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CARINA oxygen database

I. Stendardo et al.

CARINA-Oxygen: a new high-quality oxygen database for the Atlantic Ocean

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Abstract

In the CARINA project, a new dataset with many previously unpublished hydrographic data from the Atlantic, Arctic and Southern Ocean was assembled and subjected to careful quality control (QC) procedures. In this paper, we present the dissolved oxygen measurements in the Atlantic region of the database and describe in detail the secondary QC procedures that aim to ensure optimal consistency between different cruises in order to permit studies of long-term change. The secondary QC is based on a cross-over analysis, i.e. the comparison of deep ocean data at places that were sampled by different cruises at different times. Initial adjustments to the individual cruises were then determined by an inverse procedure that computes a set of adjustments that requires the minimum amount of adjustment and at the same time reduces the offsets in an optimal manner. The initial adjustments were then reviewed by the CARINA members, and only those that passed the following two criteria were adopted: (i) the region not subject to substantial temporal variability, and (ii) the adjustment must be based on at least three stations from each cruise. No adjustment was recommended for cruises that did not fit these criteria. The final CARINA-Oxygen database has 113005 oxygen samples from 9535 stations obtained during 98 cruises covering three decades. The sampling density of the oxygen data is particularly good in the North Atlantic north of about 40° N especially after 1987. In contrast, the sample density in the South Atlantic is much lower. Some cruises appear to have poor data quality, and were subsequently omitted from the adjusted data base. Of the data included in the adjusted data base, 20% were adjusted with a mean adjustment of 2%.

Data coverage and parameter measured

Repository-Reference: Will be provided from CDIAC soon

Available at: http://cdiac.ornl.gov/oceans/CARINA/Carina_inv.html
Coverage: 60° S–75° N; 80° W–34° E
Location Name: Atlantic Ocean
Date/Time Start: 1977-10-07
Date/Time End: 2006-02-02

For a list of parameters see Key et al. (2009).

1 Introduction

CARINA is a data synthesis project with the aim to assemble a large collection of ocean interior data from hydrographic cruises in the Arctic, Atlantic and Southern Ocean, many of which were previously unavailable to the public (Tanhua et al., 2009a). Because the CARINA database consists of data collected by many different laboratories over several decades and often using different methods, these data need to be carefully quality controlled in order to obtain datasets that are useful for describing the large-scale distribution of properties. In addition, if the goal is to study long-term trends, it is crucial to obtain an internally consistent database, which can only be achieved by applying secondary quality control (QC) procedures to the data (Key et al., 2004; Lamb et al., 2002; Johnson et al., 2001).

While the primary QC consists in the identification of the outliers and errors in the data, the secondary QC consists of the quantification and reduction of the analytical errors in the reported values without the elimination of real temporal changes (Johnson et al., 2001). The goal is to ensure internal consistency. Given the lack of traceable

standards for many oceanographic variables, including oxygen and nutrients, the secondary QC may not result in more accurate values, however. The quality of the data and the offsets are assessed using a crossover analysis whereby property differences between individual cruises on deep-ocean isopycnals are quantified. Such a crossover

5 analysis is based on the assumption that the investigated properties, e.g. oxygen, salinity and nutrients, in the deep waters have not changed in between the individual cruises (Lamb et al., 2002), so that the identified difference is usually attributed to an analytical error. On the basis of the identified offsets, a set of adjustments is inferred that are then applied to the original data in order to obtain an adjusted, internally consistent data set

10 (see e.g. the GLobal Ocean Data Analysis Project (GLODAP) (Key et al., 2004)).

As part of the CARINA project, the primary and secondary QC has been undertaken for the following parameters: salinity (Tanhua et al., 2009a), total inorganic carbon (TCO_2) (Pierot et al., 2009), total alkalinity (TA) (Velo et al., 2009), nitrate, phosphate, silicic acid (Tanhua et al., 2009c), oxygen (this study), CFC-11, CFC-12, CFC-13 and

15 CCl_4 (Steinfeldt et al., 2009). Readers that are interested in the details are invited to read Key et al. (2009) and Tanhua et al. (2009b) in this issue, as they carefully describe the methods developed for the primary and secondary QC and the assemblage of the database.

