ANFOG
Australian National Facility for Ocean Gliders
IMOS Integrated Marine Observing System

ANFOG Slocum Oxygen data: new computation

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Contents

1. Introduction

1.1. Purpose of the document

This document presents the work done on oxygen data obtained from ANFOG Slocum gliders, all equipped with 3835 Aanderaa Optodes. It shows the main issues we have observed in oxygen data, and describes how we have improved these data in the new processing, taking advantage of having access to raw parameters outputs from the optodes and temperature measured by the CTD installed on each ANFOG Slocum glider. Unfortunately, the raw parameters from the optodes are only available for datasets where gliders were deployed after mi-2011, which prevent us to improve the oxygen data of datasets anterior to mi-2011.

The work presented here is similar to what is described in (Bishop 2008).

1.2. Aanderaa Optodes: principle

The measurements of oxygen concentration in the sea water using Optodes from Aanderaa manufacturer is described in details in Aanderaa (2007) and summarized for Argo floats in Thierry et al. (2013).

In summary, for the types of Optodes installed on ANFOG Slocum gliders (3835 – 5013W) , the uncalibrated phase measurement (UNCAL_PHASE) is the difference between phase obtained with blue light excitation (BPHASE) and phase obtained with red light excitation (RPHASE) (Figure 1):

UNCAL_PHASE = BPHASE – RPHASE

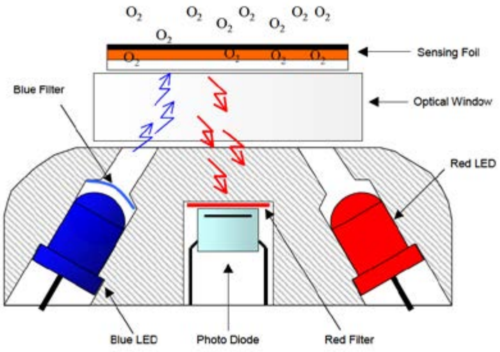


Figure 1. Optode optical design (Figure A4 of Aanderaa (2007)).

In 3835 Optodes, RPHASE is not used and set to zero. Thus:

UNCAL_PHASE= BPHASE

A calibrated phase (DPHASE) is calculated as a 3rd degree polynomial of UNCAL_PHASE (or BPHASE in our case):

$$DPHASE = A + B*BPHASE + C*BPHASE^2 + D*BPHASE^3$$

A, B, C and D are the *PhaseCoef* calibration coefficients, where C and D are usually equal to zero.

DPHASE is then converted to dissolved oxygen concentration in µmol/L, using additional foil-dependant coefficients in a 4th degree polynomial:

$$MOLAR\_DOXY = C_0 + C_1*DPHASE + C_2*DPHASE^2 + C_3*DPHASE^3 + C_4*DPHASE^4$$

where C0, C1, C2, C3, C4 are temperature dependant coefficients calculated as:

$$C_i = C_{i0} + C_{i1}*T + C_{i2}*T^2 + C_{i3}*T^3$$

T is the temperature in °C, and Cij are 20 foil-dependant calibration coefficients. One set of these 20 calibration coefficients is associated with each batch of foils.

Salinity compensation:

The dissolved oxygen concentration must also be corrected for salinity effects. The compensation is estimated as:

$$MOLAR\_DOXY_{SAL\text{-}compensated} = MOLAR\_DOXY * \exp\left[(S_{set}) (B_0 + B_1T_S + B_2{T_S}^2 + B_3{T_S}^3) + C_0*({S_{set}}^2)\right]$$

Where Sset=35 in our case.

2. ANFOG Slocum gliders Oxygen measurements

2.1. Glider configuration

The dissolved oxygen concentration in µmol/L is calculated inside our Slocum gliders, using BPHASE measurements, temperature measurements taken by the Optode, and the calibration coefficients (PhaseCoef and Cij) presented in section 1.2.

Early ANFOG Slocum deployments were performed with the glider configured so that it only outputs the final dissolved oxygen data in µmol/L. However, in May/June 2011 the gliders configuration settings were changed to “wphase” (`sci_oxy3835_wphase_is_installed =1`), allowing outputs of many more parameters. Thus, for deployments performed after mid-2011, we also have access to BPHASE, DPHASE and the Optode temperature measurements. This is of critical importance if one wants to improve oxygen data quality, as it is shown below.

