

Argo data management

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# Argo Quality Control Manual For CTD and Trajectory Data

Version 3.2

1 February 2019

**ARGO**

*part of the integrated global observation strategy*



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## **Argo Quality Control Manual for CTD and Trajectory Data**

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## Table of contents

<b>1. INTRODUCTION</b>	<b>7</b>
<b>2. REAL-TIME QUALITY CONTROLS</b>	<b>8</b>
<b>2.1. ARGO REAL-TIME QUALITY CONTROL TEST PROCEDURES ON VERTICAL PROFILES</b>	<b>8</b>
2.1.1. INTRODUCTION	8
2.1.2. QUALITY CONTROL TESTS ON VERTICAL PROFILES	9
2.1.3. TESTS APPLICATION ORDER ON VERTICAL PROFILES	16
2.1.4. QUALITY CONTROL FLAG APPLICATION POLICY	16
<b>2.2. ARGO REAL-TIME QUALITY CONTROL TEST PROCEDURES ON TRAJECTORIES</b>	<b>17</b>
<b>2.3. ARGO REAL-TIME ADJUSTMENTS ON VERTICAL PROFILES</b>	<b>20</b>
2.3.1. REAL-TIME PRESSURE ADJUSTMENT FOR NON AUTO-CORRECTING FLOATS	20
2.3.2. REAL-TIME SALINITY ADJUSTMENT	21
2.3.3. REAL-TIME FILES WITH DATA_MODE = 'A'	21
<b>2.4. FEEDBACK FROM STATISTICAL TEST AT CORIOLIS</b>	<b>22</b>
<b>2.5. ARGO REAL-TIME QUALITY CONTROL TEST PROCEDURES ON NEAR-SURFACE DATA</b>	<b>23</b>
<b>2.6. INTERIM REAL-TIME QUALITY CONTROL FLAG SCHEME FOR FLOAT DATA DEEPER THAN 2000 DBAR</b>	<b>27</b>
<b>2.7. INTERIM REAL-TIME QUALITY CONTROL FLAG SCHEME FOR RBR CTD DATA</b>	<b>28</b>
<b>3. DELAYED-MODE QUALITY CONTROLS</b>	<b>29</b>
<b>3.1. EDITING RAW QC FLAGS IN DELAYED-MODE</b>	<b>29</b>
<b>3.2. DELAYED-MODE PROCEDURES FOR JULD, LATITUDE, LONGITUDE</b>	<b>29</b>
<b>3.3. DELAYED-MODE PROCEDURES FOR PRESSURE</b>	<b>29</b>
3.3.1. DELAYED-MODE PRESSURE ADJUSTMENT FOR APEX FLOATS	29
3.3.2. TRUNCATED NEGATIVE PRESSURE DRIFT (TNPD) IN APEX FLOATS	31
3.3.3. SUMMARY FLOWCHART FOR UNADJUSTABLE APEX PRESSURES	37
<b>3.4. DELAYED-MODE PROCEDURES FOR TEMPERATURE</b>	<b>38</b>
<b>3.5. DELAYED-MODE PROCEDURES FOR SALINITY</b>	<b>39</b>
3.5.1. INTRODUCTION	39
3.5.2. QUALITY CONTROL AND THE SEMI-AUTOMATIC PART	40
3.5.3. SPLITTING THE FLOAT SERIES AND LENGTH OF CALIBRATION WINDOW	41

3.5.4.	THE P <small>I</small> EVALUATION PART	42
3.5.5.	ASSIGNING ADJUSTED SALINITY, ERROR ESTIMATES, AND QC FLAGS	44
3.5.6.	SUMMARY FLOWCHART FOR SALINITY	46
3.5.7.	TIMEFRAME FOR AVAILABILITY OF DELAYED-MODE SALINITY DATA	47
3.5.8.	REFERENCES	47
<b>3.6.</b>	<b>COMPULSORY VARIABLES TO BE FILLED IN A D FILE</b>	<b>48</b>
3.6.1.	MEASUREMENTS FOR EACH PROFILE	48
3.6.2.	SCIENTIFIC CALIBRATION INFORMATION FOR EACH PROFILE	48
3.6.3.	OTHER VARIABLES IN THE NETCDF FILE	50
<b>4.</b>	<b>APPENDIX</b>	<b>51</b>
<b>4.1.</b>	<b>REFERENCE TABLE 2: ARGO QUALITY CONTROL FLAG SCALE</b>	<b>51</b>
<b>4.2.</b>	<b>REFERENCE TABLE 2A: PROFILE QUALITY FLAGS</b>	<b>52</b>
<b>4.3.</b>	<b>REFERENCE TABLE 11: RTQC TESTS BINARY ID</b>	<b>53</b>
<b>4.4.</b>	<b>COMMON INSTRUMENT ERRORS AND FAILURE MODES</b>	<b>54</b>
<b>4.5.</b>	<b>CRITERIA FOR CTD PROFILES TO BE RETAINED IN THE REFERENCE DATABASE</b>	<b>57</b>
<b>4.6.</b>	<b>CRITERIA FOR ARGO PROFILES TO BE RETAINED IN THE REFERENCE DATABASE</b>	<b>58</b>
<b>4.7.</b>	<b>CONSISTENCY CHECKS FOR D FILES FORMAT AT THE GDACs</b>	<b>59</b>

## History

Date (dd/mmm/yyyy)	Comment
01/Jan/2002	Creation of the document.
28/Mar/2003	Changed lower limit of temperature in Med Sea to 10.0°C.
08/Jun/2004	Modified spike and gradient tests according to advice from Yasushi. Added inversion test.
24/Oct/2003	Real-time qc tests 15 and 16 proposed at ADMT4 in Monterey. Test 10 removed.
07/Oct/2004	1. Real-time and delayed-mode qc manuals merged in "Argo quality control manual". 2. Frozen profile real time qc test 17 proposed at ADMT5 in Southampton. 3. Deepest pressure real time qc test 18 proposed at ADMT5 Southampton. 4. Order list for the real time qc tests. 5. "Regional Global Parameter Test" renamed "Regional range test", test 7. 6. Grey list naming convention and format, test 15. 7. Real time qc on trajectories.
23/Nov/2004	§1: new introduction from Annie Wong. §3: delayed mode quality control manual from Annie Wong.
26/Nov/2004	§3: update of summary flow chart for salinity delayed mode qc.
31/Aug/2005	§2.1.2: update on test 17, visual qc.
17/Nov/2005	§2.3: added a section on real-time salinity adjustment. §3.2: added usage of SURFACE PRESSURE from APEX floats. §3.4.5: added some more guidelines for PSAL_ADJUSTED_QC = '2'. §3.5: clarified that PROFILE_<PARAM>_QC should be recomputed when <PARAM>_ADJUSTED_QC becomes available.
16/Oct/2006	§3: updated delayed-mode section based on DMQC-2 Workshop.
20/Nov/2006	§2.1.2: test 19: deepest pressure delta set to 10%. §2.1.2: test 14: density inversion test applied downward and upward.
14/Nov/2007	§2.1.2: test 6: minimum salinity set to 2 PSU instead of 0 PSU. §2.1.2: test 7: minimum salinity set to 2 PSU instead of 0 PSU. This change was decided during ADMT8 in Hobart.
14/Nov/2007	§3.2.1: use "known pressure drift" instead of delta P > 5dbar. This change was decided during ADMT8 meeting in Hobart.
14/Nov/2007	§3.1: delayed-mode operators can edit real-time QC flags. This change was decided during ADMT8 in Hobart.
14/Nov/2007	§2.1.4: values with QC flag = '4' are ignored by real-time quality control tests. This change was decided during ADMT8 in Hobart.
14/Nov/2007	§2.1.4: when salinity is calculated from temperature and conductivity, if temperature is flagged as bad then salinity is flagged as bad. This change was decided during ADMT8 in Hobart.
21/Jan/2008	§2.2: test 6: minimum salinity set to 2 PSU instead of 0 PSU. §2.2: test 7: minimum salinity set to 2 PSU instead of 0 PSU.
04/Nov/2008	§2.1.2: "Sigma0" specified in density inversion test. §2.3.1: added a section on real-time pressure adjustment for APEX floats. §3.4.5: updated delayed-mode section based on DMQC-3 Workshop.
14/Feb/2009	§3.2: added a section on delayed-mode pressure adjustment for APEX floats.
19/Oct/2009	§2.1.2 & §2.2: test 6: minimum P set to -5 dbar. §3.1: added a section on editing raw qc flags in delayed-mode. §3.2.2: updated delayed-mode treatment for APEX TNPDs, after DMQC-4.
15/Jul/2010	§2.4: added a section on Feedback from Statistical Test at Coriolis.
05/Nov/2010	§3.2.2: revised definition for TNPD after ADMT11 in Hamburg.

Date (dd/mmm/yyyy)	Comment
01/Dec/2011	§2.1.2: added threshold of 0.03 kg m <sup>-3</sup> to RT test 14, Density Inversion Test, for profile data, following ADMT12 in Seoul. Test to use potential density referenced to mid-point pressure between the two levels to be compared. §2.2: Added RT test 20, "Questionable Argos position test" from JAMSTEC, as a new real-time qc test for trajectory data, following 3 <sup>rd</sup> Trajectory Workshop and ADMT12 in Seoul.
03/Jan/2013	§2.3.1: clarified real-time pressure adjustment for non auto-correcting floats when SP=0.
03/Jan/2013	§2.1.2: addition of real-time quality control for dissolved oxygen DOXY. The real-time qc tests 6, 9, 11 and 13 are applied to DOXY.
04/Nov/2013	§2.5: addition of real-time qc test procedures for near-surface data.
04/Nov/2013	§3.4.5: added upper limit of delayed-mode salinity adjustment as 0.05 PSU.
18/Nov/2014	§2.6: addition of interim real-time qc flag scheme for float data deeper than 2000 dbar.
10/Nov/2015	Argo QC Manual split into Argo QC Manual for CTD & Trajectory Data and Argo QC Manual for Biogeochemical Data, after ADMT16 in Bermuda.
07/Dec/2015	Real-time qc test 2, Impossible Date Test, re-written in JULD instead of day-month-year.
07/Dec/2015	Test 23 assigned to interim rtqc flag scheme for data deeper than 2000 dbar.
07/Dec/2015	§2.1.1: description of the BUFR format added by Anh Tran.
08/Dec/2017	Reference Table 2, Argo qc flag scale: '8' meaning changed from "interpolated" to "estimated".
08/Dec/2017	§2.1.2: action for Test 15, the "grey list", updated to include no GTS distribution by TESAC or BUFR.
08/Dec/2017	§2.7: addition of interim real-time qc flag scheme for float data from experimental sensors, including the RBR CTD.
16/Jan/2019	Test 15, greylist definition revised and allow qc='2'.
16/Jan/2019	Test 7, Red Sea temperature lower limit changed from 21.7C to 21.0C.
16/Jan/2019	In the delayed-mode section, specified that the operator can decide how recent a profile to send out in 'D' mode.
16/Jan/2019	In the delayed-mode section, added examples on how to fill the SCIENTIFIC_CALIB section.

# 1. Introduction

A CTD (conductivity, temperature, depth) device measures temperature and salinity versus pressure. Trajectory data involve positions and time. This document is the Argo quality control manual for CTD and trajectory data. It describes two levels of quality control:

- The first level is the real-time system that performs a set of agreed automatic checks.
- The second level of quality control is the delayed-mode system.

These quality control procedures are applied to the core Argo parameters:  
JULD, LATITUDE, LONGITUDE, PRES, TEMP, PSAL and CNDC.

## 2. Real-time quality controls

### 2.1. Argo Real-time Quality Control Test Procedures on vertical profiles

#### 2.1.1. Introduction

Because of the requirement for delivering data to users within 24-48 hours of the float reaching the surface, the quality control procedures on the real-time data are limited and automatic. These tests are described here. If data from a float fail these tests, those data will not be distributed on the Global Telecommunication System (GTS) in TESAC code form. However, all of the data, including those having failed the tests, are distributed on the GTS in BUFR format, and are converted to the agreed netCDF format and forwarded to the Global Argo Data Assembly Centres (GDACs).

The TESAC code form contains only profile data as a function of depth not pressure. It is recommended that the UNESCO routines be used to convert pressure to depth (Algorithms for computation of fundamental properties of seawater, N.P. Fofonoff and R.C. Millard Jr., UNESCO Technical Papers in Marine Science #44, 1983). If the position of a profile is deemed wrong, or the date is deemed wrong, or the platform identification is in error, then none of the data should be sent on the GTS. For other failures, only the offending values need be removed from the TESAC message. The appropriate actions to take are noted with each test.

For the BUFR format, all of the data with their quality control flags will be distributed on the GTS. The BUFR format contains data as a function of pressure. If the date or platform identification is wrong, then none of the data should be sent on the GTS. However, if the position of a profile is questionable, the data will be distributed on the GTS with the appropriate flag for the position.



## 2.1.2. Quality control tests on vertical profiles

### 1. Platform identification

Every centre handling float data and posting them to the GTS will need to prepare a metadata file for each float and in this is the WMO number that corresponds to each float ptt. There is no reason why, except because of a mistake, an unknown float ID should appear on the GTS.

Action: If the correspondence between the float ptt cannot be matched to the correct WMO number, then none of the data from the float should be distributed on the GTS.

### 2. Impossible date test

This test requires that the Julian day of a float profile be later than 1<sup>st</sup> January 1997 and earlier than the current date of the check (in UTC time). Hence if JULD = number of days elapsed since 1<sup>st</sup> January 1950, then this test checks that

$$17167 \leq \text{JULD} < \text{UTC date of check}$$

Action: If JULD of a profile fails this test, the date of the profile should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS.

### 3. Impossible location test

This test requires that the observation latitude and longitude from a float profile be sensible.

- Latitude in range  $-90$  to  $90$
- Longitude in range  $-180$  to  $180$

Action: If either latitude or longitude fails this test, the position should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS.

### 4. Position on land test

This test requires that the observation latitude and longitude from a float profile be located in an ocean. Use can be made of any topography/bathymetry file that allows an automatic test to check if a position is located on land. We suggest use of at least the 5-minute bathymetry file that is generally available. This is commonly called ETOPO5/TerrainBase and can be downloaded from <http://www.ngdc.noaa.gov/mgg/global/etopo5.html>.

Action: If a position cannot be located in an ocean, the position should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS.

### 5. Impossible speed test

Drift speeds for floats can be generated given the positions and times of the floats when they are at the surface and between profiles. In all cases we would not expect the drift speed to exceed  $3 \text{ ms}^{-1}$ . If it does, it means either the positions or times are bad data, or a float is mislabeled. Using the multiple positions that are normally available for a float while at the surface, it is often possible to isolate the one position or time that is in error.

Action: If an acceptable position and time can be used from the available suite, then the data can be distributed on the GTS. Otherwise, the position, the time, or both, should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS in TESAC format.

