RBR

Conductivity pressure correction for the 2000dbar conductivity cell

1 Summary

In 2016 several new models of conductivity cell were released by RBR. Those new conductivity cells are called combined CT cells and are available in three versions: 1000dbar, 2000dbar, and 6000dbar.

The 1000dbar version uses a pressure vessel made from POM and ceramic while the 2000dbar and 6000dbar models use OSP and ceramic. Until recently, the pressure correction of conductivity was done using a parameter derived empirically from an earlier design of the cell. In situ comparisons of RBR data to bench top salinometer data showed that higher accuracy could be achieved with a new calibration equation which extends the pressure dependency from first to third order in the case of the 2000dbar combined CT cell. Firmware version 1.093 and higher, available since September 2018, uses the updated correction, but the new compensation can be retroactively applied to data collected with previous firmware versions as detailed below.

The new pressure correction for conductivity, together with accurate temperature measurements, result in a salinity accurate to within Argo standards.

2 Conductivity calibration

Although electrode based conductivity cells are simple to characterise in terms of pressure sensitivity, particularly when the electric field is entirely self-contained and the cell shape is a geometric primitive (hollow cylinder) with isotropic material properties, the mechanical behaviour of an inductive cell under pressure can be more complex to understand. The electric field in an inductive cell forms a toroid that passes through the centre of the cell (typically also a hollow cylinder, though one with a much lower aspect-ratio than the electrode-based counterpart) but then out and around the exterior volume of the cell. This may also be a geometric primitive (a larger cylinder) and in cells designed for moored applications, this is the most efficient form factor as hydrodynamic concerns are less significant. However, for cells intended for profiling use, considerable design effort is expended in order to achieve optimal flushing of the cell due to the movement of the host platform. This results in a cell exterior which does not have an easily calculated physical deformation as a function of hydrostatic pressure.

The RBR combined CT cell (where the thermistor housing and the conductivity cell are manufactured as a single combined unit) is of such a shape.

3 First order correction

3.1 Original linear x2 coefficient

The equation that produces a conductivity value using a linear pressure correction is as follows:

$$C_{corrected} = \frac{C_{uncorrected} - x_0 \cdot (T - x_3)}{1 + x_1 \cdot (T - x_3) + x_2 \cdot (P - x_4)}$$

where **P** is the absolute pressure (dbar), **T** is the internal temperature of the conductivity cell (°C). Coefficients **x0** ((mS/cm)/°C) and **x1** (°C^{-1}) are the temperature correction coefficients, **x2** (dbar^{-1}) is the pressure correction coefficient, **x3** is the temperature during calibration (°C), and **x4** is always 10 (dbar), indicating the nominal pressure during calibration.

The pressure sensitivity is modelled as a simple first order dependence, and has no effect to the nominal conductivity calibration performed at 10dbar (**x4**, atmospheric pressure).

In instruments shipped for the past few years, **x2** was set to 4e-7dbar^{-1}. This value was determined empirically through sea trials on board the R/V "Thomas G. Thompson" (TN298 cruise) in 2013 using the old conductivity cell design. However, our results with the combined cell have shown a consistent bias to high salinity using that value. This can be seen in buddy-float deployments, rosette casts, and WOA comparisons. Comparing data from three RBR*argo* Teledyne Apex floats to such reference data indicates that the salinity bias at 2000dbar is +0.05 (C = 31mS/cm).

The bias results from applying the conductivity pressure correction developed for the moored cell to the combined RBR*argo* CT cell. The RBR*argo* CT cell pressure correction term is different because its construction differs from that of the moored cell.

3.2 Provisional linear x2 coefficient

The realization that an updated pressure compensation was necessary became clear after analyzing salinity from Second Institute of Oceanography RBR*argo* Apex float WMO 2902730. As a temporary solution, RBR calculated a new linear pressure correction coefficient of **x2** = 1e-6dbar^{-1}. This value was derived by matching salinity from

RBR*argo* profiles to the local average WOA salinity at 2000dbar. In fact, Argo China (temporarily) applied this new compensation to the Second Institute of Oceanography RBR*argo* Apex float WMO 2902730 in April 2018.

4 Third order correction

In the summer of 2018, RBR worked with JAMSTEC and DFO Canada to assess whether the pressure correction *model* itself should be changed, either as an increased order polynomial or a power law. In addition, a large salt water pressure tank (1.4m deep by 0.7m diameter) was used to provide more controlled evaluation of these terms.

The saltwater pressure tank study provided the best data for deriving a new correction because of the tightly controlled, constant salinity environment. The main result of this study is that the optimal correction factor is a cubic polynomial instead of a linear function of pressure. F-tests showed that increasing the polynomial degree beyond three does not increase the explained variance in a statistically significant way. Quantitatively, the F-test statistics, when changing from a polynomial of degree *n* to *n+1* ($F_{n,n+1}$), are $F_{1,2} = 223$, $F_{2,3} = 112$, and $F_{3,4} = 0.008$ ($F_{3,4}$ is well below the 99% significance level).