The new processing of Oxygen data presented in section 3 has been performed routinely on recent datasets, since June 2013 (first mission being the February 2013 Pilbara mission, ie ProcID=1028). It is included in all the processing versions ≥ v3.11.

2.2. Issues

Figure 2 shows an example of raw oxygen data, in ml/L (ie µmol/L x 0.0223916).

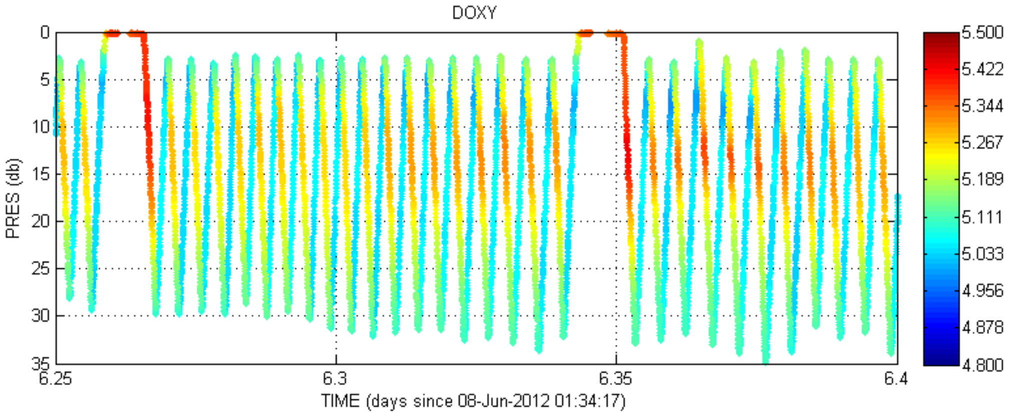


Figure 2. Raw oxygen data (coloured dots) for a sample of the StormBay June 2012 mission, as a function of time since the mission start (days, x axis) and pressure (y axis).

We observe a difference between up and down casts of up to 0.3ml/L, as well as significantly higher values on first dives after the glider has surfaced. These two phenomenons can be partly explained by a problem in the temperature data used to compute the final dissolved oxygen concentration from raw phase measurements. Indeed, we see on the corresponding optode temperature plot (Figure 3) that temperature measurements are not symmetrical on up and down casts either. The manufacturer specifies a time constant for the optode temperature sensor of ~10 seconds, that is not taken into account in the data shown in Figure 3 and that could explain part of the difference between up and down casts.

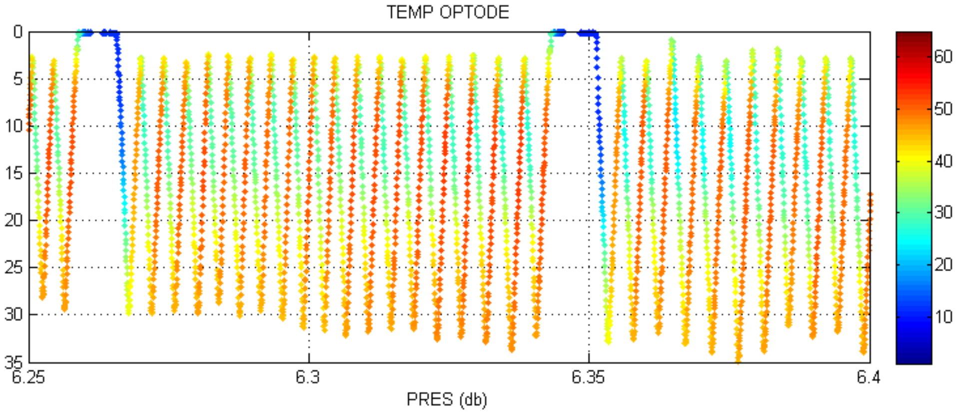


Figure 3. Optode temperature (coloured dots) for a sample of the StormBay June 2012 mission, as a function of time since the mission start (days, x axis) and pressure (db, y axis).

The temperature of the optode for this deployment is compared to the temperature of the CTD also installed on the glider in Figure 4. A difference between temperature of the two different sensors appears clearly, with enhancement when the glider crosses strong temperature gradients. This phenomenon is a known issue of Optodes. The optode temperature is impacted by the fact that the measurement is made inside the instrument; where the foil tends to soften high temperature variations. It is indeed recommended by Aanderaa (Aanderaa (2007)) to use temperature measurements from fast response sensors when available to compensate for temperature effect on Oxygen. This is presented in section 3.