(Note: Floats that use the Argos system to obtain position data can use Test 20 in Section 2.2.)

## 6. Global range test

This test applies a gross filter on observed values for pressure, temperature and salinity. The ranges need to accommodate all of the expected extremes encountered in the oceans.

- Pressure cannot be less than  $-5$  dbar
- Temperature in range  $-2.5$  to  $40.0^{\circ}\text{C}$
- Salinity in range 2 to 41.0 PSU

Action: If a value fails this test, it should be flagged as bad data ('4'), and that value should be removed from TESAC distribution on the GTS. If temperature and salinity values at the same pressure both fail this test, both values should be flagged as bad data ('4'), and values for pressure, temperature and salinity should be removed from TESAC distribution on the GTS.

## 7. Regional range test

This test applies to certain regions of the world where conditions can be further qualified. In this case, specific ranges for observations from the Mediterranean Sea and the Red Sea further restrict what are considered sensible values. The Red Sea is defined by the region 10N, 40E; 20N, 50E; 30N, 30E; 10N, 40E. The Mediterranean Sea is defined by the region 30N, 6W; 30N, 40E; 40N, 35E; 42N, 20E; 50N, 15E; 40N, 5W; 30N, 6W.

Red Sea

- Temperature in range 21.0 to  $40.0^{\circ}\text{C}$
- Salinity in range 2 to 41.0 PSU

Mediterranean Sea

- Temperature in range 10.0 to  $40.0^{\circ}\text{C}$
- Salinity in range 2 to 40.0 PSU

Action: If a value fails this test, it should be flagged as bad data ('4'), and that value should be removed from TESAC distribution on the GTS. If temperature and salinity values at the same pressure both fail this test, both values should be flagged as bad data ('4'), and values for pressure, temperature and salinity should be removed from TESAC distribution on the GTS.

## 8. Pressure increasing test

This test requires that the profile has pressures that are monotonically increasing (assuming the pressures are ordered from smallest to largest).

Action: If there is a region of constant pressure, all but the first of the consecutive levels of constant pressure should be flagged as bad data ('4'). If there is a region where pressure reverses, all of the pressures in the reversed part of the profile should be flagged as bad data

(‘4’). All pressures flagged as bad data and all of the associated temperatures and salinities should be removed from TESAC distribution on the GTS.

## 9. Spike test

The difference between sequential measurements, where one measurement is significantly different from adjacent ones, is a spike in both size and gradient. This test does not consider differences in pressure, but assumes a sampling that adequately reproduces changes in temperature and salinity with pressure. The algorithm is used on vertical profiles of temperature and salinity.

$$\text{Test value} = | V2 - (V3 + V1)/2 | - | (V3 - V1) / 2 |$$

where V2 is the measurement being tested, and V1 and V3 are the values above and below.

Temperature: The V2 value is flagged when

- the test value exceeds 6.0°C for pressures less than 500 dbar, or
- the test value exceeds 2.0°C for pressures greater than or equal to 500 dbar.

Salinity: The V2 value is flagged when

- the test value exceeds 0.9 PSU for pressures less than 500 dbar, or
- the test value exceeds 0.3 PSU for pressures greater than or equal to 500 dbar.

Action: If the value V2 fails this test, it should be flagged as bad data (‘4’), and only that value should be removed from TESAC distribution on the GTS. If temperature and salinity values at the same pressure both fail this test, both values should be flagged as bad data (‘4’), and values for pressure, temperature and salinity should be removed from TESAC distribution on the GTS.

## 10. Top and bottom spike test: obsolete

## 11. Gradient test

This test is failed when the difference between vertically adjacent measurements is too steep. The test does not consider differences in pressure, but assumes a sampling that adequately reproduces changes in temperature and salinity with pressure. The algorithm is used on vertical profiles of temperature and salinity.

$$\text{Test value} = | V2 - (V3 + V1)/2 |$$

where V2 is the measurement being tested, and V1 and V3 are the values above and below.

Temperature: The V2 value is flagged when

- the test value exceeds 9.0°C for pressures less than 500 dbar, or
- the test value exceeds 3.0°C for pressures greater than or equal to 500 dbar.

Salinity: The V2 value is flagged when

- the test value exceeds 1.5 PSU for pressures less than 500 dbar, or
- the test value exceeds 0.5 PSU for pressures greater than or equal to 500 dbar.

Action: If the value V2 fails this test, it should be flagged as bad data ('4'), and only that value should be removed from TESAC distribution on the GTS. If temperature and salinity values at the same pressure both fail this test, both values should be flagged as bad data ('4'), and values for pressure, temperature and salinity should be removed from TESAC distribution on the GTS.

## 12. Digit rollover test

Only so many bits are allowed to store temperature and salinity values in a profiling float. This range is not always large enough to accommodate conditions that are encountered in the ocean. When the range is exceeded, stored values rollover to the lower end of the range. This rollover should be detected and compensated for when profiles are constructed from the data stream from the float. This test is used to make sure the rollover is properly detected.

- Temperature difference between adjacent pressures  $> 10^{\circ}\text{C}$
- Salinity difference between adjacent pressures  $> 5$  PSU

Action: Values that fail the test should be flagged as bad data ('4') and should be removed from TESAC distribution on the GTS. If temperature and salinity values at the same pressure both fail this test, both values should be flagged as bad data ('4'), and values for pressure, temperature and salinity should be removed from TESAC distribution on the GTS.

## 13. Stuck value test

This test looks for measurements of temperature and salinity in a profile being identical.

Action: If this occurs, all of the values of the affected parameter should be flagged as bad data ('4') and should be removed from TESAC distribution on the GTS. If both temperature and salinity are affected, then all observed values from the profile should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS.

## 14. Density inversion

This test compares potential density between valid measurements in a profile, in both directions, i.e. from top to bottom, and from bottom to top. Values of temperature and salinity at the same pressure level  $P_i$  should be used to compute potential density  $\rho_i$  (or  $\sigma_i = \rho_i - 1000$ )  $\text{kg m}^{-3}$ , referenced to the mid-point between  $P_i$  and the next valid pressure level. A threshold of  $0.03 \text{ kg m}^{-3}$  should be allowed for small density inversions.

Action: From top to bottom, if the potential density calculated at the greater pressure  $P_{i+1}$  is less than that calculated at the lesser pressure  $P_i$  by more than  $0.03 \text{ kg m}^{-3}$ , both the temperature and salinity values at  $P_i$  should be flagged as bad data ('4'). From bottom to top, if the potential density calculated at the lesser pressure  $P_{i-1}$  is greater than that calculated at the greater pressure  $P_i$  by more than  $0.03 \text{ kg m}^{-3}$ , both the temperature and salinity values at  $P_i$  should be flagged as bad data ('4'). Bad temperature and salinity values should be removed from TESAC distribution on the GTS.

## 15. Grey list

This test is implemented as a mechanism for real-time data assembly centres (DACs) to flag sensors that are potentially not working correctly.

The grey list contains the following 7 items:

- Platform: Float WMO Id
- Parameter: name of the grey listed parameter
- Start date: from that date, all measurements for this parameter are flagged as bad ('4') or probably bad ('3') or probably good ('2')
- End date: from that date, measurements are not flagged as bad ('4') or probably bad ('3') or probably good ('2')
- Flag: value of the flag to be applied to all measurements of the parameter
- Comment: comment from the PI on the problem
- DAC: data assembly center for this float

Example:

Float WMO Id	Parameter	Start date	End date	Flag	Comment	DAC
1900206	PSAL	20030925		3		IF

Each DAC manages a grey list, sent to the GDACs. The merged grey list is available from the GDACs.

- Grey list format: ascii csv (comma separated values)
- Naming convention: xxx\_greylist.csv  
xxx: DAC name (e.g.: aoml\_greylist.csv, coriolis\_greylist.csv, jma\_greylist.csv)
- PLATFORM, PARAMETER, START\_DATE, END\_DATE, QC, COMMENT, DAC  
e.g. 4900228, TEMP, 20030909, , 3, , AO  
e.g. 1900206, PSAL, 20030925, , 3, , IF

The decision to insert a float parameter in the grey list comes from the PI or the delayed-mode operator. A float parameter should be put in the grey list when sensor drift is too big to be corrected adequately in real-time, or when the sensor is judged to be potentially not working correctly.

The grey list only concerns real-time files (R-files). When an anomalous float is dead and the offending parameter has been adjusted in delayed-mode, it should be removed from the grey list. When an anomalous float is active and the offending parameter has been partially adjusted in delayed-mode, it should remain in the grey list only if real-time adjustment is not adequate.

Action: Grey-listed parameters are flagged as probably good data ('2') or probably bad data ('3') or bad data ('4'), as determined by the PI or the delayed-mode operator. DACs should also revisit the qc flags of the profiles whose observation dates are between the grey list "start date" and the grey list insertion date.

## 16. Gross salinity or temperature sensor drift

This test is implemented to detect a sudden and significant sensor drift. It calculates the average temperature and salinity from the deepest 100 dbar of a profile and the previous good profile. Only measurements with good QC are used.

Action: For salinity, if the difference between the two average values is more than 0.5 PSU, then all salinity values from the profile are flagged as probably bad data ('3'). For temperature, if the difference between the two average values is more than 1°C, then all temperature values from the profile are flagged as probably bad data ('3').

## 17. Visual QC

This is subjective visual inspection of float measurements by an operator.

To avoid delays, this test is not mandatory before real-time distribution.

## 18. Frozen profile test

This test is used to detect a float that reproduces the same profile (with very small deviations) over and over again.

Typically the differences between two profiles are of the order of 0.001 PSU for salinity and of the order of 0.01°C for temperature.

A). Derive temperature and salinity profiles by averaging the original profiles to get mean values for each profile in 50 dbar slabs (T\_prof, T\_previous\_prof; S\_prof, S\_previous\_prof). This is necessary because the floats do not sample at the same level for each profile.

B). Obtain absolute values of the difference between the averaged temperature and salinity profiles as follows:

- $\text{deltaT} = \text{abs}(T_{\text{prof}} - T_{\text{previous\_prof}})$
- $\text{deltaS} = \text{abs}(S_{\text{prof}} - S_{\text{previous\_prof}})$

C). Find the maximum, minimum and mean of the absolute values of the averaged differences between profiles for temperature and salinity:

- $\text{mean}(\text{deltaT}), \text{max}(\text{deltaT}), \text{min}(\text{deltaT})$
- $\text{mean}(\text{deltaS}), \text{max}(\text{deltaS}), \text{min}(\text{deltaS})$

D). To fail the test, require that:

- $\text{max}(\text{deltaT}) < 0.3$
- $\text{min}(\text{deltaT}) < 0.001$
- $\text{mean}(\text{deltaT}) < 0.02$
- $\text{max}(\text{deltaS}) < 0.3$
- $\text{min}(\text{deltaS}) < 0.001$
- $\text{mean}(\text{deltaS}) < 0.004$

Action: If a profile fails this test, all measurements from the profile are flagged as bad data ('4'). If a float fails this test on 5 consecutive cycles, it is inserted in the grey list.

## 19. Deepest pressure test

This test requires that a profile has pressures that are not greater than `CONFIG_ProfilePressure_dbar` plus 10%. The value of `CONFIG_ProfilePressure_dbar` comes from the meta.nc file of the float.

Action: If there is a region of incorrect pressures, those pressures and their corresponding temperature and salinity measurements should be flagged as bad data ('4'). Pressures flagged as bad data and their associated temperatures and salinities should be removed from TESAC distribution on the GTS.

### 2.1.3. Tests application order on vertical profiles

The Argo real-time QC tests on vertical profiles are applied in the order described in the following table.

Order	Test Number	Test Name
1	19	Deepest Pressure Test
2	1	Platform Identification
3	2	Impossible Date Test
4	3	Impossible Location Test
5	4	Position on Land Test
6	5	Impossible Speed Test
7	6	Global Range Test
8	7	Regional Range Test
9	8	Pressure Increasing Test
10	9	Spike Test
11	10	Top and Bottom Spike Test : removed
12	11	Gradient Test
13	12	Digit Rollover Test
14	13	Stuck Value Test
15	14	Density Inversion
16	15	Grey List
17	16	Gross salinity or temperature sensor drift
18	18	Frozen profile
19	17	Visual QC

### 2.1.4. Quality control flag application policy

The QC flag value assigned by a test cannot override a higher value from a previous test. Example: a QC flag '4' (bad data) set by Test 11 (gradient test) cannot be decreased to QC flag '3' (bad data that are potentially correctable) set by Test 15 (grey list).

A measurement with QC flag '4' (bad data) is ignored by the quality control tests.

For floats where salinity (PSAL) is calculated from temperature (TEMP) and conductivity (CNDC), if temperature is flagged '4' (or '3'), then salinity is flagged '4' (or '3').

For floats where CNDC values are reported,  $CNDC\_QC = PSAL\_QC$ .



## 2.2. Argo Real-time Quality Control Test Procedures on trajectories

The following tests are applied in real-time on trajectory data.

### 1. Platform identification

Every centre handling float data and posting them to the GTS will need to prepare a metadata file for each float and in this is the WMO number that corresponds to each float ptt. There is no reason why, except because of a mistake, an unknown float ID should appear on the GTS.

Action: If the correspondence between the float ptt cannot be matched to the correct WMO number, then none of the data from the float should be distributed on the GTS.

### 2. Impossible date test

This test requires that the Julian day of a float profile be later than 1<sup>st</sup> January 1997 and earlier than the current date of the check (in UTC time). Hence if JULD = number of days elapsed since 1<sup>st</sup> January 1950, then this test checks that

$$17167 \leq \text{JULD} < \text{UTC date of check}$$

Action: If JULD of a profile fails this test, the date of the profile should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS.

### 3. Impossible location test

This test requires that the observation latitude and longitude from a float profile be sensible.

- Latitude in range  $-90$  to  $90$
- Longitude in range  $-180$  to  $180$

Action: If either latitude or longitude fails this test, the position should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS.

### 4. Position on land test

This test requires that the observation latitude and longitude from a float profile be located in an ocean. Use can be made of any topography/bathymetry file that allows an automatic test to check if a position is located on land. We suggest use of at least the 5-minute bathymetry file that is generally available. This is commonly called ETOPO5/TerrainBase and can be downloaded from <http://www.ngdc.noaa.gov/mgg/global/etopo5.html>.

Action: If a position cannot be located in an ocean, the position should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS.

### 5. Impossible speed test

Drift speeds for floats can be generated given the positions and times of the floats when they are at the surface and between profiles. In all cases we would not expect the drift speed to exceed  $3 \text{ ms}^{-1}$ . If it does, it means either the positions or times are bad data, or a float is

misabeled. Using the multiple positions that are normally available for a float while at the surface, it is often possible to isolate the one position or time that is in error.

Action: If an acceptable position and time can be used from the available suite, then the data can be distributed on the GTS. Otherwise, the position, the time, or both, should be flagged as bad data ('4'), and none of the data from the profile should be distributed on the GTS in TESAC format.