With a cubic pressure correction, the conductivity calibration equation now looks like:

$$C_{corrected} = \frac{C_{uncorrected} - x_0 \cdot (T - x_5)}{1 + x_1 \cdot (T - x_5) + f(P - x_6)}$$

$$f(P - x_6) = x_2 \cdot (P - x_6) + x_3 \cdot (P - x_6)^2 + x_4 \cdot (P - x_6)^3$$

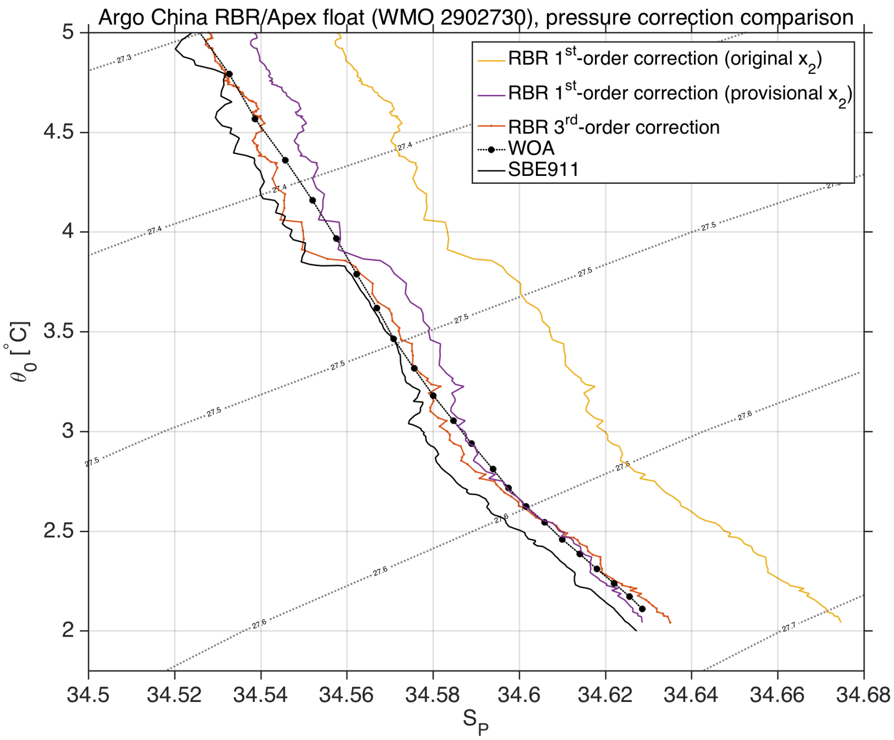
The new pressure compensation equation was incorporated into the RBR*argo* CTD firmware version 1.093 released in September 2018.

5 In situ evaluation of original first order, provisional first order, and third order conductivity corrections

5.1 Argo China float comparison

The first profile obtained by the Argo China RBR/Apex float, WMO 2902730, deployed in January 2018, was what highlighted the need to improve the conductivity pressure correction. Although Argo China applies the *provisional* **x2** coefficient, we also show data with the original coefficient, **x2** = 4e-7dbar^{-1}, because all floats shipped to date were configured with this value. The reference data in this case is a SBE911 profile taken when the float was deployed, and the nearest grid point of the ¼° World Ocean Atlas mean T/S over the years 2005 - 2012.

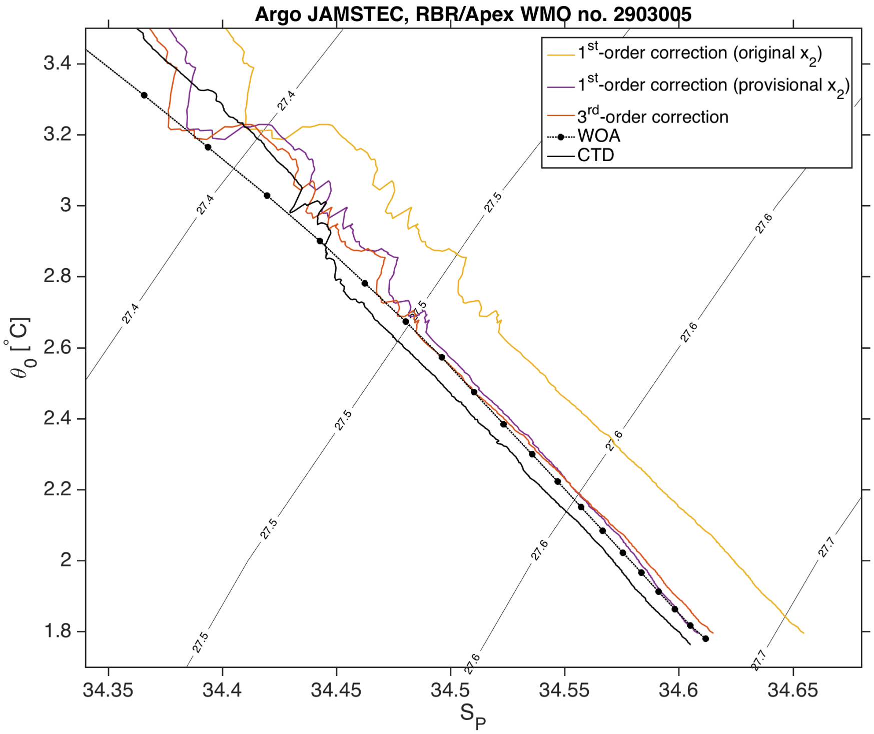
The T/S diagram shows the bottom 1000dbar of the water column ($\theta_0 < 5$°C), where it is seen that the salinity computed from conductivity using the original **x2** value is too salty by 0.03 to 0.04 relative to the WOA. The provisional linear correction brings the salinity very close to WOA values below about 3°C, however it overestimates salinity by 0.01 between 4°C and 5°C (there appears to be a salinity anomaly 3°C and 4°C, so no conclusion is drawn there). Applying the cubic correction brings the salinity below 5°C to within 0.005 of the WOA mean salinity. The average difference below 5°C is less than 0.001mS/cm, while the standard deviation is 0.0026mS/cm. While the provisional correction brought the deep values very close the WOA mean, the advantage of the cubic correction is that it minimizes the error over a wide pressure range.



5.2 Argo Japan float comparison

In early February 2018, Argo Japan launched two RBR/Apex floats, WMO nos. 2903005 and 2903327. The reference data in this case is a SBE911 profile taken one day before the floats were deployed, and also the nearest grid point of the ¼° World Ocean Atlas mean T/S over the years 2005 - 2012. The salinity from float 2903327 is offset too high by 0.02 relative to the reference CTD, and because the offset is not correlated to pressure, we do not discuss float 2903327 here.