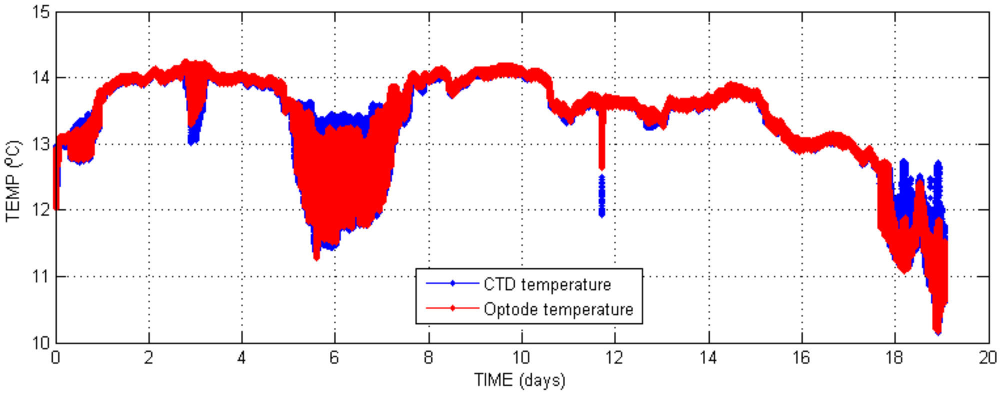


Figure 4. Comparison between temperature measured by the CTD (blue) and measured by the optode (red) for the StormBay June 2012 deployment, as a function of time since the mission start (days).

Another source of problem in dissolved oxygen data is the time response of the phase sensor, of the order of 20s, according to the manufacturer. The omission of this time response can induce a mismatch between the different parameters used to compute oxygen. The effect of this time lag appears clearly in Figure 5, where we see that the bphase data are recorded with a lag, highlighted by a dissymmetry on the profiles.

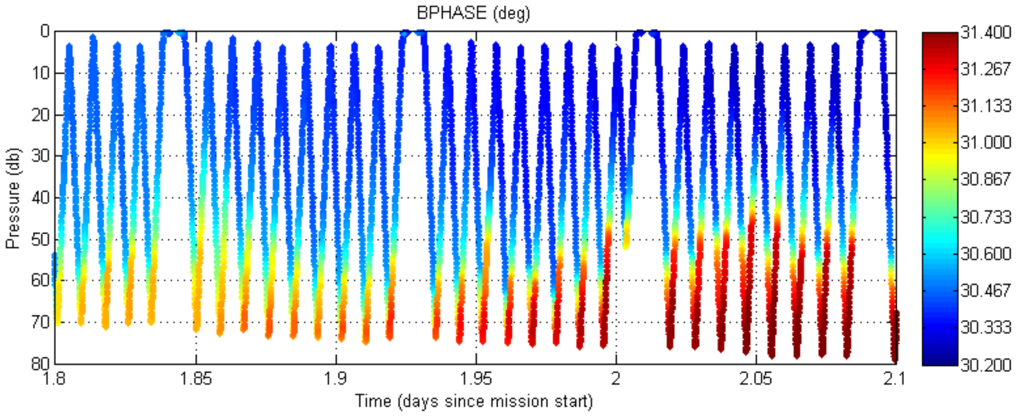


Figure 5. Raw bphase measurements from the July 2012 Kimberley mission (coloured dots, in degrees), as a function of time since the mission start (days, x axis) and pressure (db, y axis).

3. Oxygen data improvement

To improve oxygen data, instead of taking the MOLAR_DOXY data internally computed by the optode, when the glider configuration is set to “wphase” (see above), we now recompute MOLAR_DOXY, using BPHASE measurements, temperature from the CTD, and the calibration coefficients provided by Aanderaa for each sensor. Note that this re-computation can only be performed if the temperature and the BPHASE data are on the same time axis, which is achieved thanks to a linear time interpolation of one of the data on the time axis of the other.

Prior to the re-computation, we apply a correction to BPHASE data, to take into account both the BPHASE sensor time lag response, and the time delay induced by the fact that the optode is located 90 cm apart the CTD, where the temperature and the pressure are measured.

