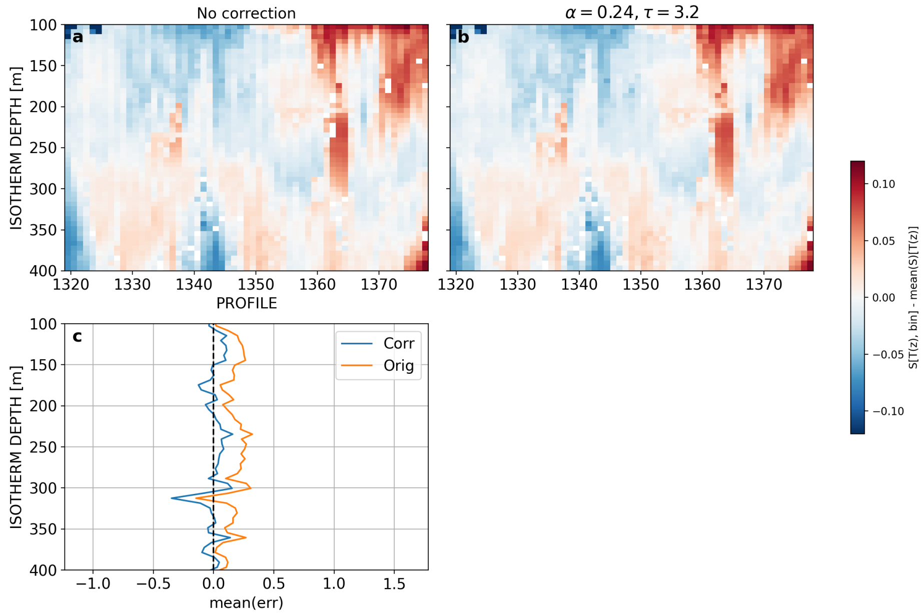


Figure 10: Salinity anomalies along isotherms from the mean salinity for profiles 1320-1380 from mission dfo-rosie713-20230810 using (a) delayed-mode and (b) thermally-adjusted salinity. (c) Mean normalized error along each isotherm in a and b.

6.2 Subsequent missions with the GPCTD

Once optimal constants are determined for a given sensor using a representative mission, they are applied to subsequent missions using the same instrument. The parameters α and τ remain broadly consistent over time for a given CTD, with small variations in the estimated values arising primarily from differences in the observed isotherm structure and stratification.

For example, the mission *dfo-rosie713-20220531* used the same GPCTD as the example mission *dfo-rosie713-20230810*. When α and τ are estimated using 20 representative profile pairs, the exact minimum differs slightly between missions (Figure 11). However, the low-error valley is located in approximately the same region of α - τ space as in the example mission, and the previously selected parameter pair lies close to this valley (Figure 7).

Because the low-error valley is consistent across missions using the same GPCTD, a single parameter pair is selected per sensor and applied to subsequent deployments. When these previously determined constants are applied, the up/down asymmetry decreases (e.g., Figure 12a–c), providing additional confidence in the robustness of the correction. As with the previous mission, this correction is applied to the QC1 delayed-mode dataset, and the corrected variable is referred to as *salinity_adjusted*.

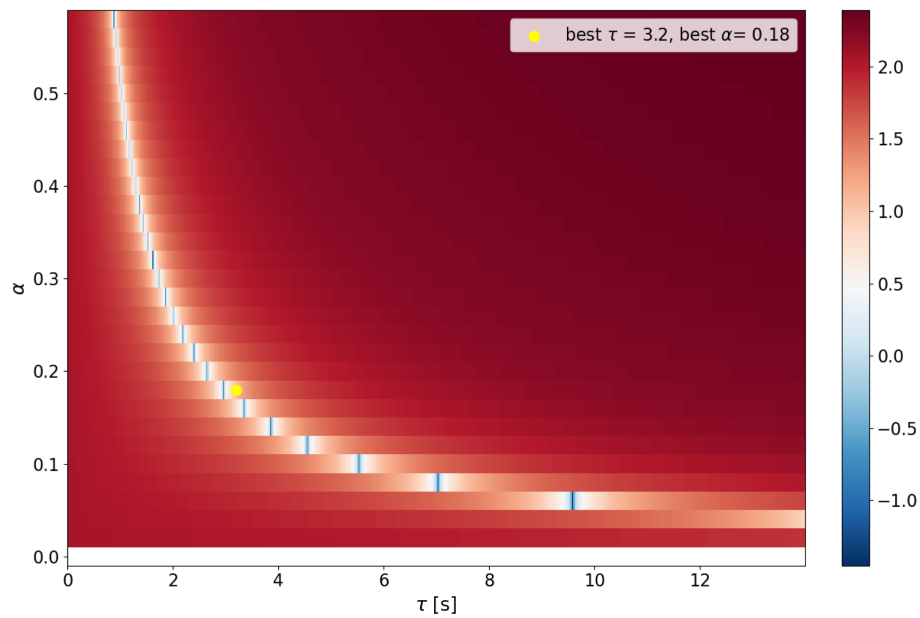


Figure 11: Example of brute-force search for optimal thermal-lag parameters of Line P mission dfo-rosie713-20220531. Colours show $\log_{10}$ error; the darkest region indicates parameter combinations minimizing up/downcast mismatch. The 'best' α and τ defined using dfo-rosie713-20230810 is plotted in yellow.