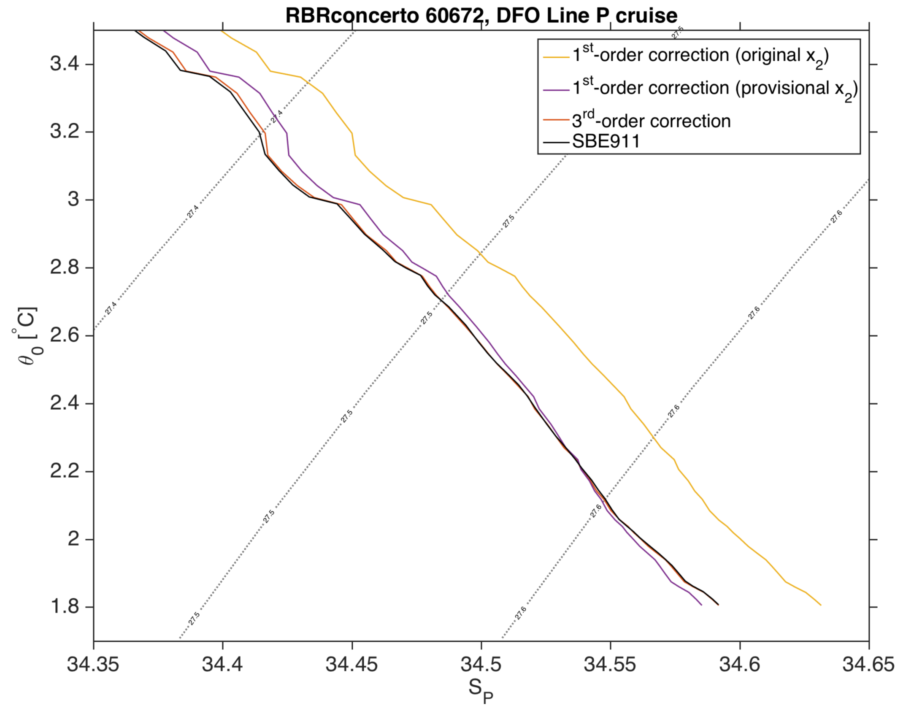
As with the Argo China float comparison, we use T/S diagrams to illustrate the impact of both the original and provisional linear coefficients, and the new cubic correction. The original linear coefficient results in a salinity that is too high by up to 0.05 relative to the reference CTD cast. The provisional linear coefficient adjusts conductivity such that the salinity differences at 2000dbar (θ_0 = 1.8°C) are within 0.002 of the WOA mean, and +0.008 relative to the CTD profile. The error is larger at lower pressures, however, because the provisional coefficient was *tuned* to match the deep salinity. When conductivity is adjusted with the cubic correction, the salinity difference at 2000dbar (θ_0 = 1.8°C) is +0.006 relative to the WOA mean, and +0.014 relative to the CTD profile. Thus, the salinity difference at 2000dbar is slightly smaller when the provisional linear correction is applied in comparison to when the cubic correction is applied. However, the provisional linear correction only matches closely at 2000dbar, and it results in an error correlated to pressure. The cubic correction both removes the pressure correlation and reduces the error over a much wider range of pressure.