The aim of this paper is to describe the oxygen data in the CARINA database, to

20 document the quality control procedures applied to the oxygen data, and to justify all the adjustment.

In Sect. 2, we will present the oxygen database, followed by a description of the methods we used to determine the final adjustments. Section 4 discusses how we determined the adjustments, including the cases that needed particular attention. The

25 concluding section outlines the many opportunities that this adjusted data base provides for advancing our understanding of the oceanic oxygen cycle.

2 The database

CARINA consists of a collection of 185 hydrographic cruises or projects, divided into 3 regions, the Atlantic (CARINA-ATL), the Arctic Mediterranean Seas (CARINA-AMS) and the Southern Ocean (CARINA-SO) regions. This paper focuses on the oxygen data from the Atlantic Ocean, which is the region with the highest number of cruises (98 cruises). The CARINA-ATL region has four cruises in common with the CARINA-AMS group and four cruises in common with the CARINA-SO group, in order to ensure consistency also across the three regions.

For the secondary quality control, 6 hydrographic cruises from the World Ocean Circulation Experiment (WOCE) as synthesized by GLODAP (Key et al., 2004) were added to ensure consistency with this prior synthesis effort. However, the data from these reference cruises are not included in the final product. 29 cruises from the CARINA-ATL database were identified as core cruises, primarily on the basis of their having a good spatial distribution and a higher expected data quality. During the computation of the adjustments, more weight was given to these core cruises as well as to the 6 WOCE cruises, ensuring that cruises with lower data quality are not causing unwarranted adjustments in the cruises with higher data quality.

2.1 Oxygen data

The CARINA-ATL database contains a total of 113005 oxygen samples from 9535 stations. A map of the locations of the hydrographic stations with at least one oxygen sample (Fig. 1) shows that CARINA-ATL has a good spatial distribution, with the densest coverage in the northeast Atlantic. The data span three decades, with the earliest samples stemming from 1977 and the latest samples taken in 2006 (Fig. 2). The majority of the data stem from the 1990s, with a reasonably good coverage between about 1990 and 2005. The years 1997, 1998, 2001 and 2003 have the greatest number of samples, largely driven by the fact that these years include basin-wide transects (Fig. 3). Maps of the data from 1977 to 2007 with a time step of 5 years show that from 1992 to 2007

the spatial coverage is good, and particularly in the last five years is dominated by long transects. From 1987 to 1991 the data are especially concentrated in the northeastern part, while from 1977 to 1986 there are only few data stemming from along the Iberian coast and in the Arctic. The only cruise in 1977 (29CS19771007) is one of the Galicia cruises (Galicia4) and has 88 stations with oxygen data only in the upper 1500 m. For this reason, we did not include this cruise in the secondary QC, i.e. no adjustment is recommended (http://cdiac.ornl.gov/oceans/CARINA/Carina_inv.html and table cruise summary from Key et al. (2009)).

In order to provide an overview of the oxygen distribution, we plot in Fig. 4 the oxygen data versus depth for 11 large-scale regions, separating the time periods by color. This plot reveals, for example, that all oxygen data before 1986 are from the upper 2000 m only (green dots in the panel d). The vertical distribution of oxygen in the Atlantic Ocean reflects the combined effects of gas exchange, of the photosynthesis/remineralization cycle, and of ocean circulation. Near the surface ocean, rapid gas exchange keeps oxygen very near the saturation concentration (Sarmiento and Gruber, 2006), despite oxygen production from photosynthesis and oxygen demand by the upwelling/mixing of low oxygen waters from below. In the interior, the oxygen demand from the reminer-alization of the sinking organic matter leads to decreasing oxygen concentrations, but this decrease is modified strongly by the level by which ocean circulation and mixing are able to transport oxygen from the upper ocean into the deep. For example, oxygen rich water penetrates into the deep North Atlantic as a result of the southward spread-ing of recently ventilated North Atlantic Deep Water. This easily identifiable water mass that occupies the depth between 1000 m to 4000 m and extends southward from the Labrador Sea to the Antarctic Divergence (Fig. 4, panel c, e, and g). The Labrador Sea Water (LSW) is also well distinguishable in the Labrador Sea as a huge volume of nearly homogeneous water with high oxygen content. This water mass is a product of winter deep convection (Fig. 4 northwest region, panel a). In the intermediate-depth eastern tropical ocean (Fig. 4 the eastern region in the tropical zones, panel f) it is also possible to identify the horizontal oxygen minimum zone (OMZ).

