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Modified Thermal Lag Correction of CTD Data from Underwater Gliders

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ABSTRACT

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A real-time data quality control process and a modified thermal lag correction procedure are proposed in this paper. The data quality control process is designed for CTD sensors (conductivity, temperature and depth) installed on Petrel gliders. A modified thermal lag correction methodology, based on the hypothesis that CTD data sampled closer in time and space would be more similar, is also put forward in this paper. Therefore, in this method, each down profile and each up profile is split into two segments. The segments with closer temporal and spatial relationships are used to calibrate each other, which is the first time the limitation of using only one profile to correct the thermal lag effect in a glider-carried CTD has been overcome. Moreover, the data obtained in sea trials with a Petrel glider and a reference SBE 911 plus CTD are used to examine the modified method and the newly designed data quality control process. The excellent alignment with the reference data and significant calibrations indicate that the CTD data were successfully corrected.

ADDITIONAL INDEX WORDS: *Real-time data quality control, thermal lag correction, underwater glider, CTD.*

INTRODUCTION

Underwater gliders (UGs) are buoyancy-driven autonomous vehicles that provide continuous and fine-resolution observations and have been widely used in ocean sampling. With advancements in technology, various suites of sensors can currently be integrated or mounted on gliders. Among them, conductivity, temperature and depth sensor sampling the essential physical variables is one of the most common types. SBE 41 CTD (unpumped, Seabird Electronics, Inc., USA) and newly developed Glider Payload CTD (GPCTD, pumped, Seabird Electronics, Inc., USA) are the two most widely used CTDs at present.

However, under the influence of thermal inertia, drifting, biofouling, *etc.* of sensors as well as the motion of the vehicle, there are unexpected errors or spikes in the obtained data; thus, data quality control is required. The United States Navy's Local Automated Glider Editing Routine (LAGER) uses an automated quality control method for Slocum and Seaglider. In addition to performing routine tests such as the global range test, spike test, and vertical gradient test, it also takes the vertical velocity and pitch angle of the glider into account (Michael, 2013). The Balearic Islands Coastal Observing and Forecasting System (SOCIB) developed a toolbox called SOCIB glider toolbox to process and analysis glider data (Tintoré *et al.*, 2013). The Australia National Facility for Ocean Glider (ANFOG) also designed a process for Slocum gliders, and it pointed out that the quality control results also rely on the experience and judgment of operators (Claire, 2014). Troupin *et al.* (2015) further improved the SOCIB glider toolbox, which unified the process of Seagliders and Slocum G1 and G2 gliders and proposed to grade the data into level 0 (raw data), level 1 (quality-controlled data) and level 2 (gridded dataset) data from the perspective of data management. Referring to the data quality control of the Argo data system, the University of Washington Applied Physical Laboratory (UWAPL) and Everyone's Gliding Observatories (EGO) also put forward some procedures to process CTD data from gliders (EGO, 2017; UWAPL, 2016). In addition, on the basis of LAGER automated processing and quality control (QC), the Seaglider QC Manual developed by the University of Washington, the Global Temperature and Salinity Profile Programme (GTSPP) and the Argo program (Carval *et al.*, 2015, U.S. IOOS, 2016; UNESCO-IOC 2010), the United States Integrated Ocean Observing System Glider Data Assembly Center (U.S. IOOS DAC) proposed a 14-test method to evaluate real-time data quality. In general, these 14 tests cover the most comprehensive range: the timing test, syntax test, location test, gross range test, pressure test, climatological range test, spike test, gratitude test, frozen profile test, multivariate test, attenuated signal test, historical profile test, temperature-salinity (T-S) curve test, and density inversion test. The specific comparison of these quality control methods is shown in Table 1.

Among all these quality control procedures, it is widely agreed that thermal lag correction is one of the most important steps in the

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Table 1. *Comparison of the available real-time data quality control processes.*