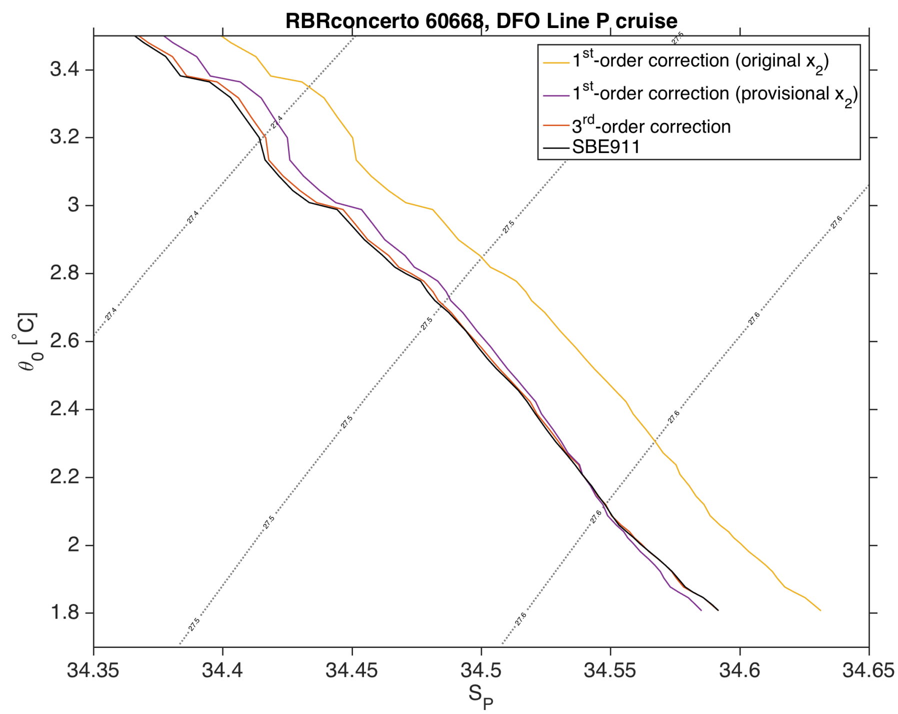


5.3 DFO Canada rosette comparison

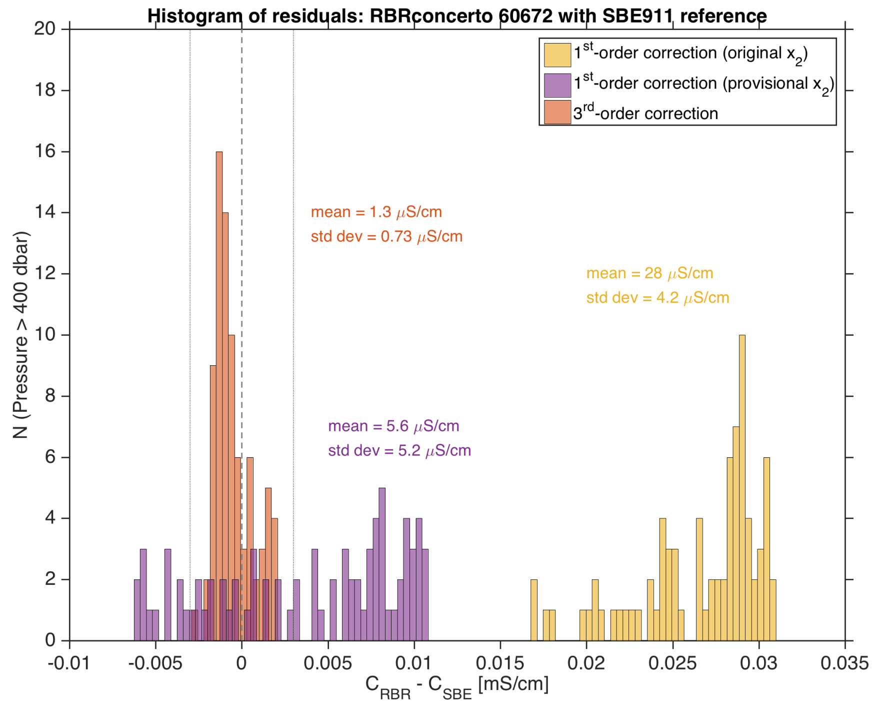
RBR equips its autonomous loggers (e.g., RBR*concerto*) with the same conductivity cell found on profiling floats, and therefore it is straightforward to assess the cell's performance by mounting it on a rosette water sampler. Comparing instruments profiled on the same rosette removes any uncertainty as to whether the reference and test instruments measured the same water mass. In June 2018, two RBR*concerto* 2000dbar CTDs and an SBE9 were profiled simultaneously on a rosette during the DFO Canada Line P cruise in the North Pacific. Both the provisional linear correction and the cubic coefficients computed from the saltwater pressure tank testing were applied to the RBR*concerto* data.

The difference between the conductivity when corrected with the original linear **x2** coefficient, the provisional **x2** coefficient, and the new cubic correction, is seen in the following T/S diagrams. The focus is on $\theta_0 < 3.5$ °C (P>1000dbar), where stratification is weak and the pressure effect dominates thermally-driven dynamic errors. The salinity error (RBR - reference), when using the original linear correction, ranges from 0.03 to 0.05 as pressure increases from 1000dbar to 2000dbar. The provisional linear correction reduces the error to 0.011 to -0.007 over the same pressure range. The third order correction brings the salinity to within ±0.003. Furthermore, the errors are consistent between two different 2000dbar RBR*concerto* CTDs.





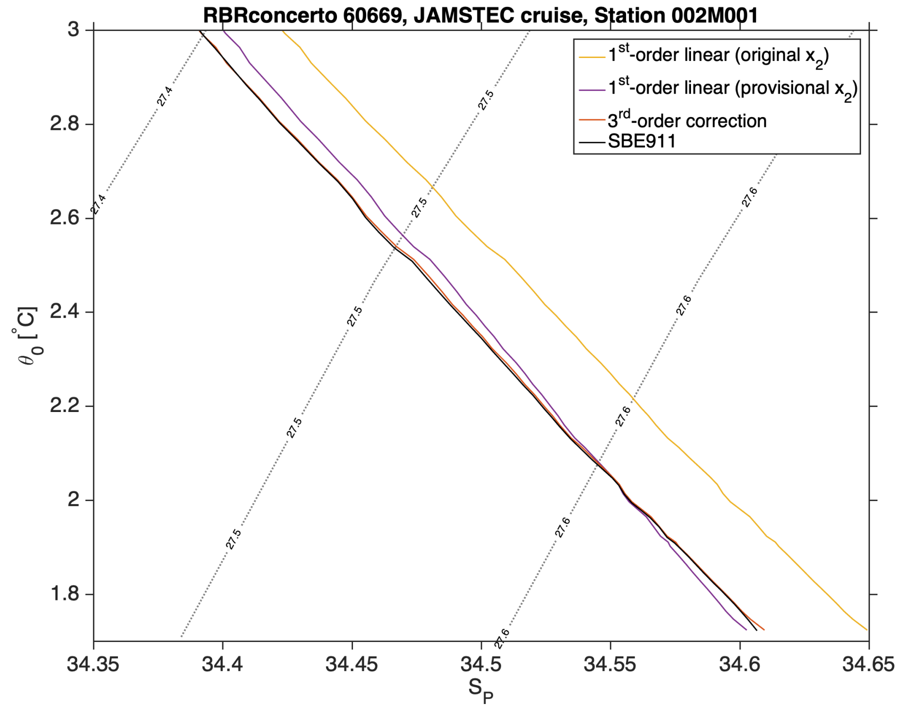
A more detailed and quantitative look at the impact of each pressure compensation function is seen by analyzing the conductivity difference between the RBR*concerto* and the SBE911. Analyzing conductivity instead of salinity removes the influence of temperature errors. Conductivity is averaged into 20dbar bins, and data at pressures less than 400dbar are excluded because strong stratification causes dynamic errors that dominate the pressure signal. The histograms show that the original linear term effectively biased the measurements too high and increased the range of the errors, while in comparison, the provisional linear correction term reduced the bias but retained the scatter. The third order correction reduces both the bias and the scatter: the average conductivity difference is 0.001mS/cm, and one standard deviation of the residuals is 0.0007mS/cm.