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3   Methods

Our subgroup was responsible only for the secondary QC of the oxygen data. The method used for the secondary QC is described in detail by Tanhua et al. (2009a). We briefly summarize here this method with emphasis on the issues specific to oxygen.

The first step of the secondary QC consists of a crossover analysis (e.g. Johnson et al., 2001), where the difference is computed between two cruises (defined as an offset) that are crossing each other or, as is often the case in the Atlantic, are along repeated tracks. For the computations of the offsets, only data deeper than 1500 dbar (about 1500 m) were used in order to eliminate from the analysis the upper water column that is more variable in time. For each crossover, stations were selected from an area that was within a radius of 2 degrees of latitude (i.e. about 222 km). The analysis was performed on σ_4 density surfaces, in order to better compare samples in the deep ocean. The oxygen offsets and their standard deviations were computed as multiplicative factors to avoid the potential problem of obtaining negative values in low oxygen regions.

To perform the crossover analysis we used the running cluster routine developed by Tanhua et al. (2009a). In this routine the offset is computed by first comparing each station from the first cruise to each station from the second cruise in the crossing area, and then by computing the weighted mean and standard deviation. Relative to other crossover analysis methods, this running cluster method minimizes the potential for comparing stations that sample different hydrographic settings and also minimizes the need for a manual definition of subregions.

The second step of the secondary QC consists of the computation of an optimal set of adjustments that are then applied to the data in order to generate an internally consistent data set. This is achieved by writing the problem as a system of linear equations that relate the data in each cruise to those in all crossing cruises and then inverting this matrix to find a set of adjustments that minimizes the offsets among all the cruises (Johnson et al., 2001). Three variants of a least square method were

used: the (unweighted) Simple Least Squares (SLSQ) method, the Weighted Least Square (WLSQ) method, and the Weighted Damped Least Square (WDLSQ) method (Johnson et al., 2001; Tanhua et al., 2009a). For the weighted schemes, the inverse of the standard deviation of the offsets were used as weights. In addition, the reference

5 and core cruises were weighted higher than the other cruises in order to ensure a lower level of adjustments in these cruises compared to the others. We use the results from the WDLSQ variant for further processing, but will show that the other variants give rather similar results. As the offsets for oxygen were computed as multiplicative factors, the adjustments were of multiplicative nature as well.

10 The third step of the secondary QC consists of the careful cruise-by-cruise inspection and evaluation of the suggested adjustments. This step was undertaken manually by the CARINA analysts. It was decided that only cruises, for which adjustments larger than 1% difference from 1, i.e. smaller than 0.99 or larger than 1.01 were considered. If in doubt, for example, if there were indications that an apparent offset was driven by

15 true variability, no adjustment is proposed. A detailed discussion for those cruises that required special attention is provided below. The cruises, with an adjustments of less than 1% from 1 are not adjusted, i.e. an adjustment factor of 1 is proposed instead.

As last step, the overall accuracy of the CARINA-ATL oxygen data was computed using the weighted mean (WM) of the absolute values of the offset (D) of L crossovers

20 with their uncertainty (σ).

$$WM = \frac{\sum_{i=1}^{L} D(i)/\sigma(i)^2}{\sum_{i=1}^{L} 1/\sigma(i)^2} \tag{1}$$

This analysis gives an accuracy of 0.8% (Fig. 5). For a typical ocean interior oxygen concentration of 250 μmol kg^{-1}, this translates into an accuracy of 2 μmol kg^{-1}, i.e. the estimated accuracy is about a factor of two larger than the typical precision of dissolved

25 oxygen measurements.