The CTD temperature that we use has already been corrected for short term mismatch with the CTD pressure, used as the reference pressure (the pressure is supposed to be measured with no time lag). So, the first thing we need to do is to align BPHASE data with pressure too.

The distance between the optode and the pressure sensor on the glider is 90 cm (Figure 6). Due to the slow glider speed, this distance induces a non-negligible time difference between when the pressure and the BPHASE measurements are recorded, that needs to be taken into account (section 3.1). Once BPHASE has been geometrically aligned with pressure and temperature, we correct for BPHASE sensor time lag (section 3.2). Finally we combine this corrected BPHASE data with the CTD temperature and the calibration coefficients, to get the final corrected dissolved oxygen data, in µmol/L.

3.1. Geometrical alignment

On Slocum gliders, the optode is installed aft, close to the fin, and the CTD is installed toward the middle of the glider, close to the wings (Figure 6).

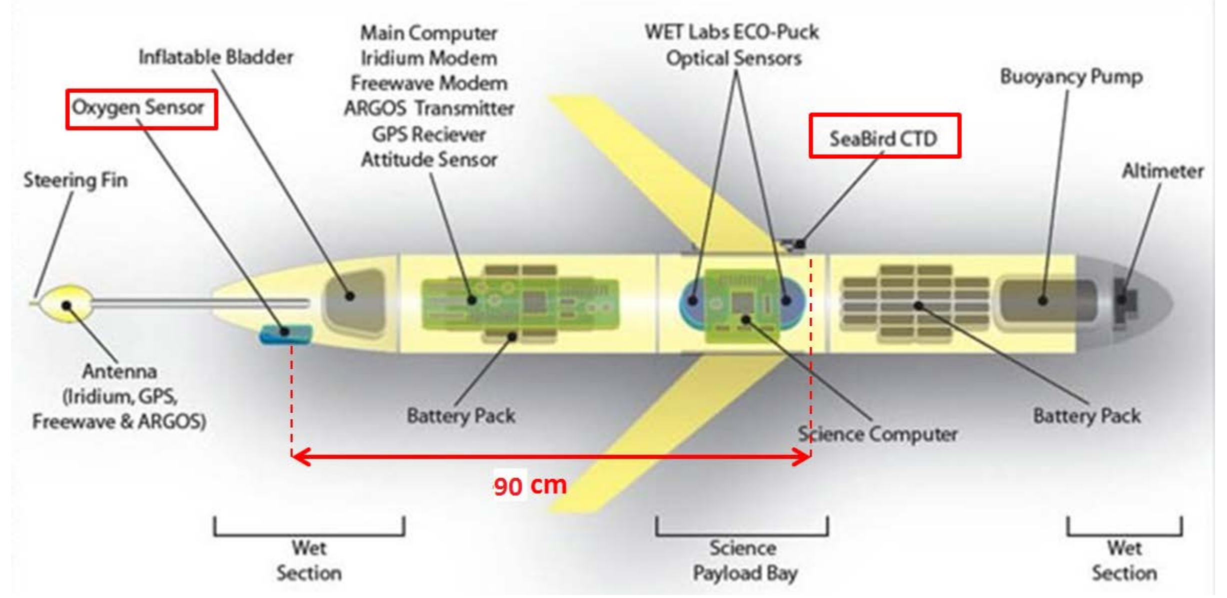


Figure 6. Slocum glider description. The Optode and the CTD have been highlighted in red.

The distance between the two sensors is 90cm, which can be converted in time, depending on the glider's displacement:

$$\tau = \frac{d}{v}$$

Where d is the distance between sensors and v is the glider's velocity, defined as follow:

$$v = \frac{r}{\sin\theta}$$

r is the depth rate, in m/s and θ is the glider pitch (Figure 7).

Finally, we can compute the time delay between oxygen (or BPHASE) and pressure:

$$\tau = \frac{d.\sin(\theta)}{r}$$

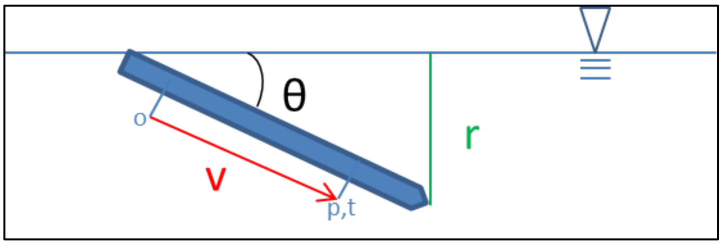


Figure 7. glider displacement diagram (dive). See text for parameters definition. (p,t) stands for pressure & temperature, (o) for oxygen.