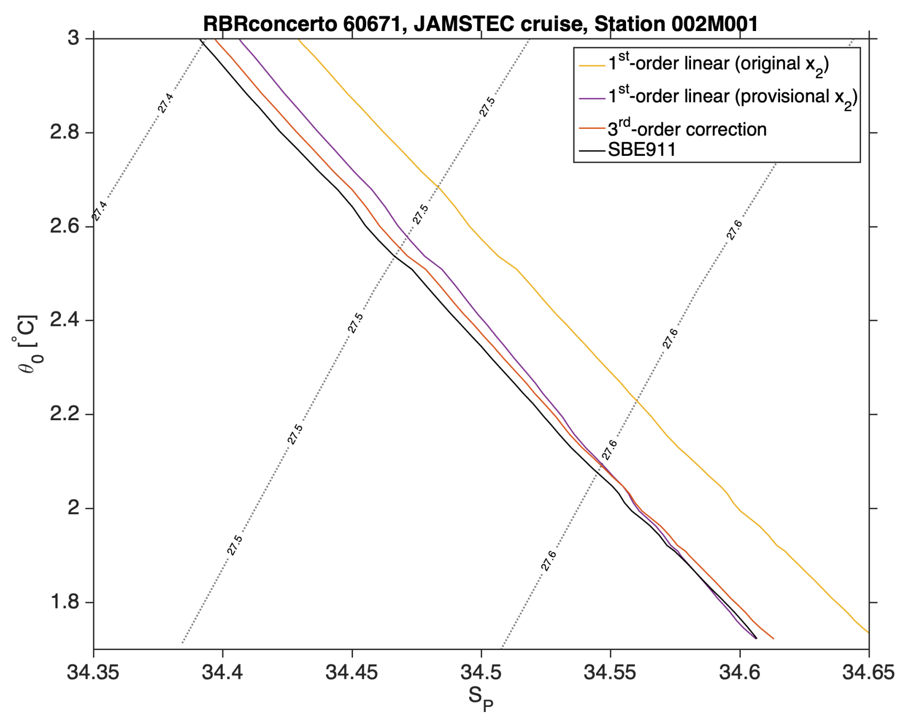


5.4 JAMSTEC rosette comparison

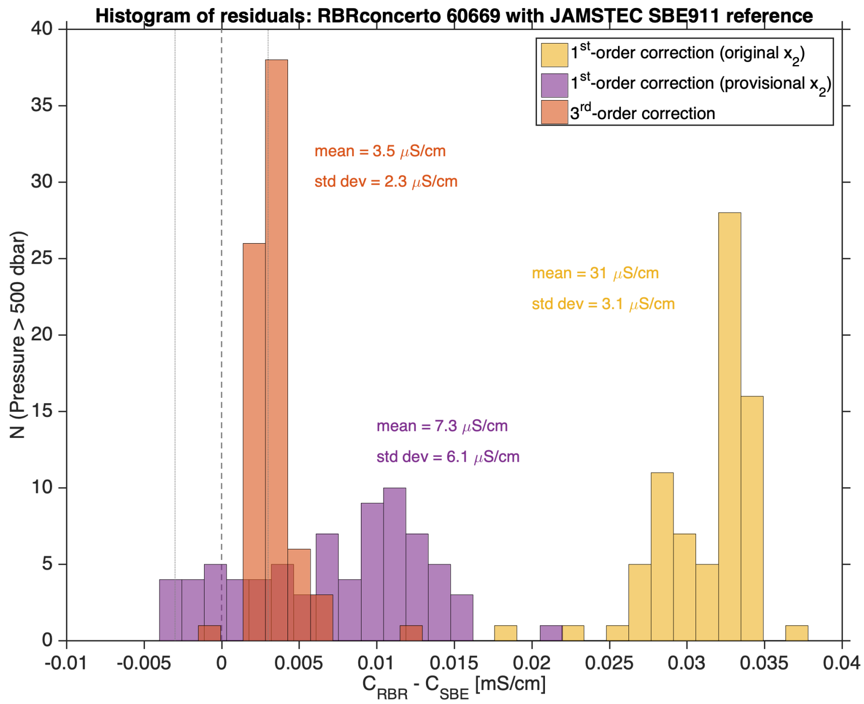
In July, August, and September 2018, two RBR*concerto* 2000dbar CTDs were profiled simultaneously on a rosette during a JAMSTEC cruise aboard the R/V Mirai in the subtropical western Pacific. A SBE9+ was also on the rosette, and the conductivity was adjusted with bottle-based salinometer measurements. Pressure compensation coefficients computed from the saltwater pressure tank testing were applied to the RBR*concerto* data.