4 Results

The offset analysis computed by the automated cluster routine reveals a large range of multiplicative offsets for oxygen, from less than 0.9 to more than 1.1 (Fig. 6a). However, given the substantial uncertainty in the offsets, 43% of the crossovers are statistically indistinguishable from 1. The smallest offset of 0.89 with a standard deviation of 0.01 exists between the Discovery cruise 74DI19890511 (cruise # 165) and the Meteor cruise 06MT19960910 (cruise # 15). This offset is driven mainly by the first cruise for which an upward adjustment of 1.11 will be proposed (see subsection 4.1.3). Regarding the second cruise (see Table 1) we also propose an adjustment of 0.985. The biggest offset of 1.11 with a standard deviation of 0.01 corresponds to the offset between the C. Darwin cruise 74AB19910501 (cruise # 160) and again the Discovery cruise in 1989 (74DI19890511). The offset is driven again by the Discovery cruise, while the C. Darwin cruise (see Table 1) does not need an adjustment.

After the first round of the inversion, the remaining offsets are much smaller, largely independent of which inversion method is used (Fig. 6b–d). In the case of the SLSQ the offset reduction leads to 77% of all cruise offsets being indistinguishable from 1, while for WLSQ and WDLSQ, this percentage is 73%. The suggested offsets for each cruise computed by the WDLSQ method (shown in black in Fig. 7) generally cluster in between our threshold barriers (0.99 to 1.01), but there are a significant number of cruises that require much larger adjustments. Particularly noteworthy are the following cruises: 74DI19890511 (cruise # 165) with the biggest upward adjustment of 1.11; cruises 74DI19890612 (cruise # 166) and 74DI19890716 (cruise # 167) that require adjustments of 1.07, cruises 74AB19910712 (cruise # 162) and 74AB19900528 (cruise # 159) needing adjustments of 1.06, cruise 29GD19821110 (cruise # 53) that needs an upward adjustment of 1.04, and finally cruise 64TR19900701 (cruise # 155) that needs an adjustment of 1.02 and cruises 64TR19900714 (cruise # 156), and 64TR19910408 (cruise # 157) for which an adjustment of 1.015 is proposed. Regarding the downward adjustments, noteworthy are the cruises 06MT19970107 (cruise # 16) that according

to the WDLSQ inversion needs an adjustment of 0.94, and cruise 06MT19920509 (cruise # 9) that requires a downward adjustment of 0.96. Also relevant are cruises 18HU19941012(cruise # 42), 06MT19960613 (cruise # 14), 18HU19931105 (cruise # 40), 33RO19980123 (cruise # 85), 06MT19990610 (cruise # 20) and 74DI19970807

5 (cruise # 171) that according to the WDLSQ inversion need adjustments of 0.98. Cruise 74DI19970807 is a special case that will be discussed in Subsect. 4.1.9.

The manual editing process started with these results and evaluated for each cruise whether the suggested adjustment was warranted or not. In general, no adjustment was applied if the suggested adjustment was within the 1% threshold barriers, while

10 the WDLSQ suggested adjustment was adopted in the other cases. Special cases are discussed below.

The distribution of the offsets after the manually edited adjustment have been applied is shown in Fig. 6e. The adjustments substantially reduced the number of crossovers that are statistically different from 1, i.e. from 57% to 35%, but it did not reduce it

15 down to zero. This is due to two factors: First, the 1% threshold was used even in cases where the recommended adjustment was significantly different from zero; second, some cruises were not adjusted despite them having substantial offsets, for reasons discussed below.

To check the results, we re-computed the adjustments using the already adjusted

20 cruise data. As shown by the red symbols in Fig. 7, the vast majority of the recommended adjustments are now indeed within the threshold barriers. Only few cruises are outside. These are the cruises that have been carefully evaluated, and were agreed to not apply any adjustment for reasons that we are going to explain in the following subsections.