(Note: Floats that use the Argos system to obtain position data can use Test 20 instead.)

## 6. Global range test

This test applies a gross filter on observed values for pressure, temperature and salinity. The ranges need to accommodate all of the expected extremes encountered in the oceans.

- Pressure cannot be less than  $-5$  dbar
- Temperature in range  $-2.5$  to  $40.0^{\circ}\text{C}$
- Salinity in range 2 to 41.0 PSU

Action: If a value fails this test, it should be flagged as bad data ('4'), and only that value should be removed from TESAC distribution on the GTS. If temperature and salinity values at the same pressure both fail this test, both values should be flagged as bad data ('4'), and values for pressure, temperature and salinity should be removed from TESAC distribution on the GTS.

## 7. Regional range test

This test applies to certain regions of the world where conditions can be further qualified. In this case, specific ranges for observations from the Mediterranean Sea and the Red Sea further restrict what are considered sensible values. The Red Sea is defined by the region 10N, 40E; 20N, 50E; 30N, 30E; 10N, 40E. The Mediterranean Sea is defined by the region 30N, 6W; 30N, 40E; 40N, 35E; 42N, 20E; 50N, 15E; 40N, 5W; 30N, 6W.

Red Sea

- Temperature in range 21.0 to  $40.0^{\circ}\text{C}$
- Salinity in range 2 to 41.0 PSU

Mediterranean Sea

- Temperature in range 10.0 to  $40.0^{\circ}\text{C}$
- Salinity in range 2 to 40.0 PSU

Action: If a value fails this test, it should be flagged as bad data ('4'), and only that value should be removed from TESAC distribution on the GTS. If temperature and salinity values at the same pressure both fail this test, both values should be flagged as bad data ('4'), and values for pressure, temperature and salinity should be removed from TESAC distribution on the GTS.

## 20. Questionable Argos position test

For floats that use the Argos system to obtain position data, this test can be used in lieu of Test 5 (Impossible Speed Test).

This test identifies questionable Argos position data collected during surface drift of a float cycle by considering the float speed at the sea surface and Argos position errors. Details of the method can be found in Nakamura et al (2008), “Quality control method of Argo float position data”, JAMSTEC Report of Research and Development, Vol. 7, 11-18. A brief description of the procedure is summarized here.

A). Collect all Argos positions during surface drift of a float cycle. The distance between two positions  $A$  and  $B$  is referred to as a segment. A segment is considered questionable if:

- (i) the float speed along the segment exceeds  $3 \text{ m s}^{-1}$ , **and**
- (ii) the length of the segment is longer than the critical error length, defined as

$$1.0 \times \sqrt{Er_A^2 + Er_B^2}$$

where  $Er_A^2$  and  $Er_B^2$  are the radii of position error of the Argos system (150m, 350m, and 1000m for Argos class 3, 2, and 1 respectively) at  $A$  and  $B$  respectively.

B). If a segment is not considered questionable, then both positions  $A$  and  $B$  are good.

C). If a segment is considered questionable, then:

- if the Argos class at  $A$  and  $B$  are different, then the position with the less accurate Argos class is flagged as ‘3’;
- if the Argos class at  $A$  and  $B$  are the same, and there is one good position before and one good position after  $A$  and  $B$  (i.e. there are 4 positions for the check), then the position that gives the higher speed along the segment from the previous good position to the later good position is flagged as ‘3’;
- if the Argos class at  $A$  and  $B$  are the same, and there is one good position either before or after  $A$  and  $B$  (i.e. there are 3 positions for the check), then the position that gives the higher speed along the segment either from the previous good position or to the later good position is flagged as ‘3’;
- if the Argos class at  $A$  and  $B$  are the same, but there are no other good positions around  $A$  and  $B$  (i.e. there are 2 positions for the check), then both  $A$  and  $B$  are flagged as ‘3’.

## 2.3. Argo Real-time Adjustments on vertical profiles

### 2.3.1. Real-time pressure adjustment for non auto-correcting floats

There are many float types in Argo, each has its own way of treating the pressure measurements. For example, while PROVOR and SOLO floats internally correct for pressure offsets, APEX floats do not make any internal pressure correction. All Argo float types and their treatment of pressure are summarized in the “Surface Pressure Correction Table”, which can be found at <http://www.argodatamgt.org/Documentation>.

Floats that do not adjust their pressure data on board before data telemetry are referred to as *non auto-correcting* floats. Pressure measurements from non auto-correcting floats need to be treated in real-time whenever valid surface pressure values are available. The section below details the real-time pressure adjustment procedures for APEX floats, which is the largest group of non auto-correcting floats in Argo.

#### Real-time pressure adjustment for APEX floats

APEX floats return “raw” pressures, which are stored in the variable PRES in the Argo netCDF files. Pressure adjustment should be applied in real-time to all APEX floats by using SURFACE PRESSURE (SP) values returned by the APEX floats. The SP measurement is taken while the float is at the sea surface just before descent, and hence is different from the shallowest measured pressure in the vertical profile, which is taken on ascent and while the float is beneath the sea surface. These SP values are stored in the Argo technical files in the variable:

PRES\_SurfaceOffsetTruncatedPlus5dbar\_dbar, or

PRES\_SurfaceOffsetNotTruncated\_dbar,

depending on the type of APEX controller used.

Subtract 5 dbar from the SP values in PRES\_SurfaceOffsetTruncatedPlus5dbar\_dbar.

SP values in PRES\_SurfaceOffsetNotTruncated\_dbar are used as they are, without needing to subtract 5 dbar.

Then erroneous outliers in SP need to be removed. This is done in real-time in two steps:

- (1). Discard SP values greater than 20 dbar or less than -20 dbar, then revert to the last valid SP.
- (2). If the most recent SP value, SP(i), is different from the last valid SP by more than 5 dbar, that is, if  $\text{abs}[ \text{SP}(i) - \text{last valid SP} ] > 5$  dbar, revert to the last valid SP.

When no valid SP value is available, no real-time pressure adjustment is available.

When there are valid SP values, real-time adjusted pressures will be recorded in the variable PRES\_ADJUSTED, where  $\text{PRES\_ADJUSTED} = \text{PRES} - \text{SP}$ .

Zero is a valid SP value. Therefore when  $\text{SP} = 0$ , PRES\_ADJUSTED should be filled. In this case,  $\text{PRES\_ADJUSTED} = \text{PRES}$ .

PRES should always record the *raw* data.

PRES\_ADJUSTED\_QC will be filled with the same values as PRES\_QC.

PRES\_ADJUSTED\_ERROR and all variables in the SCIENTIFIC CALIBRATION section of the netCDF files will be filled with FillValue.

DATA\_MODE will record 'A'.

There is no need to re-calculate salinity data in real-time by using the real-time adjusted pressure values. This is because the difference in salinity due to real-time pressure adjustment is small. Pressure adjustment of less than 20 dbar will result in salinity error of less than 0.01.

When the SP value exceeds 20 dbar (or -20 dbar) for more than 5 consecutive cycles, the float should be put on the grey list because of pressure error, after consultation with the PI.

When available, real-time adjusted values are distributed to the GTS instead of the raw values.

### 2.3.2. Real-time salinity adjustment

When delayed-mode salinity adjustment (see Section 3.3) becomes available for a float, real-time data assembly centres will extract the adjustment from the latest D\*.nc file as an additive constant, and apply it to new salinity profiles. (If a better correction is available in real-time, DACs can use that instead.) In this manner, intermediate-quality salinity profiles will be available to users in real-time.

The values of this real-time adjustment will be recorded in PSAL\_ADJUSTED.

PSAL\_ADJUSTED\_QC will be filled with the same values as PSAL\_QC.

PSAL\_ADJUSTED\_ERROR and all variables in the SCIENTIFIC CALIBRATION section of the netCDF files will be filled with FillValue.

DATA\_MODE will record 'A'.

When available, real-time adjusted values are distributed to the GTS instead of the raw values.

### 2.3.3. Real-time files with DATA\_MODE = 'A'

When real-time files have DATA\_MODE = 'A', it means real-time adjustments are available for one or more parameters. All PARAM\_ADJUSTED variables should therefore be filled, where PARAM = PRES, TEMP, PSAL and CNDC.

PARAM\_ADJUSTED = real-time adjusted values, or PARAM if no real-time adjustment is available.

PARAM\_ADJUSTED\_QC = PARAM\_QC.

PARAM\_ADJUSTED\_ERROR = FillValue.

Users should be aware that even though the \_ADJUSTED\_ fields are filled in 'A' mode, the adjustments are applied in an automated manner in real-time and are not checked by delayed-mode operators.

## 2.4. Feedback from Statistical Test at Coriolis

At Coriolis, an objective analysis is performed on a daily basis on Argo temperature and salinity profiles that have been quality-controlled during the previous 3 weeks. As results of the comparison with climatology, anomalies on Argo profiles are detected by this objective analysis. For flag correction on those profiles, daily automatic feedbacks (in text files, by email) are sent to the appropriate DAC. The email message contains the list of Argo profiles highlighted by the objective analysis, and examined by a Coriolis operator, with the recommended flag correction listed at the end. The information is also available in a csv format file on the ftp site:

- <ftp://ftp.ifremer.fr/ifremer/argo/etc/ObjectiveAnalysisWarning>

## 2.5. Argo Real-time Quality Control Test Procedures on near-surface data

The near-surface data described in this section are specialised data that are collected with vertical sampling methods different from the primary CTD profiles. For most profiling floats, the CTD pump is normally switched off at around 5 dbar during ascent to avoid contamination of the conductivity cell. Several float types continue to sample up to the sea surface (with the pump off, or with the pump on closer to the sea surface), or carry auxiliary modules for high-resolution near-surface sampling. These specialised near-surface data are focused on the top 5 dbar of the ocean. They may extend deeper than 5 dbar so as to overlap with the primary CTD profiles for the purpose of cross-calibration. They are stored as additional profiles ( $N\_PROF > 1$ ) in the single-cycle core Argo profile files, and are identifiable by **VERTICAL\_SAMPLING\_SCHEME = “Near-surface sampling”**.

(**Note:** the full character string is “Near-surface sampling: averaged/discrete/mixed, pumped/unpumped [optional description]”. Please refer to Table 16 in the Argo Users Manual for details of the various vertical sampling schemes and their full character strings.)

The following tests are applied in real-time to these specialised near-surface data.

### 6. Global range test

Same as in Section 2.1.2.

### 7. Regional range test

Same as in Section 2.1.2.

### 8. Pressure increasing test

Same as in Section 2.1.2.

### 9. Spike test

Same as in Section 2.1.2.

### 11. Gradient test

Same as in Section 2.1.2.

### 19. Deepest pressure test

Same as in Section 2.1.2.

### 21. Near-surface unpumped CTD salinity test

Details described in this section.

### 22. Near-surface mixed air/water test

Details described in this section.

## 21. Near-surface unpumped CTD salinity test

While unpumped temperature data from the primary CTD are of good quality, unpumped salinity data from the primary CTD are of dubious quality because the flow rate through the conductivity cell is wrong when the pump is switched off. This test specifies that unpumped (or partially-pumped) salinity data returned by the primary CTD should be flagged as “probably bad data” in real-time.

Action: Unpumped (or partially-pumped) salinity data returned by the primary CTD are flagged as “probably bad data” in real-time. That is, PSAL\_QC = ‘3’.

### (a). PROVOR/ARVOR (bin-averaged data)

Data returned by some PROVOR/ARVOR floats are bin-averaged and are not separated into pumped and unpumped types. This separation is done during data processing at the DACs by checking when the CTD pump is switched off. In addition, for some older versions of PROVOR/ARVOR floats, some bin-averaged data can contain a mixture of pumped and unpumped measurements if the pump cut-off pressure falls in the middle of the bin. Please refer to the document “Argo DAC profile cookbook” on how to identify unpumped or partially-pumped near-surface data from PROVOR/ARVOR floats.

### (b). PROVOR/ARVOR (spot-sampled data)

Some PROVOR/ARVOR floats use the primary CTD to measure spot-sampled near-surface data in the unpumped mode. Spot-sampled near-surface data are identified as unpumped when  $PRES \leq P_{cutoff}$ , where  $P_{cutoff}$  is the pressure at which the CTD pump is switched off.

### (c). NOVA

Some NOVA floats collect near-surface data by using the primary CTD in the unpumped mode, with the CTD pump switched off at 4 dbar. Near-surface data from NOVA floats are bin-averaged and are identified as unpumped when  $PRES \leq 4$  dbar.

### (d). APEX

Test 21 does not apply to near-surface data returned by APEX floats because APEX (Argos) floats with the NST firmware do not report unpumped salinity from the primary CTD. APEX (Iridium) floats equipped with the STS module return unpumped salinity from the auxiliary module. The STS module is designed to measure salinity in a free-flushing mode and so is different from the primary CTD.



## 22. Near-surface mixed air/water test

Most near-surface profiles extend all the way to the sea surface. Therefore the shallowest part of a near-surface profile will contain some mixed air/water measurements. This test identifies broadly the pressures at which this shallowest part of a near-surface profile takes place, and specifies that data in that pressure range are “probably bad data”.

Action: Data from the shallowest part of a near-surface profile, which may contain mixed air/water measurements, are flagged as “probably bad data” in real-time.

### (a). PROVOR/ARVOR (bin-averaged data)

For PROVOR/ARVOR floats that return bin-averaged data, if the first bin closest to the sea surface has  $PRES \leq 1$  dbar, then the temperature value from that first bin is suspected to contain averages of mixed air/water measurements and should be flagged as “probably bad data”. That is,  $TEMP\_QC = '3'$ .

### (b). PROVOR/ARVOR (spot-sampled data)

For PROVOR/ARVOR floats that return spot-sampled data, temperature observed at  $PRES \leq 0.5$  dbar should be flagged as “probably bad data”. That is,  $TEMP\_QC = '3'$ .

### (c). NOVA

For NOVA floats, if the first bin closest to the sea surface has  $PRES \leq 1$  dbar, then the temperature value from that first bin is suspected to contain averages of mixed air/water measurements and should be flagged as “probably bad data”. That is,  $TEMP\_QC = '3'$ .

### (d). APEX

The shallowest part of near-surface profiles collected by APEX floats will contain pressure readings that are not necessarily monotonic with time.

For APEX (Argos) floats with the NST firmware, when near-surface data have pressures shallower than 5 dbar, check difference in pressure between two successive measurements. If the difference is less than 0.5 dbar from the previous measurement, then data from that level and all levels after that should be flagged as “probably bad data”. That is,  $PRES\_QC = '3'$ ,  $TEMP\_QC = '3'$ .

For APEX (Iridium) floats equipped with the STS module, when near-surface data have pressures shallower than 5 dbar, check that pressure readings decrease monotonically with time. Data from the level when monotonicity stops and all levels after that should be flagged as “probably bad data”. That is,  $PRES\_QC = '3'$ ,  $TEMP\_QC = '3'$ ,  $PSAL\_QC = '3'$ .