Test Name	This Paper	IOOS	LAGER	ANFOG	SOCIB	UWAPL	EGO	ARGO
Time Test	Y	Y	N	N	Y	N	Y	Y
Syntax Test	Y	Y	N	N	N	N	Y	Y
Position Test	Y	Y	Y	N	Y	Y	Y	Y
Global Range Test	Y	Y	Y	N	Y	Y	Y	Y
Pressure Test	Y	Y	Y	Y	N	N	Y	Y
Climatological Test	Y	Y	Y	N	N	N	N	N
Spike Test	Y	Y	Y	Y	Y	Y	Y	Y
Gradient Test	Y	Y	Y	N	N	N	Y	Y
Frozen Profile Test	Y	Y	Y	N	N	N	Y	Y
Multivariate Test	N	Y[1]	N	N	N	N	N	N
Attenuated Signal Test	N	Y	N	N	N	N	Y	Y
Historical Data Test	Y	Y	N	N	N	N	N	N
Adjacent Profile Test	Y	N	N	N	N	N	N	N
Density Inversion Test	Y	Y	Y	N	N	N	Y	Y
Figure Test	Y	Y	N	N	Y	N	N	N

Y is yes, N is no, and the abbreviations/names of each process are the same as mentioned before. ([1] This test is only mentioned in IOOS, and specific information is not given.)

processing of CTD data. The thermal lag error, a common problem with all types of CTD sensors, is induced by the separation of the temperature sensor and conductivity sensor and the thermal inertia of the conductivity cell. Since CTD sensors only provide temperature, conductivity and pressure data, salinity, one of the most common hydrographic variables of interest is derived from these data by using the state equations (UNESCO, 1981), which are particularly sensitive to temporal and spatial mismatches in the temperature and conductivity sensor responses. Several attempts have been made to calibrate CTD data in recent decades. Based on previous work, Lueck and Picklo (1990) proposed a numerical model and an efficient numerical algorithm to remove the conductivity bias produced by thermal anomalies. By combining this model with the temperature-salinity (T-S) diagram, Morison *et al.* (1994) found that the coefficients in Lueck and Picklo's model were related to the average velocity through the cell in the CTD. Therefore, they developed an empirical search method as well as a generalized model to minimize the salinity separation of upcast and downcast T-S curves and determined the coefficients for the SBE 9 CTD sensor. Based on the same hypothesis, Garau *et al.* (2011) then optimized the model and used a sequential quadratic programming (SQP) method to solve the parameters on Slocum unpumped CTD glider data. Liu, Weisberg, and Lembke (2015) examined the correction of salinity data in the sharp thermocline of the West Florida Shelf and pointed out that further filtering might be necessary. Beltran, one of the coauthors of Troupin *et al.* (2015), extended the methodology proposed by Garau *et al.* (2011) to pumped CTD with MATLAB programs.

In this paper, we first design a real-time data quality control process for Petrel gliders developed by Tianjin University.

Considering the sawtooth-like profile pattern of the underwater glider as well as the variable ocean environment, a modified thermal lag correction method based on GPCTDs implemented on Petrel gliders is also proposed.

METHODS

Real-time Data Quality Control

Based on the data obtained by GPCTDs on Petrel gliders, we propose a real-time data correction method, which contains a time test, position test, pressure test, global range test, frozen profile test, spike test, gradient test, standard variation test, vertical velocity test, thermal lag correction test, climatology range test, density overturn test, adjacent profiles test, historical data test and figure test (Figure 1).

Some of the tests are similar to the procedures of IOOS as well as LAGER (LAGER, 2013; U.S. IOOS, 2016), but the thresholds of each test have been adjusted to match the Petrel glider and experimental areas. In addition, because of some unexpected accidents, a few profiles would have different T-S structures, which are abnormal but challenging to identify if analyzing one dive alone. Here, in our process, we use adjacent profiles and nearby historical data such as Argo data as well as shipborne CTD data (adjacent profiles test and historical data test) to further examine the data quality. In consideration of the dynamic state of the ocean surface, we split each up profile and down profile into two segments by depth (the splitting method is the same as it is in the thermal lag correction test and will be explicitly introduced later) and use different multiples of the standard deviation to evaluate the data. Since the experimental area is not fixed and there might be few historical observations nearby, we only classify the data into two types (suspicious and good) according to the test results in the historical data test, and users can choose the type based on their needs.

Thermal Lag Correction

In general, two approaches can be followed to solve the thermal lag effect caused by mismatches in the thermometer and conductivity sensors. One is to estimate the conductivity near the temperature probe (Lueck and Picklo, 1990), while the other is to estimate the real temperature of the seawater in the conductivity cell (Morison *et al.*, 1994).