With default ideal values for the depth rate and the pitch:

$$\begin{cases} r = 0.1m/s \\ \theta = 26° \end{cases}$$

and with $d = 0.9\ m$,

we get :

$$\tau = 3.9450\ \mathrm{s}$$

However, unfortunately, the glider is usually flying with varying pitch and depth rate. Especially, depending on the ballast, the average pitch (in absolute value) on dives can be significantly different from the average pitch on climbs, which leads to different values of τ on dives and climbs. To account for that, we determine a value of τ for each cast, based on average pitch and depth rate values per cast. The results we get are then filtered along the mission, to avoid extreme values. Figure 8 shows the results of time lag estimation due to the geometrical misalignment for the July 2012 Kimberley mission.

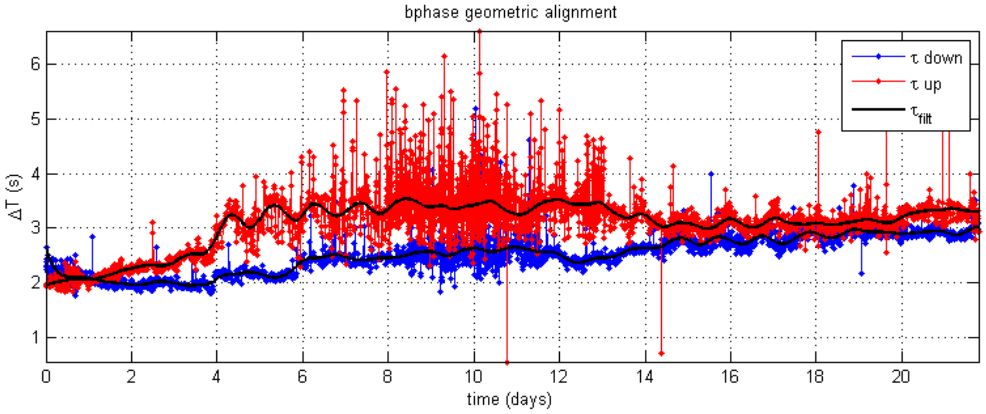


Figure 8. Time lag (in seconds) between BPHASE measurements and pressure measurements as a function of time, for the July 2012 Kimberley mission. The blue curve is for down casts and the red curve for up casts.

Then, we simply apply a linear time shift to the BPHASE data, using the filtered values of τ we got.

3.2. Time lag correction

After the geometrical misalignment has been corrected, we correct BPHASE data for the sensor time response. To do so, we use the same method as for the temperature, presented in Gourcuff (2014): we apply a linear time shift to BPHASE time series data, and compute the median Root Mean Squared (RMS) difference of data on upcasts and downcasts (one value per time shift for one given mission). We test time shift values between 0 and 40 seconds (BPHASE sensor time response is known to be of the order of 20s according to the manufacturer) and look for the time shift that gives the smallest median of the RMS difference between up and down BPHASE data. Figure 9 shows the results of the tests for the July 2012 Kimberley mission, with the minimum RMS obtained for dt = 26 s.

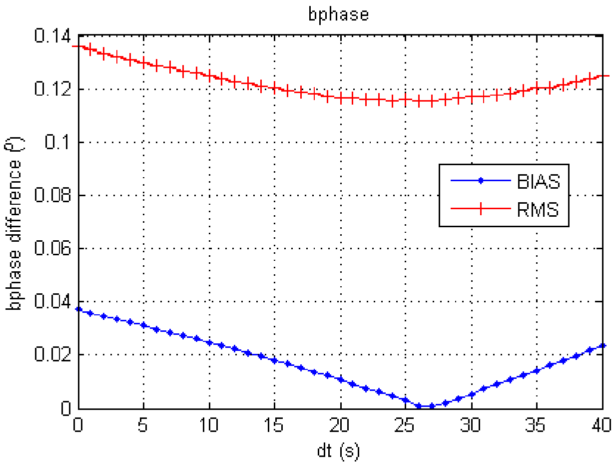


Figure 9. Median Root Mean Squared (RMS, in red) difference and median bias (blue) between up and down bphase data (in degrees) as a function of time shift, for the July 2012 Kimberley mission.