**Various types of specialised near-surface data in Argo that can be found under  
VERTICAL\_SAMPLING\_SCHEME = “Near-surface sampling”**

Float type	primary CTD or auxiliary module	operating mode	averaged or discrete	Test 21	Test 22
PROVOR/ARVOR (bin-averaged)	primary CTD	unpumped T & S	averaged	a	a
PROVOR/ARVOR (spot-sampled)	primary CTD	unpumped T & S	discrete	a	a
NOVA	primary CTD	unpumped T & S	averaged	a	a
APEX (Argos) NST	primary CTD	unpumped T only	discrete	n/a	a
APEX (Iridium) STS	auxiliary module	free-flushing T & S	discrete	n/a	a
SOLO II/S2A	primary CTD	pumped T & S	discrete	n/a	n/a
Deep SOLO	primary CTD	pumped T & S	discrete	n/a	n/a

a = applicable

n/a = not applicable

## 2.6. Interim Real-time Quality Control Flag Scheme for float data deeper than 2000 dbar

Some profiling floats have the capability to sample deeper than the original Argo profiling pressure target of 2000 dbar. However the accuracy of the raw data from these deep Argo floats below 2000 dbar is not yet well understood. Pilot studies of deep Argo data indicated possible pressure-dependent salinity bias, and the performance of the pressure sensor below 2000 dbar has not been validated by manufacturers. Therefore an interim real-time quality control flag scheme is implemented to warn users that the raw data from deep Argo floats below 2000 dbar may not be suitable for research applications requiring high data accuracy.

### Test 23. Interim rtqc flag scheme for float data deeper than 2000 dbar

This test specifies that for float data deeper than 2000 dbar:

- real-time QC flag = '2' for pressure (PRES) and temperature (TEMP);
- real-time QC flag = '3' for salinity (PSAL); and
- no distribution on the GTS.

**Action:** For profiles from deep Argo floats that extend deeper than 2000 dbar, real-time qc tests 1 to 19 should be applied to the full-depth profiles. Float data shallower than 2000 dbar should be flagged and distributed on the GTS as in Section 2.1.2. Float data deeper than 2000 dbar that have passed all previous real-time qc tests should be flagged with PRES\_QC = '2', TEMP\_QC = '2', PSAL\_QC = '3', and should be removed from both TESAC and BUFR distribution on the GTS.

## 2.7. Interim Real-time Quality Control Flag Scheme for RBR CTD data

Some Argo floats are equipped with the RBR CTD in pilot studies. However the accuracy of the raw data from the RBR CTD is not yet well understood. Therefore an interim real-time quality control flag scheme is implemented to warn users that the raw data from floats with the RBR CTD may not be suitable for research applications requiring high data accuracy.

The following real-time test is generalized to be applicable to float data from experimental sensors.

### Test 24. Interim rtqc flag scheme for float data from experimental sensors

This test specifies that for experimental sensors:

- all core parameters from the sensor: PRES, TEMP, PSAL, should be put on the grey list starting from cycle 1;
- real-time QC flag = '3' for PRES, TEMP, PSAL;
- no distribution on the GTS.

**Action:** Core parameters PRES, TEMP, PSAL from experimental sensors should be put on the grey list starting from cycle 1, and flagged with PRES\_QC = '3', TEMP\_QC = '3', PSAL\_QC = '3'. All values should be removed from both TESAC and BUFR distribution on the GTS.

## 3. Delayed-mode quality controls

### 3.1. Editing raw qc flags in delayed-mode

The QC flags determined in delayed-mode should replace those determined in real-time. This is because some bad data cannot be determined by the real-time tests, and some good data can be identified wrongly as bad by the real-time tests.

For vertical profile data in PARAM, where PARAM = PRES, TEMP, PSAL and CNDC, delayed-mode operators should examine them for pointwise errors (such as spikes) and flag them appropriately. If an error is identified, both PARAM\_QC and PARAM\_ADJUSTED\_QC should record '4'. Conversely, if good data have been identified wrongly as bad by the real-time tests, then both PARAM\_QC and PARAM\_ADJUSTED\_QC should record '1'.

### 3.2. Delayed-mode procedures for JULD, LATITUDE, LONGITUDE

Delayed-mode operators should check that JULD in the profiles are in chronological order. Erroneous or missing JULD values should be replaced with another telemetered value if available, or replaced with interpolated values and marked with JULD\_QC = '8'.

Profile positions in LONGITUDE, LATITUDE should be checked for outliers. Erroneous or missing LONGITUDE, LATITUDE values should be replaced with another telemetered value if available, or replaced with interpolated values and marked with POSITION\_QC = '8'.

### 3.3. Delayed-mode procedures for pressure

Delayed-mode qc for PRES is done by subjective assessment of vertical profile plots of TEMP vs. PRES, and PSAL vs. PRES. This assessment should be done in relation to measurements from the same float, as well as in relation to nearby floats and historical data. The assessment should aim to identify: (a) erroneous data points that cannot be detected by the real-time qc tests, and (b) vertical profiles that have the wrong shape.

Bad data points identified by visual inspection from delayed-mode analysts are recorded with PRES\_ADJUSTED\_QC = '4'. For these bad data points, TEMP\_ADJUSTED\_QC and PSAL\_ADJUSTED\_QC should also be set to '4'.

Please note that whenever PARAM\_ADJUSTED\_QC = '4', both PARAM\_ADJUSTED and PARAM\_ADJUSTED\_ERROR should be set to FillValue.

#### 3.3.1. Delayed-mode pressure adjustment for APEX floats

Similar to the real-time procedure, pressures from APEX floats should be adjusted for offsets by using SURFACE PRESSURE (SP) values in delayed-mode. These SP values are stored in the Argo technical files in the variable:

PRES\_SurfaceOffsetNotTruncated\_dbar, or

PRES\_SurfaceOffsetTruncatedPlus5dbar\_dbar,

depending on the type of APEX controller used.

The SP time series is examined and treated in delayed-mode as follows:

(1). Subtract 5 dbar from PRES\_SurfaceOffsetTruncatedPlus5dbar\_dbar.

SP values in PRES\_SurfaceOffsetNotTruncated\_dbar are used as they are, without needing to subtract 5 dbar.

(2). **Despike the SP time series to 1 dbar.** This is most effectively done by first removing the more conspicuous spikes that are bigger than 5 dbar (as in the real-time procedure), then the more subtle spikes that are between 1 to 5 dbar by comparing the SP values with those derived from a 5-point median filter. For standard Argo floats that sample every 10 days, a 5-point filter represents a filter window of 40 days ( $\pm 20$  days from a profile), which is an appropriate time scale for retaining effects from the atmospheric seasonal cycle.

(3). Replace the spikes and any other missing SP values by interpolating between good neighbouring points. If missing values occur at the ends of the SP time series, extrapolate from the nearest good points.

(4). The resulting SP time series should then be inspected visually to make sure there are no more erroneous points.

The clean SP value from cycle  $i+1$  is then used to adjust pressures from cycle  $i$  by:

$$\text{PRES\_ADJUSTED (cycle } i) = \text{PRES (cycle } i) - \text{SP (cycle } i+1).$$

The CTD profile and the associated SP is staggered by one cycle because the SP measurement is taken after the telemetry period, and therefore is stored in the memory and telemetered during the next cycle. The real-time procedure does not match SP value from cycle  $i+1$  with PRES from cycle  $i$ , because real-time adjustment cannot wait 10 days. However, in delayed-mode, it is important to match the CTD profile with the staggered telemetry of SP, because SP values can contain synoptic atmospheric variations, and because a missing CTD profile is often associated with an erroneous SP point. By this scheme, SP(1), which is taken before cycle 1 and therefore before the float has had its first full dive, is not used in delayed-mode.

Note that the real-time procedure does not adjust for pressure offsets that are greater than 20 dbar (or less than  $-20$  dbar). This is because the real-time automatic procedure cannot determine whether SP values greater than 20 dbar (or less than  $-20$  dbar) represent true sensor drift or erroneous measurements. Instead, in real-time, floats that return SP values greater than 20 dbar (or less than  $-20$  dbar) for more than 5 consecutive cycles are grey-listed in consultation with the PI. In delayed-mode, operators can inspect the SP time series visually when severe pressure sensor drift occurs. Therefore there is no upper limit to the magnitude of delayed-mode pressure adjustment.

After adjustment, delayed-mode operators should check that PRES\_ADJUSTED  $> 0$ . If PRES\_ADJUSTED  $< 0$ , delayed-mode operators should check for decoding error in SP or in the CTD pressures. In addition, the following should be observed:

PRES should always record the *raw* data.

PRES\_ADJUSTED\_QC should be set appropriately. For example, floats that have had significant pressure adjustment should have PRES\_ADJUSTED\_QC = '2'.

PRES\_ADJUSTED\_ERROR = 2.4 dbar is the recommended error to quote, with 2.4 dbar being the manufacturer quoted accuracy of the pressure sensor.

Salinity should be re-calculated by using PRES\_ADJUSTED and recorded in PSAL\_ADJUSTED. Salinity error due to pressure uncertainty is negligible and can be ignored in the consideration of PSAL\_ADJUSTED\_ERROR.

Please use the SCIENTIFIC CALIBRATION section in the netCDF files to record details of the delayed-mode adjustment.

**Note to users:** The 1 dbar despiking threshold for SP assumes that spikes greater than 1 dbar represent noise in the SP measurement that should not be integrated into float pressures. After despiking to 1 dbar, the remaining SP values contain sea surface atmospheric pressure variations and variations due to other high-frequency surface processes. While sea surface atmospheric pressure variations affect the whole water column and therefore should be adjusted for, high-frequency surface processes do not affect the whole water column. Therefore users should be aware that PRES\_ADJUSTED contains noise from high-frequency surface processes that are of the order < 1 dbar. In addition, other more subtle pressure errors such as those due to non-linear hysteresis and other temperature- and pressure-dependent effects are not accounted for in PRES\_ADJUSTED. Hence users should always heed the error bars quoted in PRES\_ADJUSTED\_ERROR.

### 3.3.2. Truncated negative pressure drift (TNPd) in APEX floats

APEX floats with Apf-5, Apf-7, or Apf-8 controllers that set negative SURFACE PRESSURE (SP) to zero (then add an artificial 5 dbar) present a challenge to delayed-mode qc because information from SP on any negative pressure offset is lost, thus making the pressure data unadjustable<sup>1</sup>. The problem with some of these APEX floats having unknown negative pressure error escalated with the discovery of the oil microleak defect in Druck pressure sensors. The Druck oil microleak defect manifests itself as increasingly negative offset at all pressures, and will eventually end the useful life of the float.

During delayed-mode qc of pressure measurements from APEX floats with Apf-5, Apf-7, or Apf-8 controllers, operators should first remove erroneous SP values and any isolated spikes in the time series by following the procedure described in Section 3.2.1. The delayed-mode operator should then examine the resulting valid and despiked SP time series, and determine whether there are long periods of zero SP readings (after removing the artificial 5 dbar) that qualify as “Truncated Negative Pressure Drift”, which has the following definition:

*Truncated Negative Pressure Drift (TNPd) refers to the part of a float’s time series from which **valid and despiked** SP (after removing the artificial 5 dbar) reads continuously zero without reverting back to positive values or containing any occasional positive values.*

*The continuous valid zero-reading period needs to span at least 6 months, preferably longer. This captures the microleakers whose oil leak rates are fastest, and allows for seasonal variability from half of an annual cycle when surface pressure values may read just below zero.*

*For floats whose useful life is less than 6 months or when the continuous valid zero-reading period is shorter than 6 months, the qualifying time span is at the PI’s discretion.*

Examples (a) to (d) below illustrate some cases that should or should not be classified as TNPd. Please note that in all of the following schematic examples, SP represents valid and despiked values (after removing the artificial 5 dbar).

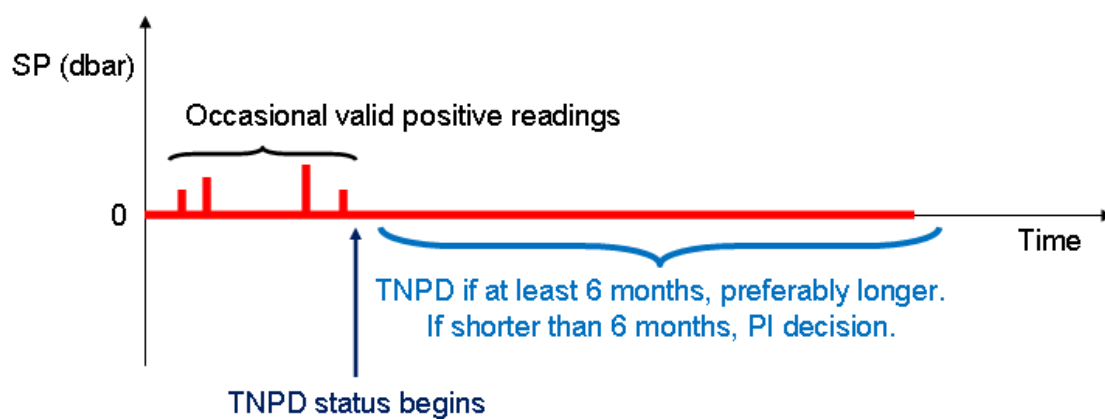
---

<sup>1</sup> This feature was corrected in the Apf-9 and later versions of the controller.

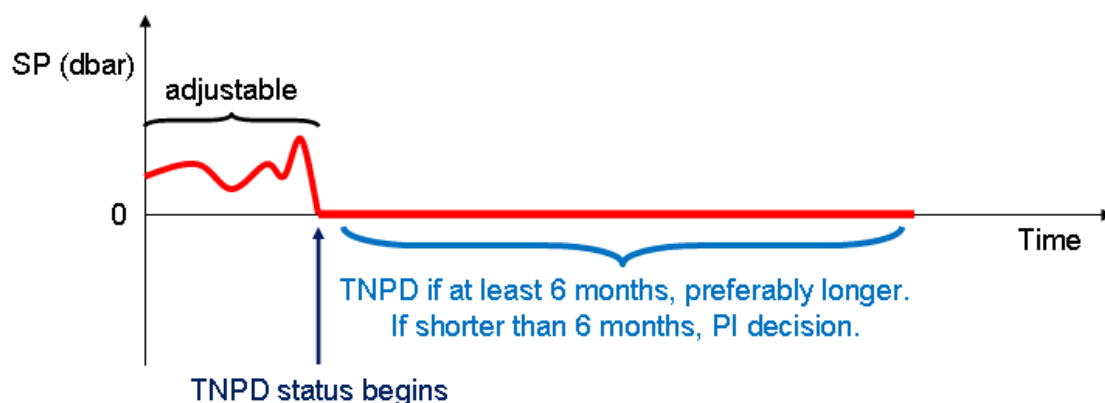
Example (a). 100% of the time series is TNPD.