In the first scheme, the conductivity correction is as follows:

$$C_T(n) = -bC_T(n-1) + \gamma a\left[T(n) - T(n-1)\right] \tag{1}$$

where T is the temperature data obtained by the CTD sensor, γ is the sensitivity of the conductivity to the temperature, and a and b are the coefficients, which are calculated as:

$$a = \frac{4f_n\tau}{1+4f_n\tau} \tag{2}$$

$$b = 1 - \frac{2a}{\alpha} \tag{3}$$

where f_n is the sample Nyquist frequency, α is the amplitude error parameter and τ is the time constant.

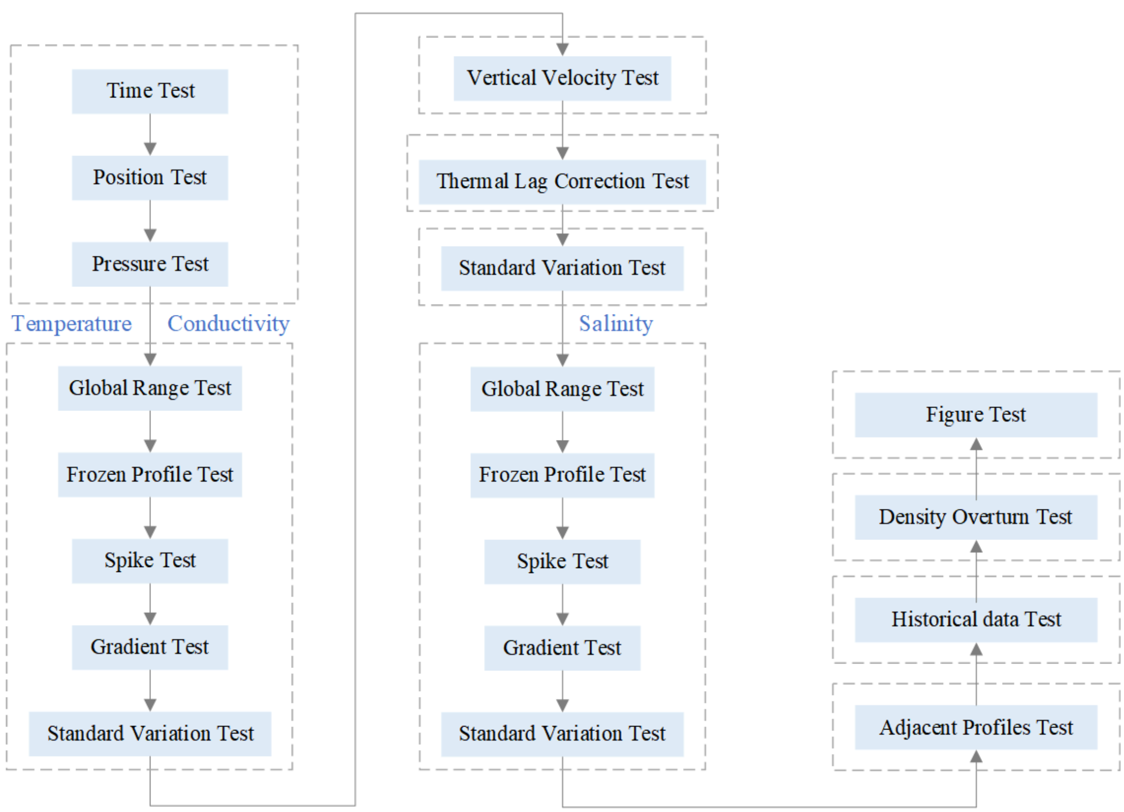

Figure 1. Procedures in the newly designed real-time data quality control process.

For the second scheme, the equation for the seawater temperature correction is:

$$T_T(n) = -bT(n-1) + a\left[T(n) - T(n-1)\right] \tag{4}$$

where parameters a and b are the same as in the first scheme. By avoiding calculating γ during calibration, the second scheme is more computationally efficient.

The modified methodology proposed in this paper is based on methods proposed by Garau *et al.* (2011) and Morison *et al.* (1994) and the toolbox developed by Troupin *et al.* (2015). The main hypothesis of these thermal lag correction approaches is that the background horizontal advection is weak, meaning that the compared the upcast and downcast of one dive are performed in the same water mass and have similar T-S curves. However, when the glider follows a sawtooth-like profile, both temporal and spatial differences are relatively significant in the upper ocean, which are approximately 4-6 hours and several kilometers, respectively, for one 1000 m dive. As shown in Figure 2, the data obtained by the upper parts of the n-1 upcast and n downcast would be more similar than those at the same depth in one dive (upper parts of the n downcast and n upcast) because they are much closer in both time and position. Therefore, it is necessary to split each profile by depth and perform thermal lag correction no longer confined in one single profile. In this paper, each yo-yo profile was cut into four segments by depth and corrected separately. The correction was performed based on the methodology proposed by Garau *et al.* (2011).