25 **4.1 Discussion of special cases**

In this section we discuss the cruises that during our evaluation needed some special considerations. We provide here only the summary statements. More details, such as figures from each crossover as well as more detailed comments about each cruise can

be found at http://cdiac.ornl.gov/oceans/CARINA/Carina_inv.html.

The cruises are identified with an expocode that contains the country information, ship information, and the date of when the ship left the port.

4.1.1 cruise 74AB19900528 cruise # 159

This cruise took place in the eastern part of the Atlantic Ridge from 28 May to 15 June 1990, covering a small area with 71 stations. Only 3 stations have oxygen data and only 1 station has samples from depths greater than 500 m. Although the inversion suggested a substantial adjustment of 1.06 (see Table 1), this result is insufficient to warrant action as it is based on a single station. We agreed to label the cruise as NC (no suggestion of adjustment possible) in the on-line table and to flag this cruise for oxygen because of the uncertainty about the quality of the data.

4.1.2 cruise 29CS19930510 cruise # 52

This cruise took place from 10 May to 1 June 1993, covering 92 stations located on the western coast of Iberian Peninsula. The WDLSQ inversion suggested a downward adjustment of 0.982 (see Fig. 7). Because of the coastal location of the cruise with less than an half of the stations deeper than 1500 m, and because the crossovers did not reveal clear offsets, especially those with the core cruises, we recommend no adjustment for this cruise.

4.1.3 cruise 74DI19890511 cruise # 165

This cruise (from 11 May to 7 June 1989) has 990 stations along a section from 46° N to 60° N on 20° W; along another section from 23° W and 59° N to 8° W and 56° N, and a station group centered on 23° W and 59° N. Almost all data are from the top 250 m. Only 5 stations have oxygen data deeper than 1500 m, and for those stations the inversion gave an adjustment of 1.11. This is outside the range in order for these data to be

considered to be good enough to be included in the database. For that reason we agreed to flag the entire cruise for oxygen because of the poor quality of the data.

4.1.4 cruise 74DI19890612 cruise # 166

This cruise (from 12 June to 9 July 1989) took place in the area 46°–60° N and 10°–22° W and has 87 stations, but only 3 stations have deep oxygen data. As was the case with the previous Discovery cruise (74DI19890511), we agreed to flag the oxygen data from the entire cruise because of the lack of sufficient deep data and too high offsets.

4.1.5 cruise 74DI19890716 cruise # 167

This cruise (from 16 June to 10 August 1989) has 34 stations with 17 of them containing deep oxygen data that can be compared with other cruises in the same area. Also for this Discovery cruise the inversion suggested a substantial upward adjustment, i.e. 1.07 (Table 1). The vertical O_2 profiles reveal a lot of scatter in the data. Taking into account the large suggested adjustment and in order to be consistent with the decisions regarding the previous Discovery cruises (see Subsects. 4.1.3 and 4.1.4), we decided to flag the oxygen data as questionable.

4.1.6 cruise 29GD19840218 cruise # 55

This cruise (18 February to 7 March 1984) is one of the Galicia cruises (Galicia 7) that took place in the northwestern part of the Iberian Peninsula. It has 33 stations but none of them have oxygen data from deeper than about 2000 m. Although the inversion WDLSQ suggested a downward adjustment of about 0.98 (see Table 1 and Fig. 7), we agreed that no adjustment was warranted. The main arguments were (i) the lack of deep oxygen data, and (ii) the lack of clear offsets to other cruises.

4.1.7 cruises 06MT19920316, 06MT19920509 and 06MT19920701 cruises # 8, 9 and 10

Originally those three cruises were considered as a single cruise 06MT19920322. But differing offsets (especially those for salinity) made it clear that this cruise needs to split into three single cruises. For oxygen, only the 06MT19920509 has stations with enough oxygen data to compute the offsets to the other cruise of the database, while cruises 06MT19920316 and 06MT19920701 do not have oxygen measurements. The cruise 06MT19920509, as shown by the solution from the inversion WDLSQ (Fig. 7), needs a conspicuous upward adjustment of 0.96 that we applied at the final product.