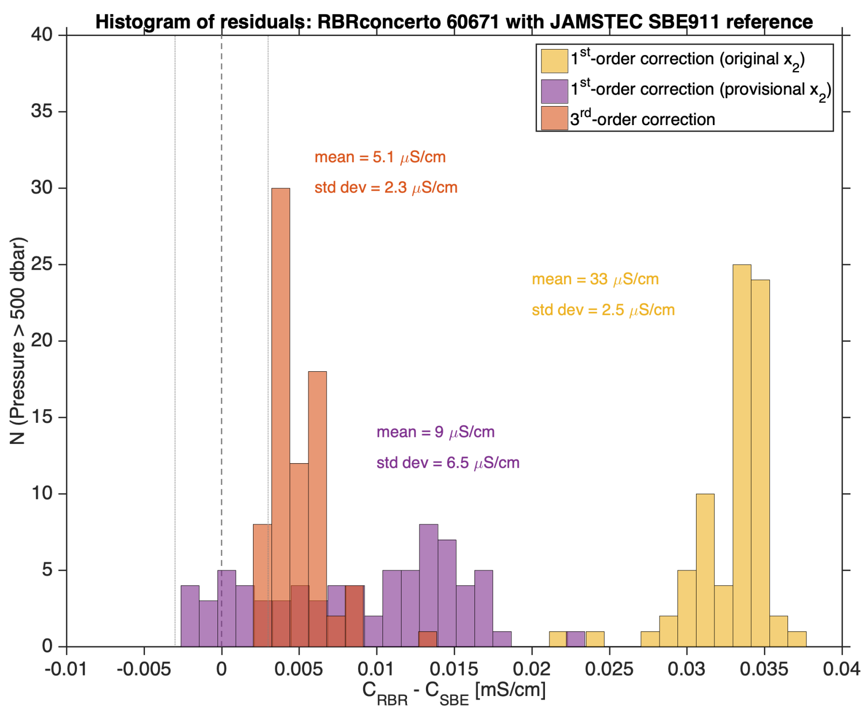
The difference between the conductivity when corrected with the new cubic correction, the original linear **x2** coefficient, and the provisional **x2** coefficient, is seen in the following T/S diagrams. The focus here is on θ_0 < 3°C (P>1000dbar), where stratification is weak and the pressure effect dominates thermally-driven dynamic errors. In the case of #60669, the salinity difference (RBR - reference), when using the original linear correction, changes from 0.032 to 0.040 as pressure increases from 1000dbar to 2000dbar. The provisional linear correction reduces the error to 0.009 to -0.006 over the same pressure range. The salinity errors after applying the third order correction lay in the range of ±0.001. In terms of conductivity, the difference is +0.002mS/cm (the temperature error is +0.002°C, which results in virtually no error in salinity), but most critically, the conductivity errors are not correlated with pressure. In the case of #60671, the progression from applying the original 1st-order correction to the provisional 1st-order correction to the third order correction yields similar improvements. However, there is a bias to high salinity in this instrument over the 1000 to 2000dbar range of 0.006 to 0.004, respectively. In this case the small bias comes from conductivity because the temperature measured by the RBR matches the SBE911 to within 0.001°C.





A more detailed and quantitative look at the impact of the various pressure compensation functions can be seen by analyzing histograms of the conductivity difference (RBR*concerto* minus Seabird SBE911). Conductivity is averaged into 20dbar bins, and data shallower than 500dbar are excluded because strong stratification causes dynamic errors that dominate the pressure signal. As with the DFO comparison, the histograms show that the original linear term effectively biased the measurements too high and increased the range of the errors, while in comparison, the provisional linear correction term reduced the bias but retained the scatter. The third order correction reduces both the bias and the scatter: the average conductivity difference for RBR*concertos* #60669 and #60671 is 0.0035mS/cm and 0.0051mS/cm, and one standard deviation of the residuals is 0.0023mS/cm and 0.0023mS/cm, respectively.



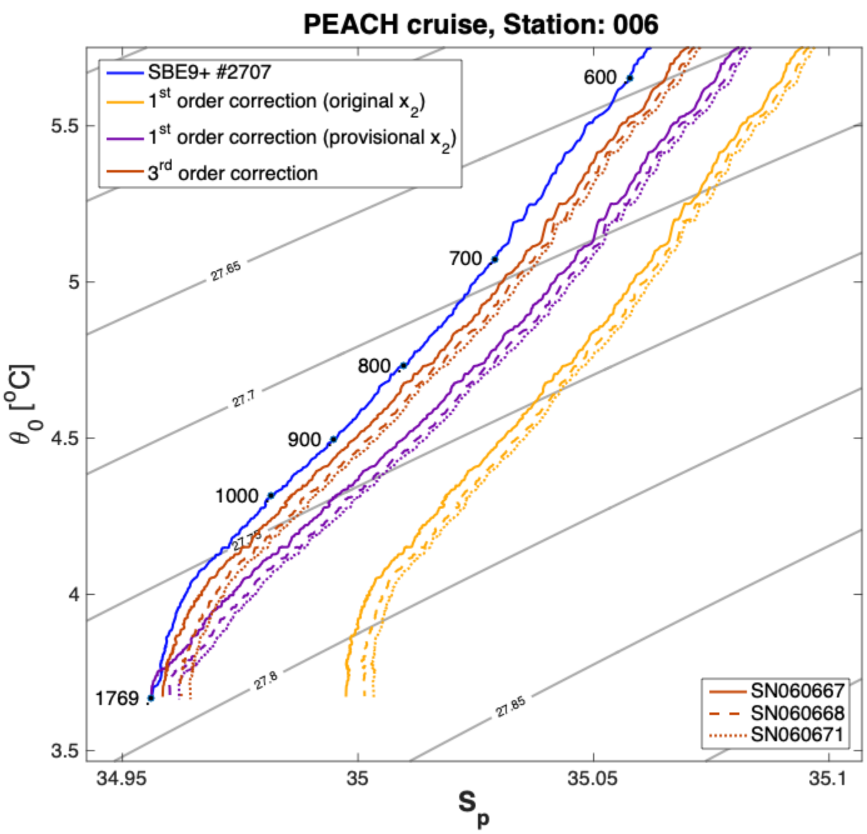


5.5 November 2018 PEACH cruise

In November 2018, three RBR*concerto* 2000dbar CTDs were profiled simultaneously on a rosette during a PEACH III cruise (Processes Driving Exchange at Cape Hatteras) aboard the *R/V Neil Armstrong* in the northwestern Atlantic near the coast of North Carolina at four deep (>1000dbar) stations in the area of CPIES (Current and Pressure recording Inverted Echo Sounders). Each of the three pressure correction factors (original linear, provisional linear, and cubic) were applied to the RBR*concerto* conductivity data, and then compared to the SBE9+ on the rosette. Note that the SBE9+ salinity was not validated against bottle samples.