The division depth was determined by the curvature of the temperature-depth curve, which is given by:

$$k = \frac{\dfrac{\mathrm{d}T^2}{\mathrm{d}^2 h}}{\sqrt{\left(1 + \dfrac{dT}{dh}\right)^3}} \tag{5}$$

where T is the initial calibrated temperature and h is the depth.

Considering that the impact of the thermocline in the South China Sea could reach approximately 300 m and the maximum depth of each dive of the glider is approximately 1000 m, here we take the lower quartile of the computed curvature as the threshold. Moreover, since some occasionally occurring ocean processes may introduce error and influence the judgment, only when the curvature is continuously larger than its lower quartile for more than 30 m can this range be considered as thermocline and its nearby water.

Sea Trial

The data used to evaluate the performance of the newly designed data quality control method were obtained by a Petrel glider equipped with a GPCTD on August 27, 2018 (16.0093 °N, 113.1712 °E), and February 28, 2019 (18.8844-18.9256 °N, 115.2267-115.3108 °E) (Figure 3). The sample rate of the GPCTD was 1 Hz, allowing its data to have the same vertical resolution order as the ship's CTD. The simultaneous vessel-based CTD was launched in the nearby area where the glider was deployed. The ship CTD casts were performed with an SBE 911 plus CTD (pumped, Seabird Electronics, Inc., USA), whose sample rate was 24 Hz.

RESULTS

Comparison between the Glider-based CTD Data and the Vessel-based CTD Data

Figure 4 shows the correction results of a profile obtained in August 2018. Both the vessel-based CTD data and the glider-based CTD data depict a strong thermocline from the surface to approximately 300 m, where the temperature decreases from 27 °C to 10 °C and the salinity varies between 33 psu (not shown) and 34.6 psu. Below 300 m, the temperature gradually decreases to 7 °C, while the salinity is constantly fluctuating around 34.43 psu.

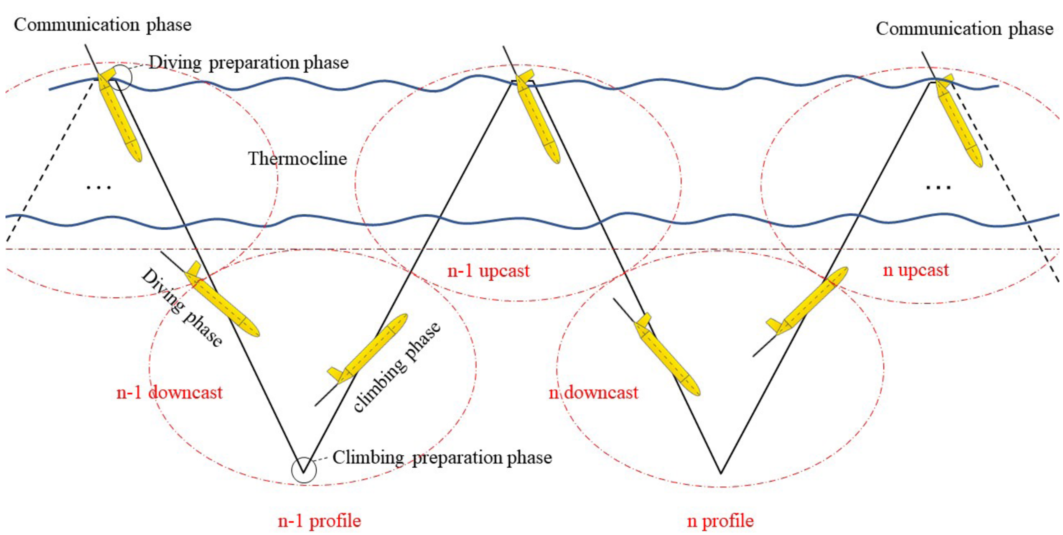

Figure 2. Schematic view of the glider's working mode. Red dotted circles indicate the split method.