4.1.8 cruise 74AB20050501 cruise # 164

This cruise is an Atlantic zonal section at 36° N. It has 144 full depth stations. The inversion suggests a downward adjustment of 0.99. However, the crossovers with core cruises reveals that the oxygen data from this cruise are higher only in the western part of the transect, while no offsets are evident in the eastern part. We checked the cruise report and we saw that the first 43 stations had a calibration problem. Based on this evidence we agreed to split the cruise into two parts: A first part from station 1 to 43, for which we recommend an adjustment of 0.94 in agreement with the crossover offsets with the two core cruises 316N19970815 and 316N20031013; and a second part from station 44 to the 144, which does not require an adjustment as evidenced by its high consistency with the core cruise 33RO20030604.

4.1.9 cruise 74DI19970807 cruise # 171

This cruise that took place from 7 August to 17 September 1997 was identified as a core cruise. It has 143 stations along 4 different sections: a long section from 60° N and 43° W (south coast of Greenland) to 40° N and 9° W (western coast of Iberian Peninsula), a section from 63° N and 20° W (south of Iceland) to 57° N and 8° W crossing

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the Iceland Basin and the Rockall Plateau, a short section of 9 stations from 63° N and 41° W to 61.4° N and 35.7° W in the Irminger Sea, and a group of 8 stations in the northern part of the Irminger Sea at around 65° N from 27 to 30° W. According to the WDLSQ inversion, this cruise needs an adjustment of 0.98, but the crossovers with other core

5 cruises do not confirm that an adjustment is appropriated. Moreover, considering that this cruise has 4 different transect, one of which is just south the Iceland that is one of the area in the Atlantic Ocean with higher temporal variabiliy, we recommend to do not adjust this cruise.

5   Summary and conclusions

10 Based on the secondary quality control of the CARINA-Oxygen data base, we recommend adjustments for 23 out of the 98 cruises. Most adjustments were between 1% and 2% (up- or downward) with only 5 cruises needing an adjustment larger than 2%. In addition, we regard the data from 4 cruises as of insufficient quality for climate-type studies, and therefore recommend these data to be flagged. However, this affects only

15 2002 datapoints out of the 113005 oxygen samples in the CARINA-Oxygen database. We also suggest an adjustment for a reference cruise (317519930704) that will not appear in the final product.

The quality controlled oxygen data in the CARINA-Oxygen data will constitute a rich source of information to exploit the impact of climate variability and change on the

20 ocean's oxygen cycle and to extend the analyses conducted so far in the Atlantic (e.g. Johnson et al., 2005; Johnson and Gruber, 2007). Oxygen is one of the best tracers to detect changes in biological and physical processes in the ocean's interior (Plattner et al., 2002; Deutsch et al., 2005; Körtzinger et al., 2006), because of its high signal-to-noise ratio. Its signal is particularly large because the physical and biological

25 processes driving oxygen variability tend to enhance each other (Gruber et al., 2001), which is different from dissolved inorganic carbon, for which most processes tend to lead to opposing effects (Gruber and Sarmiento, 2002). As a result, one expects sub-

stantial decreases in the ocean's oxygen content in the future, since ocean warming and increased stratification will reduce the ocean's holding capacity for oxygen and the replenishment of the interior ocean with oxygen from the near surface (Matear et al., 2000; Plattner et al., 2002; Bopp et al., 2002; Keeling et al., 2009). This may be aggravated by ocean acidification, which will lead to reduced production of mineral $CaCO_3$ and hence less ballasting, causing the exported organic matter to remineralize at shallower depth. As a consequence, the thermocline regions with already low oxygen may substantially expand (Oschlies et al., 2008; Hoffmann and Schellnhuber, 2009). Such expansions of the oxygen minimum zones have been observed (Stramma et al., 2008), although it is presently unclear whether this is already a consequence of climate change.