Example (b). There are occasional valid positive SP readings in the first part of the time series, followed by a continuous zero-reading period that does not contain any occasional valid positive readings.

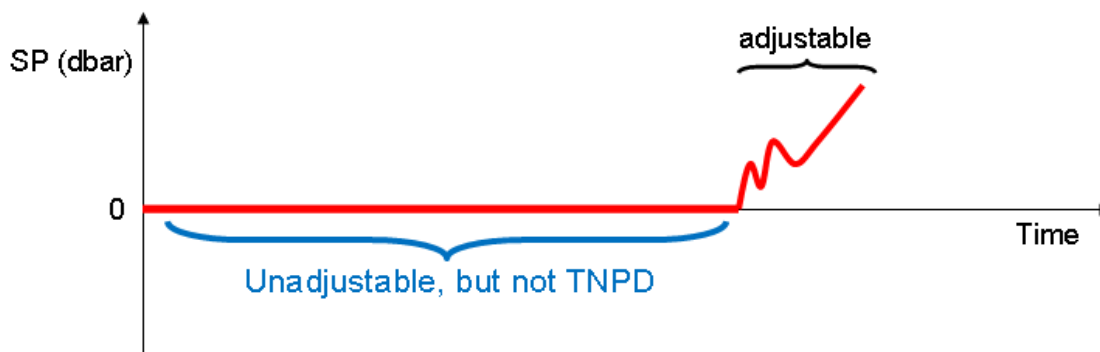


Example (c). The time series starts with continuous valid positive readings, then becomes continuously zero with no occasional valid positive readings.





Example (d). The time series starts with a continuous zero-reading period, then reverts back to valid positive values. The initial zero-reading period does not qualify as TNPD. This is because pressure drifts are typically monotonic and therefore a reversal back to positive values indicates that the pressure sensor is not likely to have developed a negative drift.



After determining which part of the time series qualifies as TNPD, the delayed-mode operator should then determine the probability of the TNPD data being affected by the Druck oil microleak problem. According to SeaBird, the date of manufacturing change at Druck that led to the oil microleak defect occurred sometime in mid-2006. The microleak failure rate jumped from 3% before 2006 to 30% in 2007. Any Druck pressure sensor with serial number greater than **2324175** falls into the group that has 30% likelihood of being affected by oil microleaks. Cross checking between the various APEX groups within Argo indicated that deployment of floats with Druck serial number greater than 2324175 occurred after October 2006. Since July 2009 SeaBird has begun screening Druck pressure sensors in order to identify those transducers that have microleaks.

One way to identify affected floats is by T/S analysis, since severe pressure error will lead to observable T/S anomalies. Anomalies associated with severe negative pressure drift include:

- (a). Positive salinity drift; e.g. pressure error of  $-20$  dbar will cause a positive salinity error of approximately 0.01 PSS-78. Statistical comparison methods that are used to determine conductivity sensor drift (e.g. WJO, BS, OW) can be used as diagnostic tools for these cases. Please refer to Section 3.4.1 for descriptions of these statistical comparison methods.
- (b). Cold temperature anomaly whose size depends on vertical temperature gradient.
- (c). Float-derived dynamic height anomalies significantly lower than satellite-derived sea level anomalies.
- (d). Shoaling of isotherm depths independent of time/space migration of the float.

In addition to T/S analysis, delayed-mode operators should also observe when a float begins telemetering highly erratic data. This is a sign that it may be suffering from the Druck oil microleak problem, and that the pressure sensor may be about to fail completely. Note that symptoms of this failure are very similar to those of the Druck “snowflakes” problem, which affected floats that were manufactured in 2002 and 2003. Please refer to Appendix 4.3 for a brief description of the Druck “snowflakes” problem.

In light of these events, the following categories should be considered in assigning delayed-mode qc flags and error bars for data classified as TNPD.

1. When float data do not show observable T/S anomalies that are consistent with increasingly negative pressure drift. This means that the TNPD data may have unknown negative pressure error that is not severe. For these less severe cases, the adjusted variables should receive a delayed-mode qc flag of '2':

PRES\_ADJUSTED\_QC = '2'

TEMP\_ADJUSTED\_QC = '2'

PSAL\_ADJUSTED\_QC = '2'.

(Note that TEMP\_ADJUSTED\_QC and PSAL\_ADJUSTED\_QC can change to '3' or '4' if TEMP and PSAL contain additional errors that are independent of the pressure error; e.g. pointwise temperature spike, conductivity cell drift, etc.)

For these less severe cases, two groups should be considered in assigning the pressure error bars in delayed-mode.

**(a). For TNPD data belonging to floats that used Druck pressure sensors with serial numbers less than 2324175, or were deployed before 1 October 2006 if the Druck serial numbers are unknown,** the likelihood of them being affected by the oil microleak problem is low, about 3%. Hence it is reasonable to cite the manufacturer quoted accuracy of 2.4 dbar as the pressure error for this group:

PRES\_ADJUSTED\_ERROR = 2.4 dbar.

**(b). For TNPD data belonging to floats that used Druck pressure sensors with serial numbers greater than 2324175, or were deployed after 1 October 2006 if the Druck serial numbers are unknown,** the likelihood of them being affected by the microleak disease is elevated, about 30%. For these suspicious data, an *upper bound* of the estimated error should be cited. Since a negative 20 dbar pressure error will cause a positive 0.01 salinity error, at which point T/S anomalies will become observable and data should be flagged as '4' as described in Category 2(b) below, 20 dbar has been chosen as the upper bound of the data error for this group:

PRES\_ADJUSTED\_ERROR = 20 dbar.

*Note that SeaBird will eventually provide a list of serial numbers that represents Druck sensors that have been screened as healthy. These healthy Druck sensors should be excluded from receiving the larger pressure error bar. Moreover, SeaBird has records that connect the Druck serial number to CTD number, and Teledyne WRC can make the connection to the float hull number.*

2. When float data show observable T/S anomalies that are consistent with increasingly negative pressure drift after cycle-*n*. This means that the TNPD data have unknown negative pressure error, and that the error becomes severe after cycle-*n*.

(a). **For the less severe part of the TNPD data before cycle-*n*,** the adjusted variables should receive a dmqc flag of '2':

PRES\_ADJUSTED\_QC = '2'

TEMP\_ADJUSTED\_QC = '2'

PSAL\_ADJUSTED\_QC = '2',

while the pressure error should increase to 20 dbar:

PRES\_ADJUSTED\_ERROR = 20 dbar.

(b). **For the severe part of the TNPD data after cycle-*n*,** the adjusted variables should receive a dmqc flag of '4':

PRES\_ADJUSTED\_QC = '4'

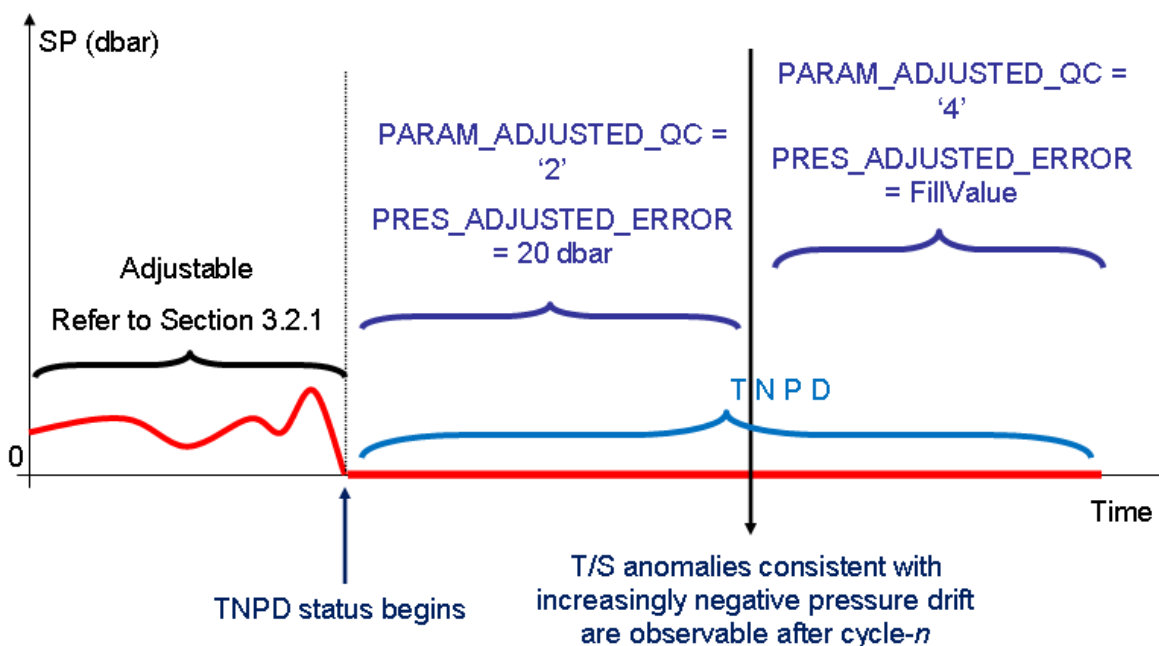
TEMP\_ADJUSTED\_QC = '4'

PSAL\_ADJUSTED\_QC = '4'.

Please note that whenever PARAM\_ADJUSTED\_QC = '4', PARAM\_ADJUSTED = FillValue, and PARAM\_ADJUSTED\_ERROR = FillValue.

**Note:** For the severe cases in Category 2(b), delayed-mode operators in consultation with float PIs should consider putting the real-time data on the grey list.

Example (e). A complex case belonging to Category 2, where T/S anomalies consistent with increasingly negative pressure drift are observed after cycle-*n*, part way through the TNPD portion of the time series.



All TNPD data should receive a standard label in SCIENTIFIC\_CALIB\_COMMENT in the Argo single-cycle netcdf files, in the dimension corresponding to PRES. The standard label consists of the character string **“TNPD: APEX float that truncated negative pressure drift”**. The delayed-mode operator may append to the end of this character string any other comments regarding PRES that he/she wishes to make.

For the portion of the time series that contains occasional valid positive SP readings (Example b), it is the PI's decision, based on the frequency of occurrence of the valid positive SP readings, on whether or not to adjust those profiles.

For the unadjustable but non-TNPD data (Example d, and cases in Example b where the PI decides to not adjust), any negative pressure offset is likely to be less than the manufacturer quoted accuracy of 2.4 dbar. For these unadjustable but non-TNPD data, if no additional error is found, then:

PRES\_ADJUSTED\_QC = '1'

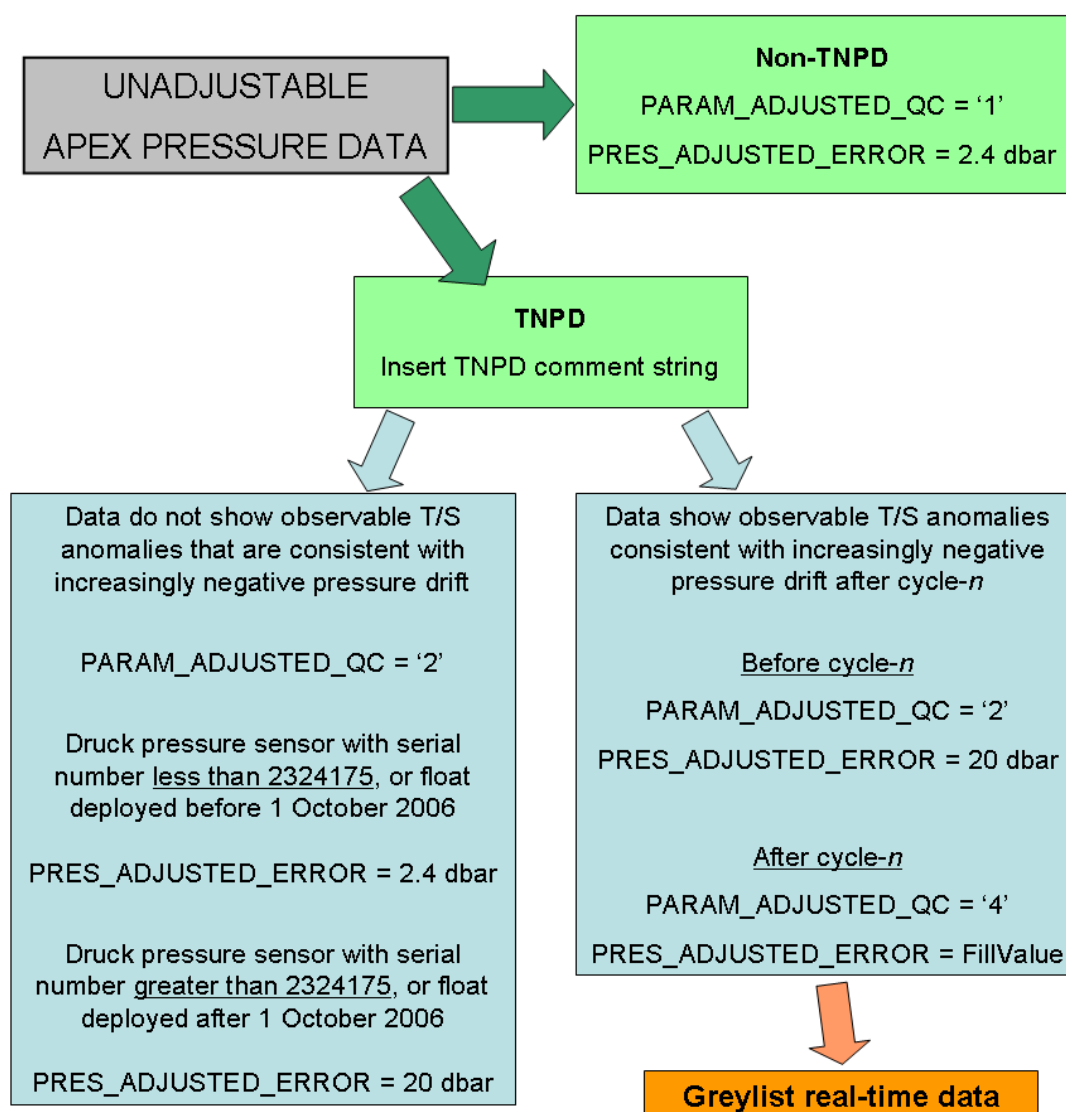
TEMP\_ADJUSTED\_QC = '1'

PSAL\_ADJUSTED\_QC = '1'

PRES\_ADJUSTED\_ERROR = 2.4 dbar.

### 3.3.3. Summary flowchart for unadjustable APEX pressures

#### Procedures for processing unadjustable APEX pressure data in delayed-mode



### 3.4. Delayed-mode procedures for temperature

Delayed-mode qc for TEMP is done by subjective assessment of vertical profile plots of TEMP vs. PRES, and PSAL vs. TEMP. This assessment should be done in relation to measurements from the same float, as well as in relation to nearby floats and historical data. The assessment should aim to identify: (a) erroneous data points that cannot be detected by the real-time qc tests, and (b) vertical profiles that have the wrong shape.