The BPHASE data are then finally linearly shifted by the value obtained, 26 s in the example presented here (Kimberley July 2012 mission).

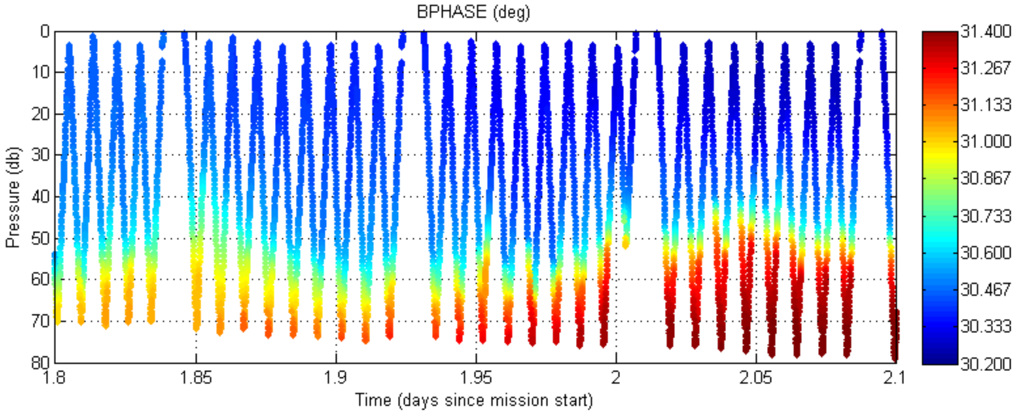


Figure 10. Same as Figure 5 but after bphase has been corrected.

The dissymmetry observed on bphase raw data between upcasts and downcasts (Figure 5) is significantly reduced by the bphase corrections, as it is shown as an example for the July 2012 Kimberley mission (Figure 10).

3.3. Results

Figure 11 shows the impact of the re-computation using the CTD temperature and the corrected BPHASE data for a sample of the June 2012 Storm Bay mission. Although still not perfect (a dissymmetry remains between up and down casts), the improvement of oxygen data quality is obvious on this example.

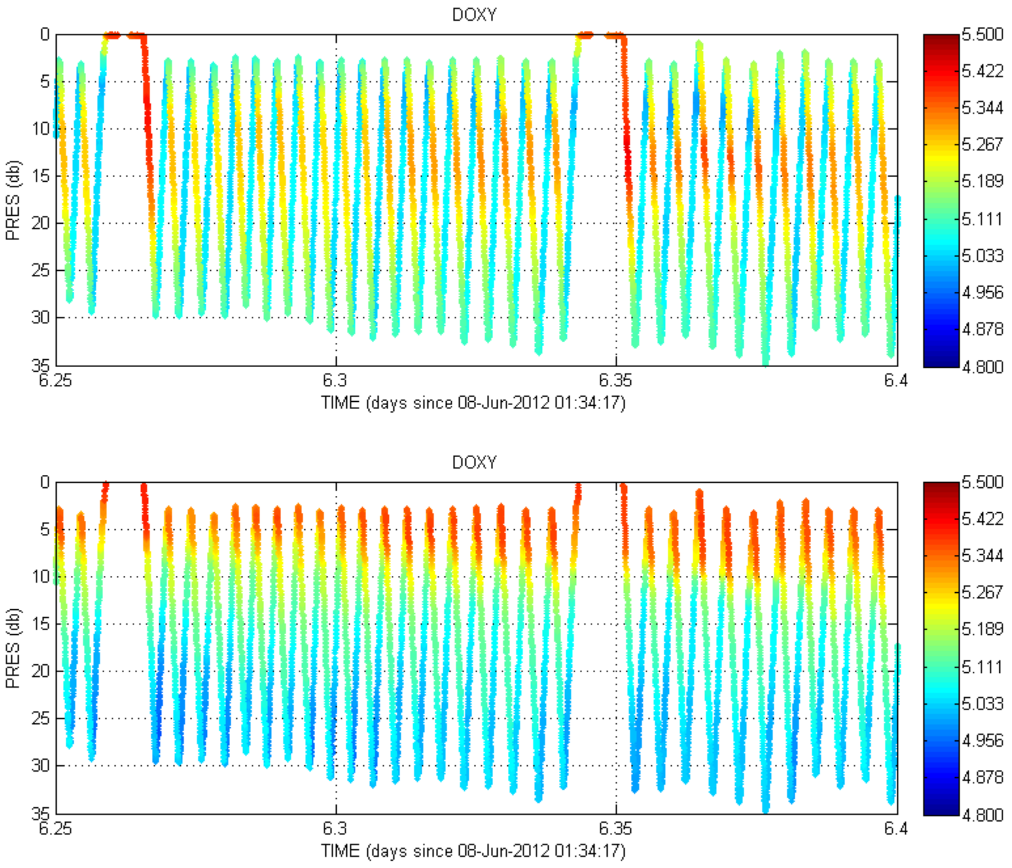
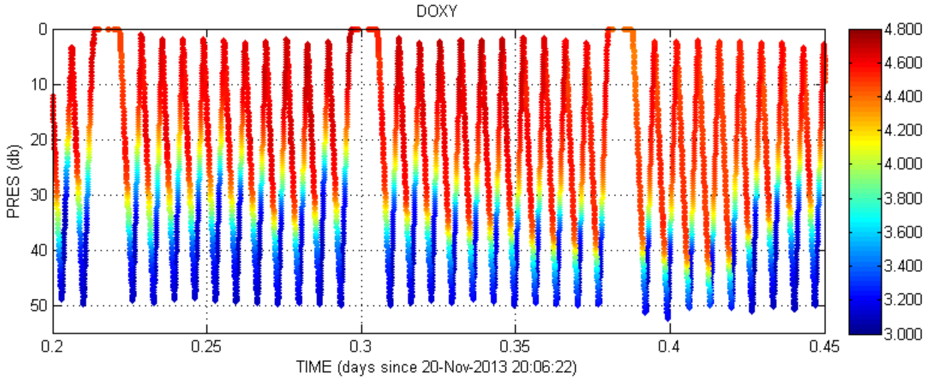


