Global Argo data fast receiving and post-quality-control system

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Abstract. Within the past 20 years, the international Argo program has acquired more than 2 million temperature and salinity profiles throughout the global ocean. It has become the most efficient means of obtaining ocean observations from upper-intermediate layers. The profile data provided by the Argo Global Data Assembly Centres (GDACs) are submitted by 11 data centres in 9 countries after undergoing quality control. However, because the quality of the submitted data lacks uniformity, users must conduct post-quality-control processing prior to using the data. For this purpose, the China Argo Real-Time Data Centre (CARDC) has developed a system to achieve both rapid global Argo data reception and post-quality-control processing of all temperature and salinity profiles. Already in operation, the system allows daily transfer of global post-quality-controlled Argo data to various operating divisions. The system synchronizes with the GDAC server once each day, extracts all updated Argo profiles, and then automatically reads the data and performs a post-quality-control process comprising 15 quality control tests. The automatic post-quality-control system can detect errors in observation time and satellite fix, as well as identify temperature and salinity spikes, frozen profiles, density inversions and salinity drift/offset. The data quality following the post-quality-control processing has been shown improved effectively. In the future, it is expected that CARDC will update the Argo global ocean observational data set once a quarter.

1. Introduction

The international Argo program, which is an important component of the Global Ocean Observing System, is dedicated to monitoring changes in the temperature and salinity of the upper ocean. The Argo program was launched 20 years ago and it currently manages a global ocean real-time
observation array of approximately 3900 floats [1-4]. At inception, the Argo program was intended to focus mainly on observing pressure, temperature and salinity (conductivity) through the upper 2000 m of the ocean. However, with the continuous advancements of float and sensor technologies, newly developed sensors now allow profiling floats to also observe biogeochemical properties with sufficient accuracy for climate studies and observe water depths of 6,000 meters. This extension of Argo will enable an observing system that can determine the seasonal to decadal-scale variability in biological productivity, the supply of essential plant nutrients from deep-waters to the sunlit surface layer, ocean acidification, hypoxia, ocean uptake of CO₂ and the budget of heat content above the 6,000 meters ocean [5-7]. To date, the Argo program has acquired more than 2 million data profiles, analyses of which have led to important contributions in basic research, national and international climate assessments, education, ocean forecasting and heat content estimations [8,9].

Argo data can be obtained in various ways. For example, all the autonomous profile float observations can be downloaded from the Argo Global Data Assembly Centres (GDACs) based in the USA and France. Argo data and products, including the global gridded Argo data set, can also be downloaded from various other national Argo data centres [10,11]. To ensure the quality of the data downloaded by users, the international Argo Data Management Team (ADMT) developed a manual of quality control procedure that is applied to each profile exchanged using a unified format, i.e., NetCDF [12]. However, the quality of data submitted by national Argo data centres lacks uniformity. This can be attributed to various factors, e.g., the fact that the real-time quality control tests cannot identify some erroneous data, technical defects of deployed floats, lack of knowledge and experience of data inspection technicians, and even neglect to perform the visual inspection [13], all of which have affected related scientific research to a certain extent.

The China Argo Real-Time Data Centre (CARDC) committed to download all Argo data from the GDAC server for post-quality-control processing. Given that some users do not understand the format and method of reading NetCDF files, the output of the CARDC post-quality-control system are written in text format, which means they can be viewed directly. A user manual is provided when the data set is updated, and the reference code for reading the data in the MATLAB version is provided for the convenience of the user [14]. Given the recent increase in the number of BGC-Argo floats, this update separates the BGC-Argo data from the core Argo data (temperature and salinity), which simplifies the format and content of the data and allows users to obtain the data they need based on different parameters. Based on the improvements to the real-time quality control processing of Argo data developed by the ADMT, this study designed a post-quality-control process comprising 15 detection steps. The designed system, which is already in operation, allows daily transfer of global post-quality-controlled Argo data to various operating divisions. The quality of Argo data following manual post-quality-control processing is improved effectively. In the future, it is expected that CARDC will update the Argo global ocean observational data set once every quarter.

2 Data and method

2.1 Data

All the data used in this study were downloaded from the French GDAC server (ftp://ftp.ifremer.fr/ifremer/argo/dac). The FTP directory contains all the float profile data shared internationally by the 11 data centres in 9 countries (i.e., USA/aoml, UK/bodc, France/coriolis, China/csi
o&nmdis, Australia/csiro, India/incois, Japan/jma, Korea/kma&kordi and Canada/meds). The data submitted by the Argo data centre of each country not only include data that have undergone real-time quality control but also some data that have undergone delayed-mode quality control. Therefore, CARDC will download all available updated data when performing data post-quality-control processing.