Bad data points identified by visual inspection from delayed-mode analysts are recorded with TEMP\_ADJUSTED\_QC = '4'. Please note that whenever PARAM\_ADJUSTED\_QC = '4', PARAM\_ADJUSTED = FillValue, and PARAM\_ADJUSTED\_ERROR = FillValue.

TEMP\_ADJUSTED, TEMP\_ADJUSTED\_ERROR, and TEMP\_ADJUSTED\_QC should be filled even when the data are good and no adjustment is needed. In these cases, TEMP\_ADJUSTED\_ERROR can be the manufacturer's quoted accuracy at deployment.

Please use the SCIENTIFIC CALIBRATION section in the netCDF files to record details of the delayed-mode adjustment.

## 3.5. Delayed-mode procedures for salinity

### 3.5.1. Introduction

Delayed-mode qc for PSAL described in this section are specifically for checking sensor drifts and offsets. Operators should be aware that there are other instrument errors (e.g. conductivity cell thermal mass error, see Johnson *et al.* 2007; contact Gregory.C.Johnson@noaa.gov for the related adjustment software), and should attempt to identify and adjust them in delayed-mode. It is recommended that float salinity be adjusted for pressure offset and cell thermal mass error before sensor drift adjustment. If a measurement has been adjusted for more than one instrument error, operators should attempt to propagate the uncertainties from all the adjustments.

The free-moving nature of profiling floats means that most float salinity measurements are without accompanying in-situ “ground truth” values for absolute calibration (such as those afforded by shipboard CTD measurements). Therefore Argo delayed-mode procedures for checking sensor drifts and offsets in salinity rely on reference datasets and statistical methods. However, since the ocean has inherent spatial and temporal variabilities, these drift and offset adjustments are subject to statistical uncertainties. **Users therefore should include the supplied error estimates in their usage of Argo delayed-mode salinity data.**

Three methods are available for detecting sensor drifts and offsets in float salinity, and for calculating adjustment estimates and related uncertainties:

1. Wong, Johnson, Owens (2003) estimates background salinity on a set of fixed standard isotherms, then calculates drifts and offsets by time-varying weighted least squares fits between vertically-interpolated float salinity and estimated background salinity. This method suits float data from open tropical and subtropical oceans.
2. Boehme and Send (2005) takes into account planetary vorticity in its estimates of background salinity and chooses a set of desirable isotherms for calculations. This method suits float data from oceans with high spatial and temporal variabilities, where multiple water masses exist on the same isotherm, and where water mass distribution is affected by topographic barriers.
3. Owens and Wong (2009) improves the objective mapping scheme of WJO based on the method suggested by BS and performs an optimal linear piecewise continuous fit in potential conductivity space. This method suits float data from the global ocean.
4. Cabanes et al (2016) modifies the covariance function used for mapping and improves the calculation of the error on the fit.

All four methods require an adequate reference database and an appropriate choice of spatial and temporal decorrelation scales, as well as input of good/adjusted float pressure, temperature, position, and date of sampling. Therefore operators should first check the reference database for adequacy and determine a set of appropriate spatial and temporal scales before using these methods. Operators should also ensure that other float measurements (PRES, TEMP, LATITUDE, LONGITUDE, JULD) are accurate or adjusted before they input them into the statistical tools for estimating reference salinity.

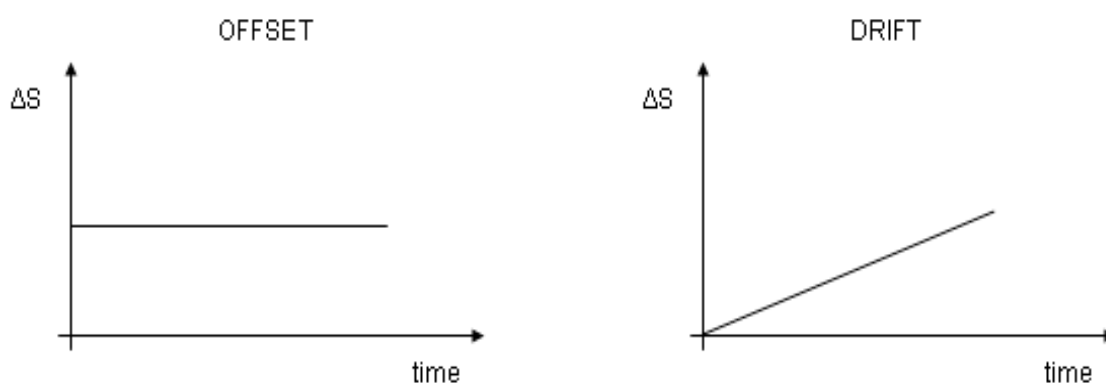
### 3.5.2. Quality control and the semi-automatic part

The real-time qc procedures (described in Section 2) issue a set of qc flags that warns users of the quality of float salinity. These are found in the variable PSAL\_QC. Float salinity with PSAL\_QC = '4' are bad data that are in general unadjustable. However, delayed-mode operators can evaluate the quality and adjustability of these bad data if they have a reason to do so. Please refer to Section 4.1 for definitions of the Argo qc flags in real-time. The delayed-mode operators can edit <PARAM>\_QC if they consider that data are flagged inappropriately.

In delayed-mode, float salinity values that have PSAL\_QC = '1', '2' or '3' are further examined. Anomalies in the relative vertical salinity profile, such as measurement spikes and outliers that are not detected in real-time, are identified. Of these anomalies, those that will skew the least squares fit in the computation for drift and offset adjustments are excluded from the float series for evaluation of drifts and offsets. These measurements are considered unadjustable in delayed-mode.

Float salinity values that are considered adjustable in delayed-mode are assembled into time series. Sufficiently long time series are compared with statistical recommendations and associated uncertainties to check for sensor drifts and offsets. These statistical recommendations and associated uncertainties are obtained by the accepted methods listed in Section 3.5.1, in conjunction with appropriate reference datasets. These methods are semi-automatic and have quantified uncertainties.

Drifts and offsets can be identified in the trend of  $\Delta S$  over time, where  $\Delta S$  is the difference in salinity between float-measured values and statistical recommendations. If  $\Delta S = a + bt$ , where  $t$  is time, then  $a$  is the offset and  $b$  is the drift rate. Note that these drifts and offsets can be sensor-related, or they can be due to real ocean events. Evaluation by salinity experts is needed to distinguish between sensor errors and real ocean events.





### 3.5.3. Splitting the float series and length of calibration window

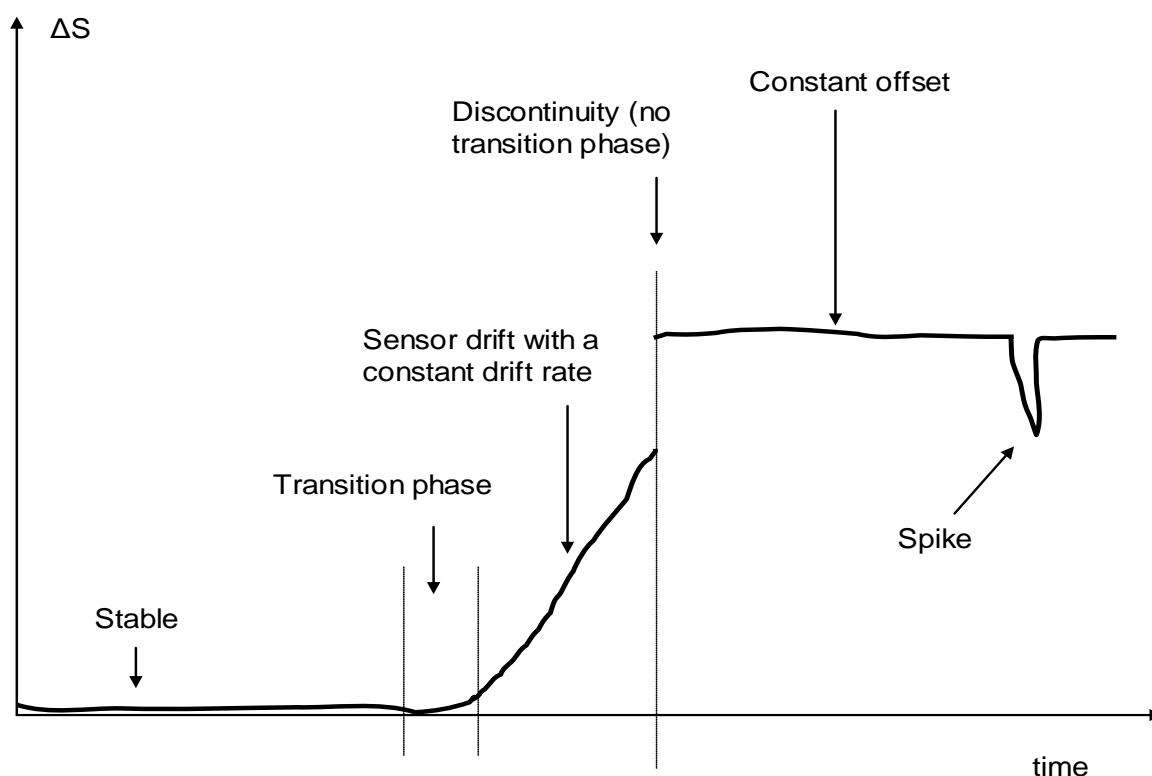
If a float exhibits changing behaviour during its lifetime, the time series of  $\Delta S$  should be split into separate segments according to the different behaviours, so that a time segment does not contaminate the other during the least squares fit process (e.g. the slowly-fouling segment does not contaminate the stable segment).

The following is a step-by-step guide on how to deal with float salinity time series with changing behaviours.

1). Identify different regimes in the time series. These can be:

- Stable measurements (no sensor drift), including constant offsets.
- Sensor drift with a constant drift rate.
- Spikes.
- Transition phase where drift rate changes rapidly e.g. ‘elbow region’ between stable measurements and constant drift, or initial biocide wash-off.

2). Split the time series into discrete segments according to these different regimes or when there are too many missing cycles. Here is an example:



3). Choose length of sliding calibration window for each segment. These can be:

- Long window (+/- 6 months or greater) for the stable regime, or highly variable regimes where a long window is required to average over oceanographic variability to detect slow sensor drift, or period of constant drift rate.
- Short window (can be as short as +/- 10 days) for the transition phase.
- Zero length window for spikes. That is, adjust single profile.

4). Select temperature levels for exclusion from least squares fit (e.g. seasonal mixed layer, highly variable water masses).

5). Calculate proposed adjustment for each segment. The assembled proposed adjustments for the entire float series should be continuous and piecewise-linear within error bars, except where the delayed-mode operator believes there is a genuine discontinuity.

In general, the delayed-mode operator should aim to use as long a calibration window as possible, because a long calibration window (where the least squares fit is calculated over many cycles) will average over oceanographic noise and thus give a stable calibration. Hence splitting the float series into short segments is to be avoided (short segments mean short calibration windows, hence unstable calibrations).

#### 3.5.4. The PI evaluation part

The PI (PI means Principal Investigator, or responsible persons assigned by the PI) should first check that the statistical recommendations are appropriate. This is because the semi-automatic methods cannot distinguish ocean features such as eddies, fronts, and water mass boundaries. Near such ocean features, semi-automatic statistical methods are likely to produce erroneous estimations. The associated uncertainties reflect the degree of local variability as well as the sparsity of reference data used in the statistical estimations. However, these associated uncertainties are sensitive to the choice of scales. Hence the PI also needs to determine that the associated uncertainties are realistic.

The PI then determines whether the proposed statistical adjustment is due to sensor malfunction or ocean variability. Care should be taken to not confuse real ocean events with sensor drifts and offsets. This is done by inspecting as long a float series as possible, and by evaluating other independent information. Some of the diagnostic tools are:

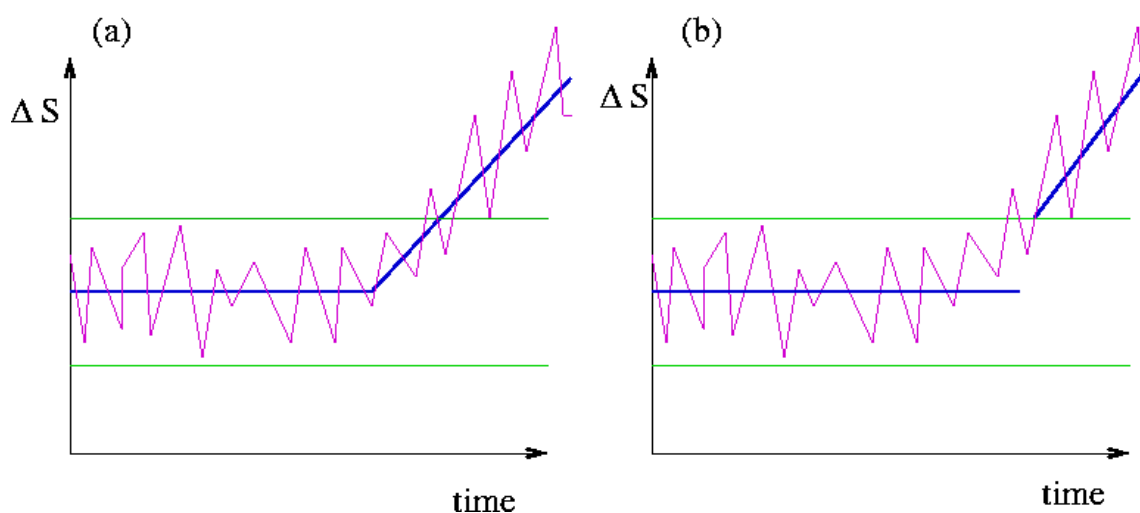
- Inspecting the trend of  $\Delta S$  over time. Trends that reverse directions, or oscillate, are difficult to explain in terms of systematic sensor malfunction. These are often caused by the float sampling oceanographic features (e.g. eddies, fronts, etc.) that are not adequately described in the reference database.
- Visually checking the float trajectory with reference to oceanographic features such as eddies and rings that can introduce complications to the semi-automatic methods.
- Inspecting contour plots of float salinity anomaly time series. Systematic sensor malfunction should show up as salinity anomalies over several water masses.

- Using other independent oceanographic atlases to anticipate water mass changes along the float trajectory that can be misinterpreted as sensor malfunction.
- Inspecting residuals from objective maps.
- Cross-checking with nearby stable floats in cases of suspect sensor calibration offset.

If the PI is confident that sensor malfunction has occurred, then the recommended threshold for making an adjustment is when  $\Delta S$  is greater than 2 times the error from the statistical methods, but the PI can provide an alternative estimate of uncertainty if they have a basis for doing so. Note that this guideline is to help the PI in deciding whether a slope or offset is statistically significant, and so should be used to evaluate the entire float segment being fitted, and not to single points.