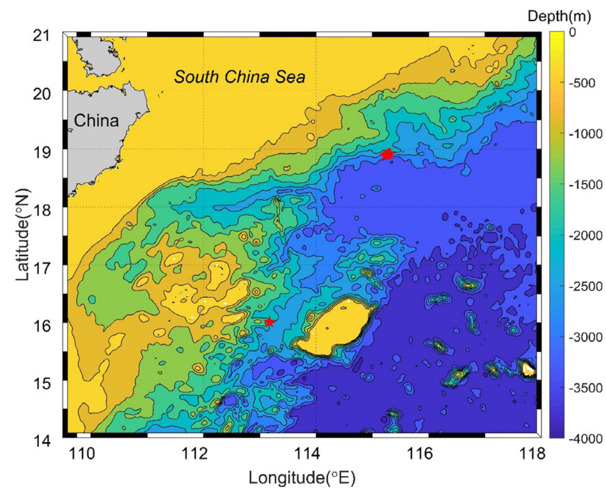

Figure 3. Map of the sea trial region and the trajectory of the glider. The stars represent the positions of the observations.

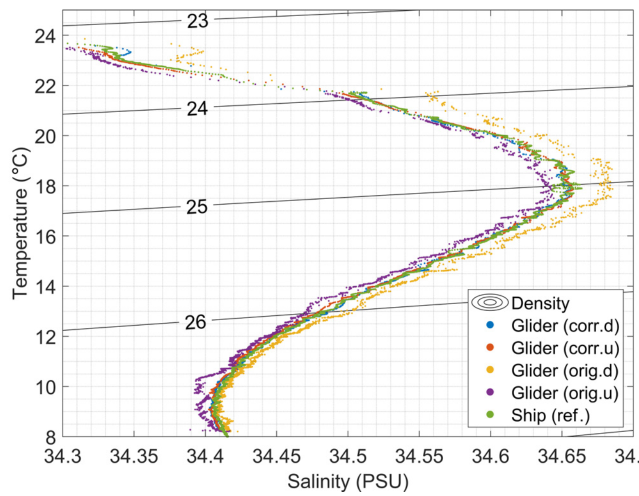

Figure 5. Temperature–salinity diagram from the glider CTD (downcast (d) vs upcast (u)) and the reference shipborne CTD. The abbreviations in the legend are the same as those in Figure 4.

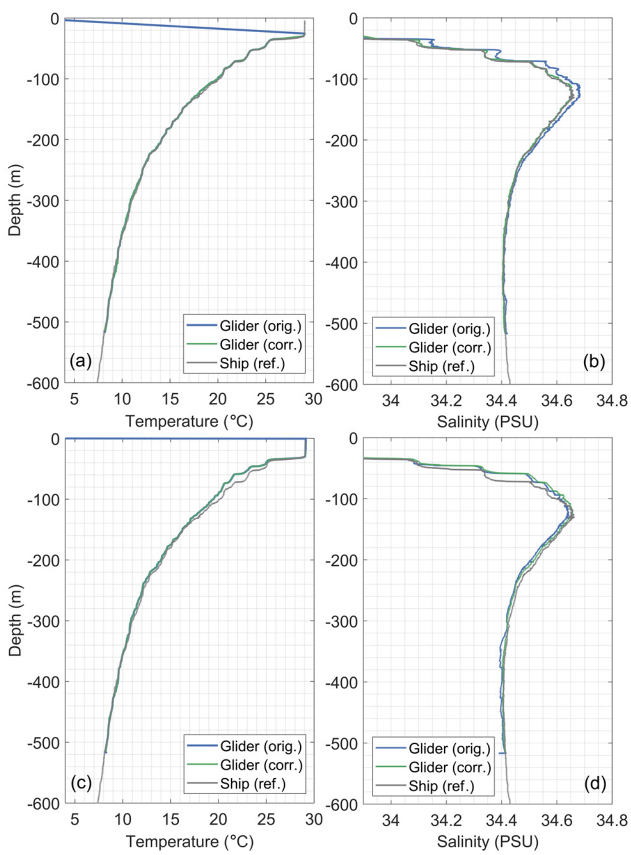

Figure 4. Downcast (top) and upcast (bottom) the temperature (left) and salinity (right) profiles from the glider and the reference shipborne CTD. Reference: ref. (gray lines), original: orig. (blue lines), corrected with the proposed method: corr. (green lines).