The sparsity of the hydrographic observations of O_2 makes estimates of inventory changes difficult (Hamme and Keeling, 2008). Considering that the analysis of some historical O_2 data measured during the latter decades of the 20th century has already revealed large-scale in subsurface O_2 concentration in different basins of the global ocean (Johnson and Gruber, 2007; Emerson et al., 2001; Bindoff and McDougall, 2000), the necessity to have a database like CARINA with a good temporal and spatial coverage is becoming increasingly relevant. Furthermore, the possibility to combine the CARINA oxygen data with the quality controlled carbon data from the CARINA-carbon database (Steinfeldt et al., 2009; Tanhua et al., 2009a,c; Velo et al., 2009) and with other tracers, provides ample opportunity to make a substantial step forward in our ability to describe the recent changes in ocean biogeochemistry.

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CARINA oxygen database

I. Stendardo et al.

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Table 1. Table of adjustments estimated from WDLSQ method. The column # shows the cruise number in the final product. The columns "Core" and "Ref" identify the core and references cruises (marked as x). The inversion method adjustment column refers to the results from the WDLSQ inversion with the corresponding mean and standard deviation in the sub-colums. The recommendation column represents the adjustment proposed on the base of the crossover analysis and inversions, the cruises in common with the two other group are labeled as ATL+AMS and ATL+SO. The reference cruises are included in the table and marked with stars in the # column although they will not be included in the final CARINA product. The cruises where it was not possible to compute the adjustment are labeled as NC (Not considered), the cruises where it was not possible to suggest an adjustment because of few or no data are labeled as ND. The cruises that belong the CARINA-AMS group are label as AMS. The last two columns are the references for the oxygen samples and the chief scientists of the cruises.

#	expocode	Core	Ref	inversion method adjustment		recommend adjustment	O_2 analyst/ institute	Chief Scientist
				mean	standard deviation			
5	06BE20001128	0	0	ND	ND	**ND**	Not available	M. Rhein
6	06GA19960613	0	0	ND	ND	**ND**	Not available	A. Sy
7	06GA20000506	x	0	0.99	0	**0.99**	H. Johannsen	P. Kolterman
8	06MT19920316[a]	0	0	ND	ND	**ND**	Not available	H. Thiel
9	06MT19920509[a]	0	0	0.96	0	**0.96**	T. Korner	J. Duinker
10	06MT19920701[a]	0	0	ND	ND	**ND** (ATL+AMS)	Not available	G. Graf, O. Pfannkuche
11	06MT19940219	0	0	1	0	**1**	L. Stramma	F. Schott
12	06MT19941012	0	0	1	0	**1**	L. Stramma	Koltermann
13	06MT19941115	x	0	1	0	**1**	J. Duinker, L. Mintrop	J. Meincke
14	06MT19960613	0	0	0.98	0	**0.98**	L. Mintrop	Kremling
15	06MT19960910	0	0	0.99	0	**0.985**	Lendt	C. Hemleben

[a] The original cruise 06MT19920322 was several legs, so we decided to split the cruise in 3 different cruises: 06MT19920316, 06MT19920509 and 06MT19920701.

[b] Recommended by the AMS group.

[c] Added in the later stage of the project, because few samples deeper that 1500 m, the minimum depth for the crossovers was set manually at 1000 m.

[d] No deep data for the stations in the North Atlantic. Recommended by the AMS group.

[e] No deep data, so not included in the 2nd level QC.

[f] The first number refers to the adjustment recommended only from stations 1 to 43, the second number refers to no adjustment from station 44 to last.

Table 1. Continued.