2.2 Method of post-quality-control processing

The ADMT has developed a quality control manual that explains the content and detection methods of the Argo real-time data quality control process in detail. Each Argo data element on the GDAC servers is given a quality control (qc) flag, as listed in Table 1 [12]. Based on this, Racape spike detection and climatology tests have been incorporated as automatic detection steps.

| Flag | Meaning |
|------|---------|
| 0    | No QC was performed |
| 1    | Good data |
| 2    | Probably good data |
| 3    | Probably bad data that are potentially correctable |
| 4    | Bad data |
| 8    | Estimated value |
| 9    | Missing value |

The Racape spike test was designed based on a national report that was delivered by Dr. C. Coatanoan of the Coriolis Data Centre at the 19th Argo Data Management Team meeting in France [15]. The main idea behind the Racape test is that the threshold values of the standard deviation of temperature and salinity measurements are different in different depth ranges (see Table 2). A 5-point moving median method is used to test spikes; if a spike is detected, the qc flag is set as ‘4’. Unfortunately, this method is not effective for detecting continuous spikes with more than two points.

| Pressure(dbar) | Standard deviation of temperature(°C) | Standard deviation of salinity (psu) |
|---------------|--------------------------------------|-------------------------------------|
| <10           | 8.0                                  | 1.1                                 |
| 10~500        | 6.0                                  | 0.9                                 |
| >500          | 2.0                                  | 0.2                                 |

The climatology test is based on the high-quality historical conductivity–temperature–depth (CTD) data (or historical Argo data) provided by the Coriolis Data Centre in France. It searches for nearby historical data according to the position of each profile and it calculates the standard deviation of both temperature and salinity at different depths. When the temperature or salinity value of the float exceeds 6.5 times the standard deviation, its qc flag is recorded as ‘3’. Results of the climatology test for the 93rd cycle of Float 2902261 are shown in Fig. 1. It can be seen that salinity data deeper than 500 dbar fall outside the threshold of 6.5 times the historical CTD standard deviation, indicating a
potential salinity offset problem of this float; consequently, the qc flag is recorded as ‘3’.

Figure 1. Example results of climatology test for the 93rd cycle of Float 2902261 (blue: Argo data; grey: historical CTD data; green: mean (bold) and 6.5 times the standard deviation calculated from historical CTD data; red circles: salinity data other than 6.5 times the standard deviation).

The method of visual inspection constitutes an indispensable element of post-quality-control processing. For data quality problems that cannot be determined automatically by computer, e.g., data with obvious errors or abnormalities and abnormal positioning of a float’s drift trajectory, it is necessary to depict graphically the data of each float for visual inspection. This process must be undertaken with consideration of the hydrological characteristics of the position of the float. For example, special attention is required in the Labrador Sea area of the North Atlantic Ocean because the temperature and salinity of the deep water can change abruptly \cite{16}. The data depicted for visual inspection include the temperature waterfall and vertical distribution of temperature observed by each float, salinity waterfall and vertical distribution of salinity, a temperature–salinity diagram and float trajectory (Fig. 2).
When checking data manually, obvious abnormalities or errors in the profile data are usually obvious. The location of an abnormality or error is flagged using a MATLAB script, and the qc flag of the corresponding data is modified accordingly. Generally, this step does not modify original data; instead, a qc flag of ‘1’ is usually adjusted to a flag of ‘3’ or ‘4’ to remind the user to pay particular attention when using the data. If a problem exists with location information, this quality control process will estimate the location at which the problem occurred through interpolation, replace the original data and then modify the qc flag of the location data to ‘8’.

3 Problems and solutions
In the visual inspection process following the automatic detection and modification of qc flags, problems such as temperature or salinity profile anomalies, spikes, drift, salinity bottom anomalies and positional errors can still be found. The handling of such issues is discussed in the following.