In cases where the time series has been split into separate segments, the PI must ensure that the assembled adjustment for the entire time series is continuous within error bars, except where the PI believes there is a genuine discontinuity (see Step 5 in Section 3.4.3). This is to ensure that no artificial jump is introduced where the separate segments join. Adjustment continuity between separate float segments can be achieved by making adjustment in the transition phase even though the adjustment is below the 2 times error threshold limit.

In the following example, the float experiences salinity sensor drift after a stable period. The time series has been split for calibration. However, the time series has no discontinuity, so the final assembled adjustment should be continuous. Adjustment continuity is achieved by using model (a), not (b).



### 3.5.5. Assigning adjusted salinity, error estimates, and qc flags

After evaluating all available information, the PI then assigns adjusted salinity values, error estimates, and delayed-mode qc flags. In Argo data files, these are found respectively in the variables PSAL\_ADJUSTED, PSAL\_ADJUSTED\_QC, and PSAL\_ADJUSTED\_ERROR. Please refer to Section 4.1 for definitions of the Argo qc flags in delayed-mode.

The following is a set of guidelines for assigning values to PSAL\_ADJUSTED, PSAL\_ADJUSTED\_QC and PSAL\_ADJUSTED\_ERROR in Argo data files.

#### For float salinity that are considered good and need no adjustment in delayed-mode

These are measurements that are considered to be unaffected by any instrument errors, such as sensor drift or calibration offset. For these good salinity data, the recommended value for PSAL\_ADJUSTED\_ERROR is 0.01, or higher if statistical uncertainty exceeds 0.01.

PSAL\_ADJUSTED = PSAL (original value);

PSAL\_ADJUSTED\_QC = '1' or '2';

PSAL\_ADJUSTED\_ERROR = maximum [ statistical uncertainty, 0.01 ].

Note that a subset of these good salinity data is selected for inclusion in an Argo-based reference database. In cases where a float is considered to need no salinity adjustment in delayed-mode, but that the data may not be suitable for use as reference because statistical uncertainty is high, PSAL\_ADJUSTED\_ERROR should increase to > 0.015. Please refer to Section 4.5 for the list of selection criteria used in compiling the Argo reference database.

#### For float salinity that are considered bad and unadjustable in delayed-mode

For example, large spikes, or extreme behaviour where the relative vertical T-S shape does not match good data. These measurements are bad and unadjustable.

PSAL\_ADJUSTED = FillValue;

PSAL\_ADJUSTED\_QC = '4';

PSAL\_ADJUSTED\_ERROR = FillValue.

#### For float salinity that are affected by minor instrument errors and that are considered adjustable in delayed-mode

These are measurements that are affected by minor instrument errors whose effects can be rectified by delayed-mode adjustments. These include minor calibration offsets and minor sensor drifts, where the data still retain a relative vertical T-S shape that is close to good data. When an adjustment has been applied,

PSAL\_ADJUSTED = original value + adjustment recommended by statistical analysis, or adjustment provided by PI;

PSAL\_ADJUSTED\_QC = '1' or '2';

PSAL\_ADJUSTED\_ERROR = maximum [  $(\sum \text{adjustment\_error}^2)^{1/2}$ , 0.01 ], where "adjustment\_error" is the uncertainty from each type of adjustment applied to PSAL. These can be statistical uncertainty from sensor drift adjustment, uncertainty from conductivity cell thermal mass adjustment, etc.

### Upper limit of delayed-mode salinity adjustment

0.05 PSS-78 should be considered as the upper limit of good salinity adjustment in delayed-mode. If the magnitude of sensor drift or calibration offset exceeds 0.05, then either i). salinity data are considered unadjustable in delayed-mode,

PSAL\_ADJUSTED = FillValue;

PSAL\_ADJUSTED\_QC = '4';

PSAL\_ADJUSTED\_ERROR = FillValue;

or ii). salinity data are considered adjustable but confidence in adjustment is low,

PSAL\_ADJUSTED = original value + adjustment > 0.05;

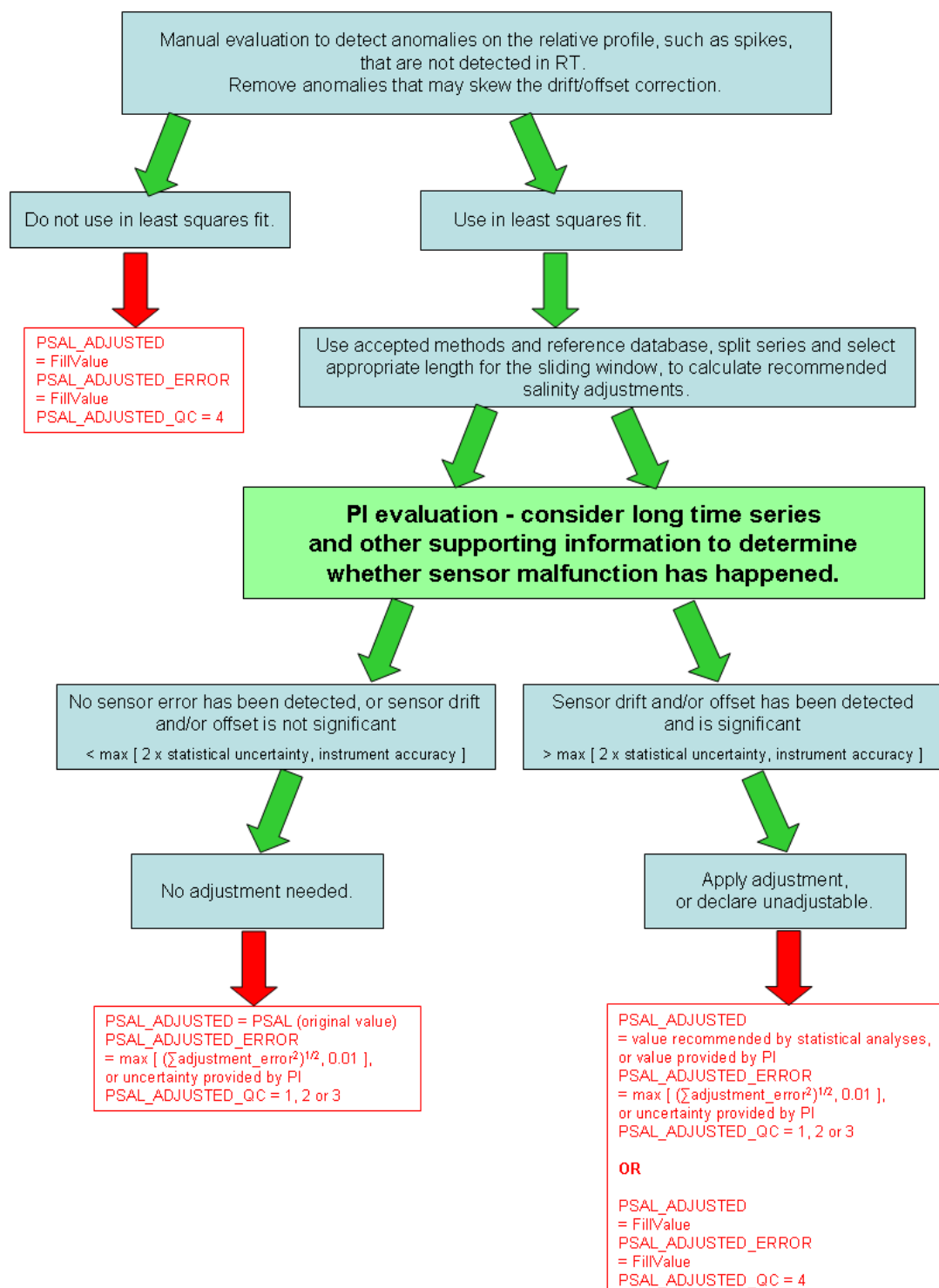
PSAL\_ADJUSTED\_QC = '2';

PSAL\_ADJUSTED\_ERROR = uncertainty provided by PI, but has to be > 0.015.

### The following are some cases where PSAL\_ADJUSTED\_QC = '2' should be assigned

- Adjustment is based on unsatisfactory reference database.
- Adjustment is based on a short calibration window (because of sensor behaviour transition, or end of sensor life) and therefore may not be stable.
- Evaluation is based on insufficient information.
- Sensor is unstable (e.g. magnitude of salinity adjustment is greater than 0.05, or sensor has undergone too many sensor behaviour changes) and therefore data are inherently of mediocre quality.
- When a float exhibits problems with its pressure measurements, e.g. APEX TNPDP.

## 3.5.6. Summary flowchart for salinity

**Argo salinity sensor drift & offset QC procedures**

### 3.5.7. Timeframe for availability of delayed-mode salinity data

The statistical methods used in the Argo delayed-mode process for checking sensor drifts and offsets in salinity require the accumulation of a time series for reliable evaluation of the sensor trend. Timeframe for availability of delayed-mode salinity data is therefore dependent on the sensor trend. Some floats need a longer time series than others for stable calibration and evaluation. Thus delayed-mode salinity data for the most recent profile may not be available until sufficient subsequent profiles have been accumulated. The *default* length of time series for evaluating sensor drift is 12 months (6 months before and 6 months after the profile). This means that in general, the timeframe of availability of drift-adjusted delayed-mode salinity data is 6+ months after a profile is sampled. However, in instances of known sensor stability or known adjustment stability, the delayed-mode operator can decide how recent a profile to send out.

Users should also be aware that changes may be made to delayed-mode files at any time by DACs and delayed-mode operators. For example, delayed-mode files may be revised when new CTD or float data become available after the original delayed-mode assessment and adjustment. The date of latest adjustment of a parameter can be found in SCIENTIFIC\_CALIB\_DATE.

Anytime an Argo file is updated for any reason, the DATE\_UPDATE variable will reflect the date of the update. The "profile index file" on the GDACs contains the DATE\_UPDATE information (along with other information) for every file on the GDACs and can be used to monitor updates. The profile index file is maintained in the top-level GDAC directory and is named "ar\_index\_global\_prof.txt"; index files also exist for the meta-data and trajectory files.

### 3.5.8. References

- Böhme, L. and U. Send, 2005: Objective analyses of hydrographic data for referencing profiling float salinities in highly variable environments. *Deep-Sea Research II*, **52/3-4**, 651-664.
- Cabanes, C., V. Thierry, and C. Lagadec, 2016: Improvement of bias detection in Argo float conductivity sensors and its application in the North Atlantic. *Deep Sea Research Part I: Oceanographic Research Papers*, **114**, 128-136.
- Johnson, G.C., J.M. Toole, and N.G. Larson, 2007: Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. *Journal of Atmospheric and Oceanic Technology*, **24**, 1117-1130.
- Owens, W.B. and A.P.S. Wong, 2009: An improved calibration method for the drift of the conductivity sensor on autonomous CTD profiling floats by  $\theta$ -S climatology. *Deep-Sea Research, Part I: Oceanographic Research Papers*, **56(3)**, 450-457.
- Wong, A.P.S., G.C. Johnson, and W.B. Owens, 2003: Delayed-mode calibration of autonomous CTD profiling float salinity data by  $\theta$ -S climatology. *Journal of Atmospheric and Oceanic Technology*, **20**, 308-318.

### 3.6. Compulsory variables to be filled in a D file

This section lists the compulsory variables that must be filled in an Argo netCDF profile file that has been through the delayed-mode process.

#### 3.6.1. Measurements for each profile

The following are compulsory measurement variables that must be filled in a D file:

```
<PARAM>_ADJUSTED;
<PARAM>_ADJUSTED_QC;
<PARAM>_ADJUSTED_ERROR.
```

The variable PROFILE\_<PARAM>\_QC should be recomputed when <PARAM>\_ADJUSTED\_QC becomes available. See Section 4.2 for definitions. Here, <PARAM> denotes all the measurement parameters that are reported in the netCDF file. <PARAM> = PRES, TEMP, PSAL (and sometimes CNDC) are the core Argo measurement parameters. See Sections 3.3, 3.4, 3.5 on how to fill their related \_ADJUSTED\_ variables.

For <PARAM> = CNDC, CNDC\_ADJUSTED, CNDC\_ADJUSTED\_QC, and CNDC\_ADJUSTED\_ERROR can be their respective FillValues. If they are not their respective FillValues, then CNDC\_ADJUSTED must be calculated to be consistent with PSAL\_ADJUSTED, TEMP\_ADJUSTED, and PRES\_ADJUSTED. CNDC\_ADJUSTED\_QC must be consistent with PSAL\_ADJUSTED\_QC, and CNDC\_ADJUSTED\_ERROR must be consistent with PSAL\_ADJUSTED\_ERROR.

#### 3.6.2. Scientific calibration information for each profile

Within each single-cycle Argo netcdf profile file is a scientific calibration section that records details of delayed-mode adjustments. It is compulsory to fill the variables in the scientific calibration section at the completion of delayed-mode qc.

In the scientific calibration section, every measurement parameter recorded in STATION\_PARAMETER in the netCDF file should be listed in the variable PARAMETER. For every measurement parameter listed in PARAMETER (e.g. PRES, TEMP, PSAL, CNDC), there are four variables to record scientific calibration details:

```
SCIENTIFIC_CALIB_EQUATION;
SCIENTIFIC_CALIB_COEFFICIENT;
SCIENTIFIC_CALIB_COMMENT;
SCIENTIFIC_CALIB_DATE.
```

Regardless of whether an adjustment has been made or not, the date of delayed-mode qc for each measurement parameter (e.g. PRES, TEMP, PSAL, CNDC) should be recorded in SCIENTIFIC\_CALIB\_DATE, in the format YYYYMMDDHHMISS.



The following are some examples on how to fill the SCIENTIFIC\_CALIB section.

Example 1. PARAMETER = PRES. APEX pressure adjustment has been applied.

SCIENTIFIC\_CALIB\_EQUATION = 'PRES\_ADJUSTED = PRES - dP'

SCIENTIFIC\_CALIB\_COEFFICIENT = 'dP = -0.2 dbar'

SCIENTIFIC\_CALIB\_COMMENT = 'Pressures adjusted by using pressure offset at the sea surface. The quoted error is manufacturer specified accuracy in dbar.'

Example 2. PARAMETER = TEMP. Data are good and no adjustment is needed.

SCIENTIFIC\_CALIB\_EQUATION = 'none'

SCIENTIFIC\_CALIB\_COEFFICIENT = 'none'

SCIENTIFIC\_CALIB\_COMMENT = 'The quoted error is manufacturer specified accuracy with respect to ITS-90 at time of laboratory calibration.'

Example 3. PARAMETER = PSAL. Data are good; no adjustment has been applied.

SCIENTIFIC\_CALIB\_EQUATION = 'none'

SCIENTIFIC\_CALIB\_COEFFICIENT = 'none'

SCIENTIFIC\_CALIB\_COMMENT = 'No significant salinity drift detected. The quoted error is max[0.01, statistical uncertainty] in PSS-78.'

Example 4. PARAMETER = PSAL. Data show sensor drift; adjustment has been applied.