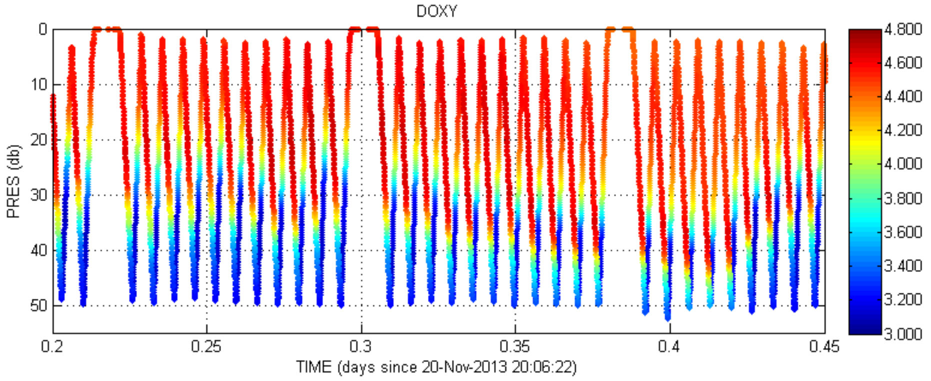
Figure 11. Sample of oxygen data for the June 2012 Storm Bay mission in color (ml/L), as a function of time (days, x axis) and pressure (db, y axis). Top panel: Raw data (same as Figure 2). Bottom panel: Final data, after bphase has been corrected and with oxygen computed using the CTD temperature.

Figure 12 shows another example, for the November 2013 Yamba (NSW) mission. In that case we see the bphase correction (c) has more impact on the global match between up and down casts than the use of CTD temperature instead of the optode temperature (b). However, the use of the optode temperature leads to lower and more realistic values on the first dive after surfacing. The best results are obtained when oxygen is re-computed using both corrected bphase data and temperature data from the CTD (d).