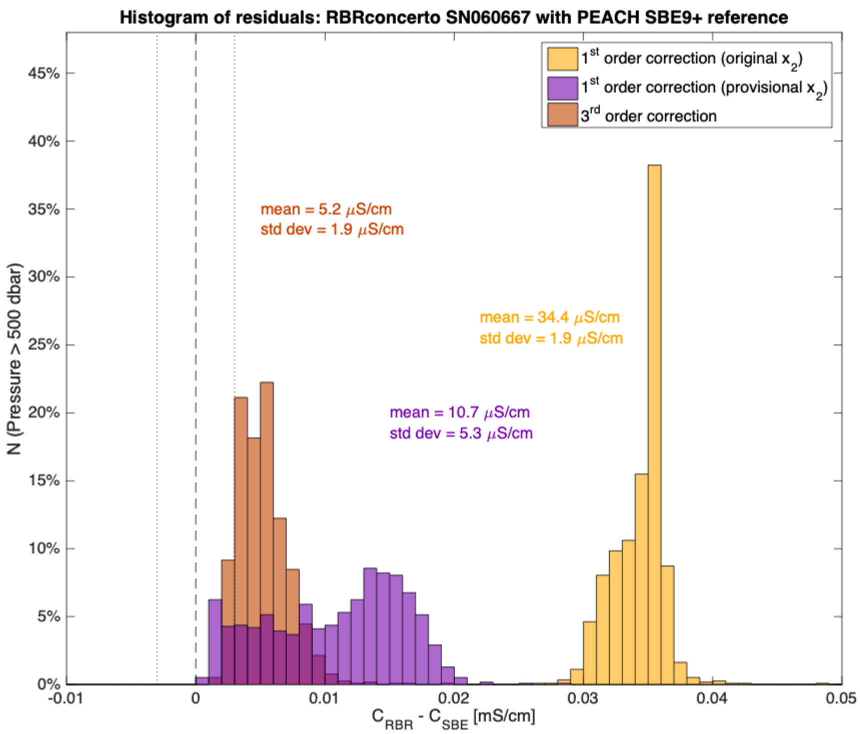
The differences between the corrected conductivities were assessed during downcasts at pressures greater than 600dbar, where stratification was weak, and thermally-driven dynamic errors did not obscure the pressure effect on conductivity measurements.

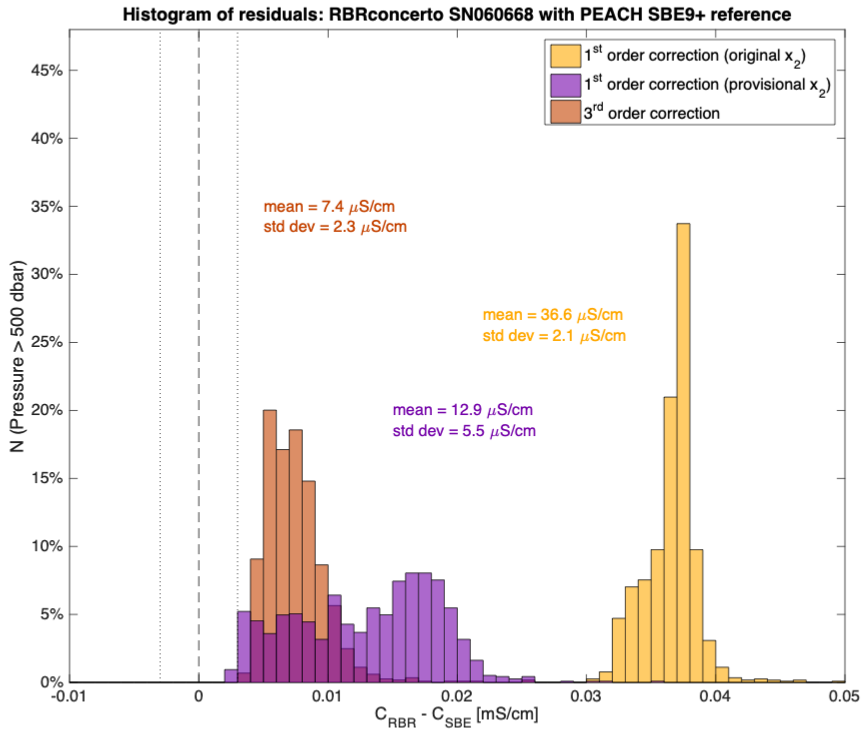
A T/S diagram illustrating the three correction terms for each of the three RBR*concerto* CTDs is plotted below along with the SBE9+ for comparison. The statistics of the comparison were similar at all four stations; for clarity, only the deepest station is shown. As with the DFO and JAMSTEC rosette comparisons, the agreement between the RBR CTDs and the SBE9+ is best when the cubic correction is applied in the conductivity calibration equation. However, this comparison illustrates the close agreement between three identical production RBR CTDs. The instruments agree in salinity to within 0.006; the range of values is caused by differences in both temperature (0.004°C) and conductivity (0.002mS/cm).