3.1 Abnormal temperature or salinity profiles
The marine environment is complex and variable, and observational sensors are affected by oil pollution on the sea surface, seawater corrosion and biological fouling. Electronic components also deteriorate over time, which can lead to abnormal temperature and salinity measurements in the Argo
data set \[^{17}\]. During the quality control process, it was found that the correction values of some float data were listed as default value and that there were no corresponding qc flags, while the original data with a qc flag of ‘1’ showed a chaotic state. As an example, temperature and salinity profile data from Float 1900245 deployed in the subtropical waters of the North Atlantic are shown in Fig. 3. It can be seen that the vertical distribution of both temperature and salinity is very confused and it is not real; thus, the qc flag for these data was changed from the original ‘1’ to ‘3’ following visual inspection, indicating those data are not recommended to be used.

![Figure 3. Examples of abnormal (a) temperature and (b) salinity profile data.](image)

For cases such as that shown in Fig. 3, only the qc flag is modified, i.e., the profile data are not deleted. Even if some sensors mounted on Argo float have problems in obtaining valid temperature and salinity measurements, the positional information remains of value because it might reflect the characteristics of certain surface or mid-level currents that could provide evidence supporting ocean current hypotheses proposed in earlier research \[^{18,19}\].

3.2 Temperature or salinity spikes

When processing Argo data, it is often found that the value of one or more points in a temperature or salinity profile can be obvious from the adjacent values (the spike phenomenon) but the qc flag associated with such data is set as ‘1’ (i.e. the Argo real-time quality control tests are unable to detect such spikes). Therefore, it is necessary to consider such data during post-quality-control processing. The occurrence of such abnormal data is related to factors that include the influence of the external environment and satellite communication errors. A spike condition in a temperature profile from Float 4900119 and the corresponding data profile after post-quality-control processing are shown in Fig. 4.
Figure 4. Examples of temperature spike: (a) before and (b) after post-quality-control processing.

The automatic detection program cannot accurately detect each spike. However, it is not difficult to identify obvious spikes in a vertical distribution of temperature (Fig. 4a), which could be caused by interference affecting the electronic components of sensors or by satellite communication error. In such cases, visual inspection is required to determine the data file containing the spike, and the qc flag of the spike data should be modified to ‘4’. The vertical profile of temperature after post-quality-control processing and spike removal is shown in Fig. 4b.

3.3 Temperature or salinity drift

Conductivity sensors can experience varying degrees of deterioration during long-term exposure in complex and variable marine environments and/or they can be affected by biological attachment that can produce salinity drift. This is a major problem in relation to Argo data that has been investigated in many previous studies [20–23]. The correction of salinity drift is mainly considered during the delayed-mode quality control stage. However, the time of delayed-mode quality control data submission is generally uncertain and the work requires considerable human and material resources; therefore, salinity drift remains a major problem in relation to GDAC salinity data.

Vertical profiles of temperature and salinity data from Float 2901633 are shown in Fig. 5. The profiles of this float, which is located in the North Pacific Ocean, show clear sensor errors in the overall temperature and salinity and therefore the qc flags of the temperature and salinity profile data are modified to ‘3’. Data drift in such cases can be corrected by delayed-mode quality control that can produce acceptable results.
3.4 Bottom salinity anomaly

Studies have shown that salinity generally changes very slowly in the global ocean in relation to deep water formation [24,25]; however, some floats have produced partial salinity profiles near the bottom of the water column (i.e., deeper than 1500 dbar) with many abnormal values. Examples of bottom salinity anomalies and treated vertical salinity profiles from Float 6900913, located in the subtropical waters of the North Atlantic Ocean, are shown in Fig. 6.

![Figure 5. Examples of (a) temperature drift and (b) salinity drift.](image)

![Figure 6. Examples of bottom salinity anomalies: (a) before and (b) after post-quality-control processing.](image)
It can be seen from the profiles in Fig. 6a that there is a sudden change in bottom salinity. Although the cause of this bottom salinity mutation remains unclear, it is obviously not caused by natural phenomena. Nevertheless, it is necessary to perform post-quality-control processing and to modify the qc flags for such abnormal data. The treatment performed on the float data is to calculate the gradient of salinity with depth. When the depth is greater than 1200 dbar and the gradient is greater than 0.035, the qc flag corresponding to the salinity data is modified to ‘4’. It is evident from the vertical section of salinity after post-quality-control processing, shown in Fig. 6b, that the sudden change in bottom salinity has been discarded, indicating that the treatment measures and parameters adopted are appropriate. In treating a similar problem for multiple floats, different parameters must be selected to remove the mutation of the bottom data for each float.