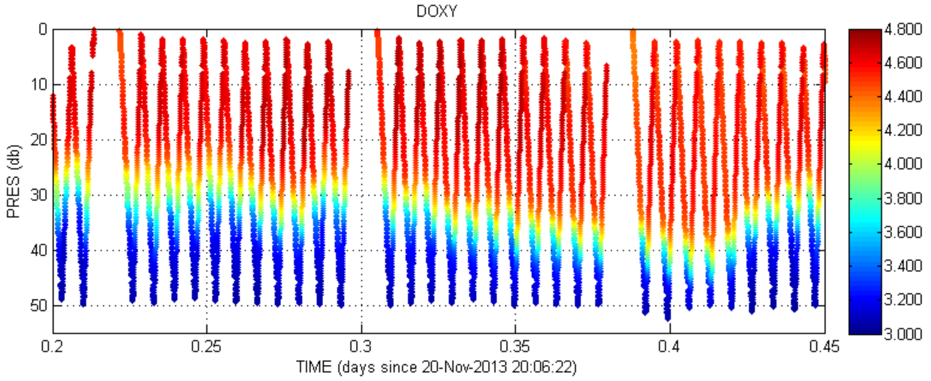
(a) Raw data (internally computed, with raw bphase and optode temperature)



(b) Oxygen recomputed with raw bphase data and CTD temperature data:



(c) Oxygen recomputed with corrected bphase and optode temperature:



(d) Oxygen recomputed with corrected bphase and CTD temperature:

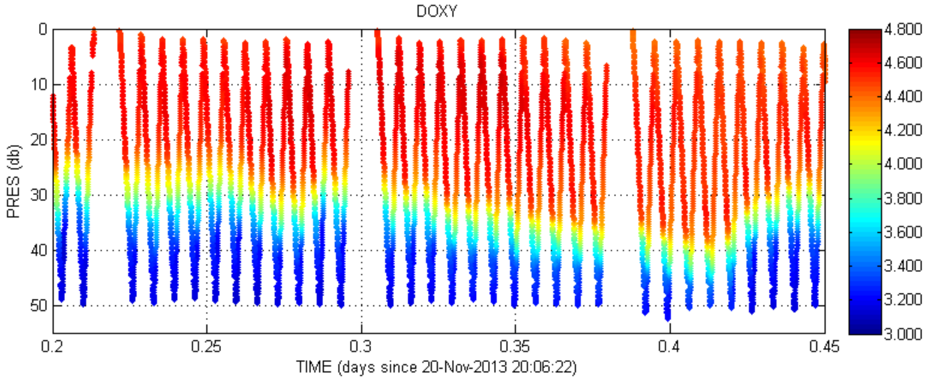


Figure 12. Oxygen data (coloured dots, ml/L) as a function of time ince mission start (days, x axis) and pressure (db, y axis) for the November 2013 Yamba mission.

4. Discussion

The results presented here show a significant improvement of dissolved oxygen data, by simply recomputing dissolved oxygen data with time shifted bphase data and temperature data from the fast response CTD instead of the optode temperature. This applies to optodes calibrated using a 2 point calibration as performed by Anderraa at the moment.

Uchida et al. (2008) propose a new calibration method for optodes based on the Stern-Volmer equation, that is believed to provide more accurate Oxygen data (Craig Neil & Lindsay Macdonald, personal communication). This new calibration has been performed on some optodes installed on the CSIRO Slocum gliders. It would be interesting to recompute dissolved oxygen using these calibration coefficients. Uchida et al. (2008) also evidence a temperature dependence of the optodes time responses. This suggests that our simple linear BPHASE time lag correction might be improved.

The current classical calibration is performed using the optode temperature, thus the calibration coefficients used to re-compute oxygen concentration with the CTD temperature are not the appropriate one. This may have an impact on the results, and it would be recommended, if possible, to try to use CTD temperature for future calibrations.

At the moment, we use a constant value of 35 psu to account for the effect of salinity on oxygen concentration. Although the impact of varying salinity on the final oxygen data is small, it would be more accurate, as our gliders are equipped with CTDs, to use the in situ salinity for the compensation.

A pressure compensation is also recommended that we don't apply on our data. The final oxygen concentration should be multiplied by the following factor:

$$F = 1 + \frac{pcoef * PRES}{1000}$$

with pcoef=0.032 (updated according to the work of Uchida et al. (2008) – was 0.04 before).

This pressure effect is small on shallow water (F=1.0064 for 200db pressure, the maximum pressure of classical Slocum missions), but should not be neglected for deep Slocum missions where the glider achieve pressures of 1000db.

Finally, we have not tried yet to correct the data for the oldest missions, where only the oxygen concentration and oxygen saturation are available. But in the work of Bishop (2008), a method is presented to back-calculate the phase measured by the optode, thanks to the oxygen saturation. This method should allow us to correct oxygen data for all the ANFOG Slocum missions, since 2008.

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