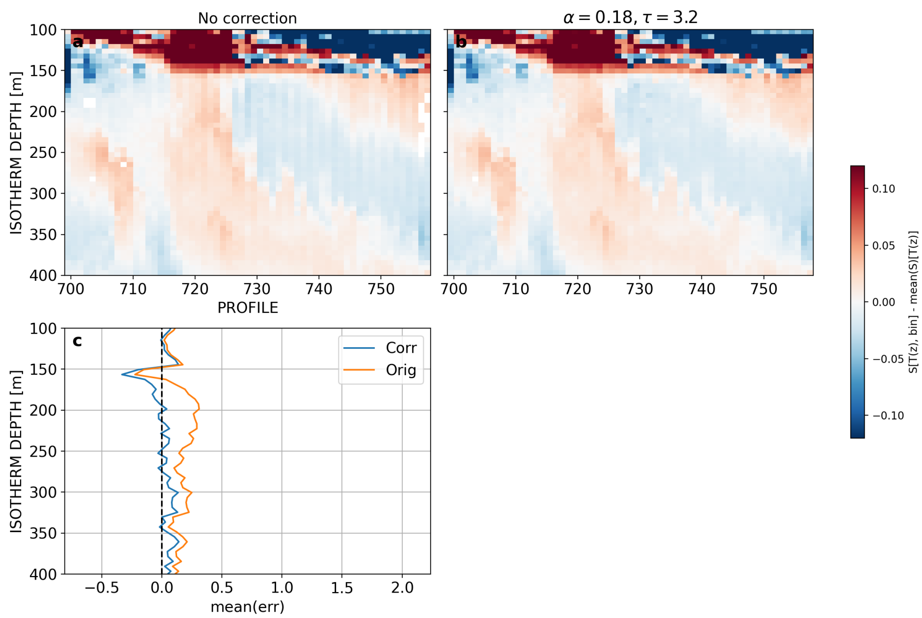


Figure 12: Salinity anomalies along isotherms from the mean salinity for profiles 700 - 760 from mission dfo-rosie713-20220531 using (a) delayed-mode and (b) thermally-adjusted salinity. (c) Mean normalized error along each isotherm in a and b.

7 Recalculate derived variables

The variables *potential_temperature_adjusted* and *potential_density_adjusted* are subsequently recalculated from *salinity_adjusted* using TEOS-10 equations. Quality-control flags assigned to *salinity_adjusted* are propagated to these derived variables.

8 Summary of Quality-Control Procedure

The following steps summarize the delayed-mode quality control workflow applied to Sea-Bird GPCTD data in C-PROOF. This procedure assigns quality flags to conductivity, temperature, and salinity and generates adjusted products for downstream use.

1. Conductivity Quality Control

1. **Outlier detection (QC 4):** Conductivity is binned by 50-profile segments and 5-m depth bins. Values more than three standard deviations from the bin mean (after an initial 5σ pre-screening) are flagged as bad (QC 4) unless the deviation is within the sensor accuracy (0.0003 S/m).

2. **Clogged-sensor identification (QC 3):** Remaining anomalies are evaluated using conductivity sections and T–S diagrams. Partial clogging is diagnosed when: (a) conductivity structure shows irregular striping, and (b) upcast and downcast T–S curves diverge. These data are flagged as QC 3.

2. Temperature Quality Control

1. **Spike detection (QC 4):** Temperature spikes exceeding 0.75 °C relative to adjacent samples are flagged QC 4.

2. **Clogged-sensor temperature (QC 3):** Temperature in conductivity-clogged regions is also flagged QC 3

3. Salinity Quality Control

1. **Flag propagation:** Salinity inherits the *worst* QC flag applied to either temperature or conductivity (QC 4 > QC 3 > QC 1).

4. Thermal Lag Correction

1. **Estimation of thermal-lag parameters:** Optimal α and τ are determined using a brute-force search that minimizes up/downcast salinity mismatch across a subset of profiles.

2. **Application of correction:** Thermal-lag–corrected temperature is used to recompute salinity. The correction is applied only to QC 1 data.

5. Re-derive variables using *salinity_adjusted*

1. Derive potential_temperature_adjusted and potential_density_adjusted. These variables inherit quality flags from *salinity_adjusted*.

References

Bartolomé Garau, Simón Ruiz, Weifeng G. Zhang, Ananda Pascual, Emma Heslop, John Kerfoot, and Joaquín Tintoré. Thermal Lag Correction on Slocum CTD Glider Data. *Journal of Atmospheric and Oceanic Technology*, 28(9):1065–1071, September 2011. ISSN 0739-0572, 1520-0426. doi: 10.1175/JTECH-D-10-05030.1.

Carol D. Janzen and Elizabeth L. Creed. Physical oceanographic data from Seaglider trials in stratified coastal waters using a new pumped payload CTD. In *OCEANS'11 MTS/IEEE KONA*, pages 1–7, Waikoloa, HI, September 2011. IEEE. ISBN 978-1-4577-1427-6 978-0-933957-39-8. doi: 10.23919/OCEANS.2011.6107290.

James Morison, Roger Andersen, Nordeen Larson, Eric D'Asaro, and Tim Boyd. The Correction for Thermal-Lag Effects in Sea-Bird CTD Data. *J. Atmos. Oceanic Technol.*, 11(4):1151–1164, August 1994. ISSN 0739-0572, 1520-0426. doi: 10.1175/1520-0426(1994)011⟨1151:TCFTLE⟩2.0.CO;2.