SCIENTIFIC\_CALIB\_EQUATION = 'PSAL\_ADJUSTED = PSAL + dS'

SCIENTIFIC\_CALIB\_COEFFICIENT = 'vertically averaged dS = 0.012 +/- 0.003'

SCIENTIFIC\_CALIB\_COMMENT = 'Significant salinity sensor drift detected. OW least squares fit adopted. Salinity also adjusted for effects of pressure adjustment. The quoted error is max[0.01, statistical uncertainty] in PSS-78.'

Example 5. PARAMETER = PSAL. Data are bad and unadjustable.

SCIENTIFIC\_CALIB\_EQUATION = 'none'

SCIENTIFIC\_CALIB\_COEFFICIENT = 'none'

SCIENTIFIC\_CALIB\_COMMENT = 'Salinity data are bad and unadjustable because of the Druck oil microleak problem.'

### 3.6.3. Other variables in the netcdf file

A history record should be appended to the HISTORY section of the netcdf file to indicate that the netcdf file has been through the delayed-mode process. Please refer to the Argo User's Manual (§5 "Using the History section of the Argo netCDF Structure") on usage of the History section.

The variable DATA\_MODE should record 'D'.

The variable DATA\_STATE\_INDICATOR should record '2C' or '2C+'.

The variable DATE\_UPDATE should record the date of last update of the netcdf file, in the format YYYYMMDDHHMISS.

Lastly, the name of the single-cycle profile file is changed from R\*.nc to D\*.nc.

## 4. Appendix

### 4.1. Reference Table 2: Argo quality control flag scale

This table describes the Argo qc flag scales. Please note that this table is used for all measured parameters. This table is named Reference Table 2 in the Argo User's Manual.

Flag Meaning		Real-time comment	Delayed-mode comment
0	No QC was performed	No QC was performed	No QC was performed
1	Good data	All Argo real-time QC tests passed.	The adjusted value is statistically consistent and a statistical error estimate is supplied.
2	Probably good data	Probably good data	Probably good data
3	Probably bad data that are potentially correctable	Test 15 or Test 16 or Test 17 failed and all other real-time QC tests passed. These data are not to be used without scientific correction. A flag '3' may be assigned by an operator during additional visual QC for bad data that may be corrected in delayed-mode.	An adjustment has been applied, but the value may still be bad.
4	Bad data	Data have failed one or more of the real-time QC tests, excluding Test 16. A flag '4' may be assigned by an operator during additional visual QC for bad data that are uncorrectable.	Bad data. Not adjustable. Data replaced by FillValue.
5	Value changed	Value changed	Value changed
6	Not used	Not used	Not used
7	Not used	Not used	Not used
8	Estimated value	Estimated value (interpolated, extrapolated, or other estimation)	Estimated value (interpolated, extrapolated, or other estimation)
9	Missing value	Missing value	Missing value

## 4.2. Reference Table 2a: profile quality flags

Please note that this table is used for all measured parameters. This table is named Reference Table 2a in the Argo User's Manual.

$N$  is defined as the percentage of levels with good data where:

- QC flag values of 1, 2, 5, or 8 are GOOD data
- QC flag values of 9 (missing) are NOT USED in the computation
- All other QC flag values are BAD data

The computation should be taken from <PARAM>\_ADJUSTED\_QC if available and from <PARAM>\_QC otherwise.

n	Meaning
“ “	No QC was performed
A	$N = 100\%$ ; All profile levels contain good data
B	$75\% \leq N < 100\%$
C	$50\% \leq N < 75\%$
D	$25\% \leq N < 50\%$
E	$0\% < N < 25\%$
F	$N = 0\%$ ; No profile levels have good data

### 4.3. Reference Table 11: RTQC tests binary ID

This table lists the binary ID of the RTQC tests. This table is named Reference Table 11 in the Argo User's Manual.

Each RTQC test has a unique test number. The binary ID of the unique test number is used to record rtqc tests performed and failed in the history variable HISTORY\_QCTEST.

Test number	Binary ID	Test name
1	2	Platform Identification test
2	4	Impossible Date test
3	8	Impossible Location test
4	16	Position on Land test
5	32	Impossible Speed test
6	64	Global Range test
7	128	Regional Global Parameter test
8	256	Pressure Increasing test
9	512	Spike test
10	1024	<i>Top and Bottom Spike test (obsolete)</i>
11	2048	Gradient test
12	4096	Digit Rollover test
13	8192	Stuck Value test
14	16384	Density Inversion test
15	32768	Grey List test
16	65536	Gross Salinity or Temperature Sensor Drift test
17	131072	Visual QC test
18	261144	Frozen profile test
19	524288	Deepest pressure test
20	1048576	Questionable Argos position test
21	2097152	Near-surface unpumped CTD salinity test
22	4194304	Near-surface mixed air/water test
23	8388608	Interim rtqc flag scheme for data deeper than 2000 dbar

#### 4.4. Common instrument errors and failure modes

This section describes some common instrument errors and failure modes that will cause error in float measurements.

##### 1. TBTO leakage

TBTO (tributyltin oxide) is a wide spectrum poison that is used to protect conductivity cells from biofouling. However, accidental leakage of TBTO onto the conductivity cells can occur, but it usually gets washed off in time. This will result in fresh salinity offsets in float data that gradually return to normal. Delayed-mode analysts should pay special attention to salinity data at the beginning of the float's life because TBTO leakage usually affects the first few CTD profiles after deployment before the contamination gets washed off.

##### 2. Pollution events

Any pollution on the conductivity cell will result in erroneously fresh salinity measurements. When pollution washes off, reversal of sensor drift trend can occur. Delayed-mode analysts need to be careful in splitting the float time series in such cases.

##### 3. Ablation events

Any ablation of the conductivity cell, such as etching, scouring, or dissolution of the glass surface, will result in erroneously salty salinity measurements.

##### 4. Conductivity cell geometry changes

The geometry of conductivity cells can change, thus causing electrodes to change distance. This will result in either an increase or a decrease in salinity values.

##### 5. Conductivity cell circuit changes

The circuit within the conductivity cell contains capacitors and resistors. Changes to any of these electrical components will affect electrical conductivity and thus will give erroneous (fresh or salty) salinity measurements. Electrical complication can result in sensor drifts that have varying drift rates (e.g. drift rates can change from slow and linear to exponential). Usually jumps in salinity measurements are an indication of electrical malfunction. If electrical complication is suspected, delayed-mode analysts should check the shape of the vertical salinity profiles for adjustability. Usually the vertical profiles after a measurement jump are wrong and so are unadjustable.

##### 6. Low voltage at end of float life, and “Energy Flu”

Some floats experience a sudden rapid decrease in available battery energy reserves. This premature exhaustion of battery, known as “Energy Flu”, usually starts about 2 years after deployment. The sharp drop in battery voltage related to “Energy Flu”, as well as the low voltage towards the end of a float's natural life, will produce low-of-correct salinity values. Towards the end of float life, low voltage will result in large drift, followed by death. “Energy Flu” will cause spikes that get worse and more frequent, also followed by death.

## 7. Druck pressure sensor “snowflakes” problem

About 4% of SBE41 CTDs that were manufactured in late 2002 through end of 2003 have experienced the Druck pressure sensor “snowflakes” problem. SeaBird has fixed this problem in 2004, so this feature is only included in this section for identifying the historical profiles that have been affected. The Druck pressure sensor “snowflakes” problem is due to internal electrical shorting by the growth of titanium oxide particles (‘snowflakes’) in the oil-filled cavity in the pressure sensor, causing the pressure sensor to report erratic pressure measurements, or going to full scale, i.e. either report PRES ~ 3000 dbar or -3000 dbar. These erratic pressure measurements will preferentially report deeper than correct. The firmware tries to adjust the piston according to the erroneous deeper pressures, causing the float to park shallower. The float will thus progressively become a surface drifter. Erroneous deeper pressures will also result in the firmware placing the pointer at the deeper nominal sampling levels in the lookup table, thus causing the float to take a sample everytime the firmware performs a lookup (every 6 seconds). The result is a series of measurements from very close-together depth levels. Progressively shallower profiles and close-together measurements are therefore two ways to identify whether the Druck pressure sensor has been contaminated. When the Druck pressure sensor has been contaminated, pressure measurements become suspect and should be considered bad. The corresponding temperature and salinity measurements are therefore also suspect and should be considered bad.

## 8. Druck pressure sensor “oil microleak” problem

Another pathology in Druck pressure sensors is oil microleak past the glass/metal seal. This oil leak leads to an internal volume loss, which then exhibits itself as an increasing negative offset at all pressures. At the early stages of oil microleak, float measurements are still correctable and usable. However, as more and more oil is leaked, the flexible titanium diaphragm will dip so far down the oil chamber that it will short the electrical parts, causing erratic behaviour in float measurements. This is the end stage of oil microleak, and the data at this point are bad and unadjustable.

## 9. Incorrect pressure sensor coefficient

Incorrect scaling coefficient in the pressure sensor will give anomalous T-S curves at depth. The T-S relation will look acceptable, but at depth it will look as if the float is sampling an anomalous water mass relative to nearby floats. Delayed-mode analysts should try to re-scale pressure measurements (e.g.  $PRES' = PRES * X$ ) to see whether the T-S curve can be recovered. Air bubbles in the pressure transducer can also cause erroneous pressure measurements that are visible as anomalous T-S curves.

## 10. Conductivity cell thermal mass error

Salinity reported immediately after a float has crossed a strong thermal gradient can be in error as a result of conductivity cell thermal mass. This error arises because the thermal inertia in the flow duct alters the temperature of water entering the conductivity cell, thus inducing a conductivity error. For details please refer to Johnson *et al.* 2007. These errors can exceed 0.01 (PSS-78) for strong thermal gradients, and sometimes result in unstable fresh spikes at the base of the mixed layer. This salinity error can be corrected if the ascent rate of the float is known. A correction algorithm is available from Greg Johnson at [Gregory.C.Johnson@noaa.gov](mailto:Gregory.C.Johnson@noaa.gov).

## **11. Abnormal salinity “hooks” at base of profiles**

In some floats, salty or fresh salinity hooks may be observed at the base of the CTD profiles. The “hook” appearance occurs when the two deepest measurements are taken at nearly identical pressures (usually less than 5dbar apart) but salinity from the first measurement looks abnormal relative to the second measurement. The first (deeper) measurement is taken at the end point of descent; the second (shallower) measurement is the first deep sample taken during ascent. The abnormal (deeper) salinity reading is caused by water in the conductivity cell carried from the surface or park level to deep profile level not being flushed out completely before the descent-end-point sample is taken. Salty hooks are produced when surface or park-level water is saltier than deep water; fresh hooks are produced when surface or park-level water is fresher than deep water. These salinity hooks cannot be detected by the real-time tests, so delayed-mode analysts are urged to examine carefully the base of CTD profiles for these abnormal salinity values, and to flag them appropriately in delayed-mode.



#### 4.5. Criteria for CTD profiles to be retained in the reference database

The following criteria are used to select CTD data as reference for delayed-mode quality control of Argo salinity profiles in the open ocean.

- 1). Use only data that have passed all NODC quality control tests for observed level data.
- 2). Use all country codes.
- 3). Use only profiles that sampled deeper than 900 dbar.
- 4). Weed out all data points outside these ranges:  $24 < S < 41$ ,  $0.01 < P < 9999$ ,  $0^{\circ}\text{C} < T < 40^{\circ}\text{C}$ , except for WMO boxes with latitudes north of  $60^{\circ}\text{N}$  or south of  $50^{\circ}\text{S}$ , where  $-2.5^{\circ}\text{C} < T < 40^{\circ}\text{C}$ .
- 5). For WMO boxes that contain more than 10,000 profiles, only select profiles that are post-1995.
- 6). Eliminate nearby duplicates.
- 7). Do objective residual analysis using previously qc'd reference data to identify anomalies. Then do visual inspection of anomalies.
- 8). Identify each reference profile with a unique ID, e.g. under the variable SOURCE.

It is recommended that in regions with adequate reference data, that delayed-mode qc for salinity should use CTD data only. If CTD data are too sparse, bottle data (BOT) may be included.

#### 4.6. Criteria for Argo profiles to be retained in the reference database

The following criteria are used to select Argo data as reference for delayed-mode quality control of Argo salinity profiles in the open ocean.

- 1). No real-time data. Profiles must be from D-files.
- 2). Exclude all profiles that sample on descent.
- 3). Exclude floats that fail within 1 year of deployment.
- 4). No profiles within 12 months of end of record (death).
- 5). No profiles that have salinity drift adjustment ( $\Delta S > .001$  in bottom data to distinguish from thermal lag adjustment at shallower levels).
- 6). Profiles must contain data deeper than 800 dbar.
- 7). Profiles must contain 90% good salinity values ( $PRES\_ADJUSTED\_QC = '1'$ ,  $TEMP\_ADJUSTED\_QC = '1'$ ,  $PSAL\_ADJUSTED\_QC = '1'$ ).
- 8). No profiles within 2 months of deployment (due to the propensity of some floats to acquire TBTO contamination).
- 9). No profiles within 12 months of the onset of salinity drift ( $\Delta S > .001$  in bottom data).
- 10). No profiles whose bottom data have  $PSAL\_ADJUSTED\_ERROR > 0.015$ .

#### 4.7. Consistency checks for D files format at the GDACs

The following is a list that is used at the GDACs for checking D files format.

- 1). <PARAM>\_ADJUSTED and <PARAM>\_ADJUSTED\_ERROR must contain data, except when <PARAM>\_ADJUSTED\_QC = '4' or '9'. Here, <PARAM> = PRES, TEMP, PSAL, and CNDC.
- 2). If PRES\_ADJUSTED\_QC = '4', then TEMP\_ADJUSTED\_QC = '4' and PSAL\_ADJUSTED\_QC = '4'.
- 3). <PARAM>\_ADJUSTED\_QC cannot be '0'.
- 4). POSITION\_QC and JULD\_QC cannot be '0'.
- 5). No variable should be filled with the netCDF value of IEEE NaN.
- 6). In the Scientific Calibration section, PARAMETER should have N\_PARAM entries equal to the number of measurement parameters recorded in the netCDF file.
- 7). In the Scientific Calibration section, SCIENTIFIC\_CALIB\_COMMENT should have non-FillValue entries in every N\_PARAM dimension.
- 8). In the Scientific Calibration section, CALIBRATION\_DATE should have non-FillValue entries in every N\_PARAM dimension, and should have format YYYYMMDDHHMISS (seconds must be 0 to 59).
- 9). DATE\_UPDATE should be equal to or later than any CALIBRATION\_DATE, HISTORY\_DATE, DATE\_CREATION, JULD, and JULD\_LOCATION.
- 10). There should be at least one HISTORY record.
- 11). All dates must be after 1st Jan 1997, and before GDAC file time.
- 12). All dates must be 14 digit strings, in the format YYYYMMDDHHMISS (seconds must be 0 to 59).
- 13). Character strings should not contain the NULL character.