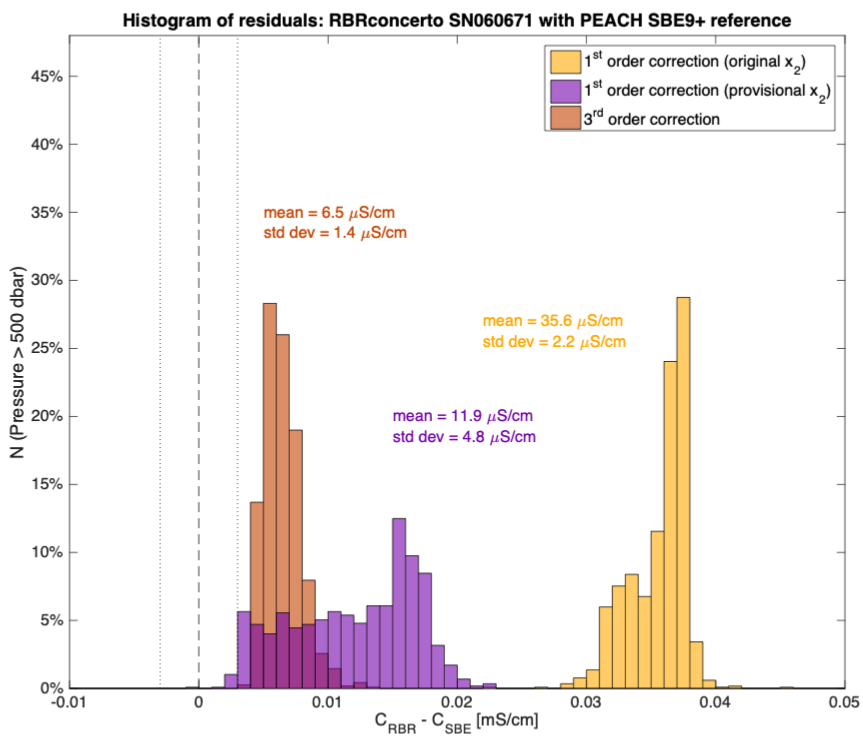


Considering all three RBR*concertos* at each station, the salinity difference (RBR minus SBE9+), when using the original linear correction, ranged from 0.032 (#60667; Station 9; 600dbar) to 0.047 (#60671; Station 6; 1770dbar). The provisional linear correction reduced the difference at 600dbar to 0.018 (#60667; Station 9) – 0.025 (#60671; Station 10) and at maximum depth to 0.0003 (#60667; Station 6; 1770dbar) – 0.017 (#60671; Station 10; 1258dbar). The third order correction reduced the salinity difference at 600dbar to 0.007 (#60667; Station 9) – 0.014 (#60671; Station 9) and at maximum depth to 0.002 (#60667; Station 9; 1167dbar) – 0.009 (#60671; Station 10; 1258dbar).

A more detailed and quantitative look at the impact made by the provisional linear and cubic corrections relative to the original linear correction makes use of histograms of the conductivity difference between the RBR*concertos* and the Seabird SBE9+ at the deepest station. Conductivity was averaged into 1dbar bins. Data at pressures less than 600dbar are excluded. The histograms show that the original linear term effectively biased the measurements as much as 0.034mS/cm (#60667) to 0.037mS/cm (#60668). In comparison, the provisional linear correction term reduced the bias to 0.0107mS/cm (#60667) to 0.0129mS/cm (#60668), but increased the standard deviation. The third order correction reduced both the bias and the scatter: the average conductivity difference was 0.0052mS/cm (#60667) to 0.0074mS/cm (#60668), and one standard deviation of the residuals was from 0.0014mS/cm (#60671) to 0.0023mS/cm (#60668).




Histogram of residuals: RBRconcerto SN060668 with PEACH SBE9+ reference
1st order correction (original x2)
1st order correction (provisional x2)
3rd order correction
mean = 7.4 μS/cm
std dev = 2.3 μS/cm
mean = 36.6 μS/cm
std dev = 2.1 μS/cm
mean = 12.9 μS/cm
std dev = 5.5 μS/cm
N (Pressure > 500 dbar)
C_RBR - C_SBE [mS/cm]


Histogram of residuals: RBRconcerto SN060671 with PEACH SBE9+ reference
1st order correction (original x2)
1st order correction (provisional x2)
3rd order correction
mean = 6.5 μS/cm
std dev = 1.4 μS/cm
mean = 35.6 μS/cm
std dev = 2.2 μS/cm
mean = 11.9 μS/cm
std dev = 4.8 μS/cm
N (Pressure > 500 dbar)
C_RBR - C_SBE [mS/cm]

6 Updating the pressure correction

Changing how conductivity is corrected for hydrostatic pressure on floats that used the original linear coefficient is easy in Matlab or any other suitable tool. The following example uses the Gibbs Seawater Matlab toolbox because on most floats it is necessary to back out conductivity from temperature and salinity.

Matlab script to apply new cubic corrrection

```
% old pressure compensation factor for conductivity
x2_orig = 4e-7;

% new coefficients for non-linear compensation
x2 = 1.8732e-06;
x3 = -7.7689e-10;
x4 = 1.489e-13;

% create an anonymous function to compute the correction. P = sea pressure
fp = @(P) x2.*P + x3.*P.^2 + x4.*P.^3;

% calculate conductivity from salinity, temperature, and sea pressure
conductivity = gsw_C_from_SP(salinity,temperature,seapressure);

% remove previous pressure compensation
conductivity = conductivity.*(1+x2_orig.*seapressure);

% apply new pressure compensation coefficient
conductivity = conductivity./(1+fp(seapressure));

% re-derive salinity
salinity = gsw_SP_from_C(conductivity,temperature,seapressure);
```

7 Impacted RBR*argo* CTD serial numbers

The RBR OEM lookup web service can be used to determine the pressure correction for each RBR*argo* CTD. If the value of the "id" key in "postprocessings" is "PP-0000001", then the conductivity data must be corrected using the new cubic equation (see example below).

Response

Status: success


```
{
  "$schema": "https://oem-lookup.rbr-global.com/schema/v1/instruments#",
  "serialNumber":
  "partNumber": "
  "productName":
  "manufactureDate": "2017-01-10",
  "firmwareType": 103,
  "firmwareVersion": "1.300",
  "postprocessings": [
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      "effectivity": "2017-01-25T20:00:00.000Z",
      "expiry": null
    }
  ],
```


Alternatively, one may consult this ASCII file (RBR P/N 0007457) which lists the serial numbers of every impacted RBR*argo* 2000dbar CTD.

8 Revision History

Date	Revision	Description
2019/08/13	C	Added section: • PEACH cruise rosette comparison
2019/01/30	B	Added sections: • Argo Japan float comparison • JAMSTEC rosette comparison • Impacted RBRargo CTD serial numbers
2018/10/09	A	Initial release.