3.5 Location errors

When an Argo float rises to the sea surface, it automatically feeds its positional information to a ground-based receiving centre via satellite. During this process, the data transfer could be affected by weather conditions or communication errors during transmission, and some errors might be inherent in the positional information. Errors in Argo positional data can be determined as follows. 1) The distance between two adjacent points in the trajectory of the float exceeds 200 km. 2) The time interval between two adjacent points is significantly smaller or larger than pre-determined cycle. 3) The calculation result of float speed at two adjacent points is > 2 m s\(^{-1}\) [26]. In a figure undergoing visual inspection, identification of a significant outlier will prompt post-quality-control processing. The drift trajectory of Float 4900228, located in the North Atlantic Ocean off the southeast coast of the USA, is shown in Fig. 7. The numbers next to certain points on the trajectory represent the cycle number of the float.

![Figure 7. Examples of Argo float positional error: (a) before and (b) after post-quality-control processing.](image)

It can be seen from Fig. 7a that the latitude and longitude information of certain profiles have errors,
i.e., cycle numbers 60, 65, 75, 134, 139 and 195. The reason why such abnormal positional information is not detected automatically is because the file of the previous profile is missing or the date is incorrect. In such cases, the treatment method is to identify the problematic profile. Then, the linear interpolation method can be used to estimate appropriate latitude and longitude values for the profile according to the observation date and the location information of the previous and subsequent profiles. These interpolated positional data can be used to replace the original latitude and longitude values, and the qc flag is changed to ‘8’. Usually, the trajectory after post-quality-control processing should be redrawn to ensure the accuracy of the interpolation results. The drift trajectory of Float 4900228 after interpolation is shown in Fig. 7b. It can be seen that the erroneous trajectory has shown a more reasonable shape, indicating that the interpolation result is reasonable. If abnormal positional information cannot be resolved using the interpolation method, the data will be replaced temporarily with the default value (-999.999) and the qc flag will be modified to ‘9’.

3.6 Abnormal date information

Usually, the cycle time of an autonomous Argo float is 10 days. Although different cycle periods can be set as needed (e.g., 1 or 2 days), the date interval of two adjacent profiles is fixed especially those floats using Argos satellite for data transmission. The time information of Float 7900385 is listed in Table 3, in which columns 1–4 indicate the cycle number, observation date, Julian day and time interval, respectively. It can be seen that the time interval of cycles 1–4 is approximately 3 days, while that of cycles 5–14 is approximately 10 days. However, the time interval of cycle 15 is 300 days, while that of cycles 16 and 17 is a negative value just below zero, which is obviously abnormal.

| Cycle No | Date       | Julian day (day) | Observation interval (day) |
|----------|------------|-----------------|----------------------------|
| 1        | 2012/12/17 | 735220.1056     | \                          |
| 2        | 2012/12/19 | 735222.8535     | 2.7479                     |
| 3        | 2012/12/22 | 735225.8518     | 2.9983                     |
| 4        | 2012/12/25 | 735228.8527     | 3.0009                     |
| 5        | 2013/01/04 | 735238.8535     | 10.0008                    |
| 6        | 2013/01/14 | 735248.8541     | 10.0006                    |
| 7        | 2013/01/24 | 735258.8542     | 10.0001                    |
| 8        | 2013/02/03 | 735268.8577     | 10.0035                    |
| 9        | 2013/02/13 | 735278.8500     | 9.9923                     |
| 10       | 2013/02/23 | 735288.8552     | 10.0052                    |
| 11       | 2013/03/05 | 735298.8555     | 10.0003                    |
| 12       | 2013/03/15 | 735308.8558     | 10.0003                    |
| 13       | 2013/03/25 | 735318.8600     | 10.0042                    |
| 14       | 2013/04/04 | 735328.8632     | 10.0032                    |
| 15       | 2014/01/29 | 735628.8833     | **300.0201**               |
| 16       | 2014/01/29 | 735628.8789     | **-0.0044**                |
| 17       | 2014/01/29 | 735628.8731     | **-0.0058**                |
From the latitude and longitude information of the float, it is evident that the float was located near Antarctica at the time of these observations. Given the span of the dates, it is likely that the float was under the seasonal ice-covered region during this part of its drift. After an observation is completed, if the float detects ice on the sea surface, it will not rise to the sea surface for data transmission until the detection of a region without ice-covered [27]. Thus, this process was repeated from 4 April 2013 to 29 January 2014. When the float finally reached the sea surface, achieved satellite communication, and transmitted the stored data to the ground-based receiving station, the dates of the observations performed under the ice were unknown. This can only be corrected by changing the date qc flag to ‘4’. In addition, although the latitude and longitude qc flags are marked as ‘8’, indicating interpolated data, the interpolation result is unsatisfactory and it is recommended that the data not be used.