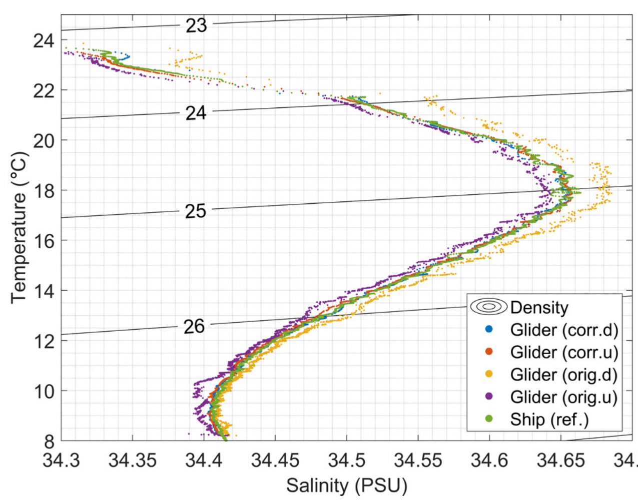

Figure 6. Salinity-depth diagrams of some adjacent profiles. The data were quality controlled through the methodology from Garau *et al.* (2011) (a) and the modified method proposed in this paper (b).

After performing the data quality control process designed for the Petrel UG, the glider data indicate significant improvement and align well with the ship's data, as shown in Figure 4. For the down profile, the discrepancy was reduced by a maximum of 0.05 psu at approximately 90 m and it shows an excellent alignment between downcast data and shipborne data, which indicates that the method we proposed is quite effective. For the up profile, the CTD underestimates the salinity by approximately 0.02 psu at first when the glider was climbing to the surface. The mismatch in Figure 4 (c) and (d) may be derived from the differences in the time and positions of the up profile and vessel-based CTD.

Comparison between the Glider-based CTD Data in the Downcast and Upcast Profiles

Figure 5 shows the T-S diagram of the same profile depicted in Figure 4, which indicates excellent uniformity in the water sampled by the glider downcasts, glider upcasts and nearby ship CTD casts. In this case, obviously, the correction reduces the salinity spikes, and both the downcast and upcast are well calibrated.

Figure 6 shows three quality-controlled adjoining glider profiles corrected by Garau *et al.* (2011) (a) and the modified method (b). As shown in the diagram, although the correction proposed by Garau *et al.* (2011) is also effective, there is an interesting and nonnegligible separation in the deeper layer (especially for the layer from 260 m to 400 m), where the dark blue line, the yellow line and the green line are much closer, and the same situation is observed for the red line and purple line. It shows a tendency that the salinity data of adjacent profiles in the same direction (*i.e.,* all the downcasts or all the upcasts in a row) are much closer than the data obtained by the downcast and upcast of one yo-yo profile in the deeper layer. This phenomenon is abnormal since the salinity of one downcast should be more similar to that of the corresponding upcast rather than with the salinity of the adjacent downcast, which also indicates that the correction proposed by Garau *et al.* (2011) is not complete. As a comparison, after splitting each downcast and each upcast into two segments, they are calibrated more reasonably. The modified thermal lag correction results shown in Figure 6 are much better, which effectively eliminate the salinity separation of the down- and upcasts.

DISCUSSION

Continuity of the Division Points in the Modified Thermal Lag Correction Method

Since the relationship between temperature and salinity is nonlinear and the correction is an iterative procedure, one of the most concerning issues over the modified thermal lag correction is the continuity at the division point. However, the corrected results seem reasonable and exhibit no false spikes at the conjunction. The reasons are as follows. First, variations in salinity in the ocean are usually on the order of 10^{-2} PSU/m in the upper layer of open seas, and the data calibration is fine-tuned, which has a measurable finite effect on the original salinity structure. In addition, while choosing the division depth, the lower quartile and other measurements are calculated to ensure the separation of the profile in a nondramatic area of change, confining the corrections to a very narrow range. Finally, there are a series of tests for further checking the data, which provide double protection to avoid discontinuities.

CONCLUSIONS

A real-time data quality control process for Petrel gliders is proposed in this paper, which first adds an adjoining profile test to further examine the abnormal profiles, whose data are reasonable in value but depict irregular ocean structures. Moreover, a modified thermal lag correction method is also proposed in this paper. Based on the curvature of temperature, the methodology first divides each profile by depth for better correction, which breaks the original understanding of the glider profile and provides a hint for future data quality control. Finally, further experiments could continue to focus on optimizing the correction model, which is the foundation of the whole data quality control process and needs to be updated to adapt to the newly developed CTDs.

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