4 Post-quality-control results and applications
In the automatic processing stage, some profiles with a maximum observation depth of <200 dbar, minimum observation depth of >50 dbar, total-observation level of <20, date qc flag of ‘4’ and descending cast observations will be discarded from the post-quality-control data set. The number of profiles without quality control (i.e., total number of profiles downloaded from the GDAC) and the monthly distribution of the number of profiles after post-quality-control processing are shown in Fig. 8a. It can be seen that the number of profiles increases gradually with time. According to statistics, the ratio of the number of profiles after post-quality-control processing to the total number of profiles is 93.7% (regardless of qc flag), indicating that the available Argo data are generally good.

![Figure 8](image-url)  
**Figure 8.** (a) Number of Argo profiles before and after post-quality-control
processing and (b) data quality by month and year.

After completion of the post-quality-control processing, depending on the number of Argo profiles, the ratio of the number of profiles in each month with high-quality data (Data with qc flag of ‘1’ in a temperature, salinity and pressure account for >90% of the observational data in this profile) compared with the total number of profiles after post-quality-control processing was determined. The distribution characteristics are shown in Fig. 8b. It can be seen that the data quality during 2004–2019 increased gradually, and that the quality of salinity data was lower than that of both temperature and pressure.

The percentage of high-quality profiles of temperature, salinity and pressure data since 2004 have increased from 72.7% to 98.3% (average: 93.1%), from 65.9% to 93.3% (average: 90.3%) and from 65.9% to 93.3% (average: 86.6%), respectively. These statistics also indicate that the Argo temperature and pressure sensors are generally stable, while the conductivity sensors that measure salinity are less stable.

Given the quantity and quality of the profiles, data from 2004 were selected to produce the global ocean Argo gridded data set [28], and the data were verified by comparison with WOA18 data using the ENSO signal test, which indicated that the Argo data set is both effective and reliable [29].

5 Conclusions
In this study, after separation of the core and BGC Argo GDAC data, the core data were subjected to comprehensive post-quality-control processing. Automatic Argo floats operate in the complex marine environment, which can cause sensors to deteriorate and lead to communication problems. Thus, the derived data profiles can include data anomalies, location errors and examples of the salinity drift phenomenon. In this paper, a post-quality-control processing solution for each of these problems was described and examples of satisfactory data correction presented. The specific conclusions are as follows.

(1) For an entire profile with abnormal temperature and/or salinity data, the qc flag is changed to ‘3’ without changing the original data nor deleting the problem profile because the location data might still be useful. For the problem of temperature and salinity spikes, the qc flag of the spike data is changed to ‘4’ and the validity of modified data should be verified. For temperature or salinity drift, simple data correction should not be conducted; instead, the qc flag is changed to ‘3’ and delayed-mode quality control should be conducted with consideration of suitable background information.

(2) Mutation of bottom salinity data is usually considered abnormal. For the phenomenon of anomalous bottom salinity, a process of selection of an appropriate gradient and depth range based on the condition and depth value of different bottom mutations is suggested, together with a change of the corresponding qc flag to ‘4’.

(3) When the drift trajectory of a float is abnormal, interpolation is required based on the observation date and location information of the previous and subsequent profiles. It is suggested that linear interpolation be used to estimate the longitude and latitude values of the section. Thus, the original erroneous latitude and longitude values can be replaced and the qc flag of the positional information changed to ‘8’. This method has been shown effective.

(4) Floats in polar regions, especially near Antarctica, can encounter sea ice. During times when
floats conduct observations beneath the ice, the data are stored until the float is able to reach the sea surface and transmit the data to a ground-based receiving station. Under such circumstances, if the phenomenon of abnormal float dates occurs, the date qc flag should be changed to ‘4’. It is recommended that float manufacturers store the observation time together with the profile data and pass it back to reduce this error occurring when the data are stored. As for determining location information beneath the ice, there is currently no adequate solution.

(5) The volume of Argo data has grown steadily since 2004 and the GDACs currently manage approximately 15,000 profiles per month. Generally, the overall quality of Argo data is good, although the quality of both temperature and pressure data is better than that of salinity data.

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