#	expocode	Core	Ref	inversion method adjustment mean	standard deviation	recommend adjustment	O_2 analyst/ institute	Chief Scientist
16	06MT19970107	0	0	0.94	0.01	**0.95**	O. Llinas	T. Muller
17	06MT19970515	x	0	0.99	0	**0.99**	Not available	W. Zenk
18	06MT19970707	x	0	0.99	0	**1**	Not available	F. Schott
19	06MT19970815	x	0	0.99	0	**1**	BSH	A. Sy
20	06MT19990610	0	0	0.99	0	**0.99**	Not available	W. Zenk
21	06MT19990711	0	0	0.99	0	**0.99**	Not available	F. Schott
22	06MT19990813	0	0	ND	ND	**ND**	Not available	J. Meincke
23	06MT20010507	0	0	0.99	0	**0.99**	L. Stramma	J. Fischer
24	06MT20010620	0	0	ND	ND	**ND**	Not available	J. Holfort
25	06MT20010717	0	0	1	0	**1**	Not available	W. Zenk
26	06MT20011018	0	0	ND	ND	**ND**	N. Kress	W. Roether
27	06MT20020607	0	0	0.99	0	**0.99**	Not available	M. Rhein
28	06MT20021013	0	0	1.01	0.01	**NC**	F. Malien	D. Wallace
29	06MT20030626	0	0	ND	ND	**ND**	Not available	J. Mortensen
30	06MT20030723	x	0	1	0	**1**	F. Malien	M. Rhein
31	06MT20030831	0	0	ND	ND	**ND**	Not available	J. Fischer
32	06MT20040311	x	0	1	0	**1**	F. Malien	D. Wallace
37	18HU19920527	0	0	1	0.01	**1**	Not available	J. Lazier
38	18HU19930405	0	0	NC	NC	**NC**	Not available	N. Oakey
39	18HU19930617	x	0	1.01	0	**1**	Not available	J. Lazier
40	18HU19931105	0	0	0.98	0	**0.98**	Not available	R. A. Clarke
41	18HU19940524	0	0	0.99	0	**0.99**	Not available	J. Lazier
42	18HU19941012	0	0	0.98	0	**0.98**	Not available	R. A. Clarke
43	18HU19950419	0	0	1	0	**1**	P. Clement	R. A. Clarke

Table 1. Continued.

#	expocode	Core	Ref	inversion method adjustment		recommend adjustment	O_2 analyst/ institute	Chief Scientist
				mean	standard deviation			
44	18HU19970509	x	0	1	0	**1**	P. Strain/J. Lazier	R. A. Clarke
51	29CS19771007	0	0	NC	NC	**NC**	Not available	F. Fraga
52	29CS19930510	0	0	0.99	0	**1**	A. Alvarez/ G. Roson	J. M. Cabanas
53	29GD19821110	0	0	1.04	0.01	**1.04**	Not available	F. Fraga
54	29GD19831201	0	0	NC	NC	**NC**	Not available	F. Fraga
55	29GD19840218	0	0	0.99	0.01	**1**	Not available	F. Fraga
56	29GD19840711	0	0	0.99	0	**0.98**	Not available	F. Fraga
57	29GD19860904	0	0	1	0	**1**	Not available	F. Fraga
60	29HE19980730	0	0	1.01	0.01	**1**	E.D. de Armas	F.F. Perez
61	29HE20010305	0	0	0.99	0.01	**0.99** (ATL+SO)	E.D. de Armas	A. Rios
62	29HE20020304	x	0	1	0.01	**1** (ATL+SO)	C. Castro	F.F. Perez
63	29HE20030408	0	0	0.99	0	**1**	C. Castro	A. Rios
64	31AN19890420	0	0	1	0	**1**	Not available	P. Brewer??
65	316N19971005	0	0	1.01	0	**1**	G. Knapp	R. Curry
66	316N20010627	0	0	ND	ND	**ND**	Not available	D. Capone, E. Carpenter
68	316N20030922	x	0	1.01	0	**1**	ODF	J. Toole, A. MacDonald
69	316N20031023	x	0	1.01	0	**1**	ODF	T. Joyce, W. Smethie
71	32EV19910328	0	0	1	0	**1**	Not available	R. Pickart
81	32OC19950529	0	0	1.01	0	**1**	Not available	R. Pickart
84	33LK19960415	0	0	1.01	0.01	**1**	C. Oudot	Y. Gouriou

Table 1. Continued.

#	expocode	Core	Ref	inversion method adjustment		recommend adjustment	O_2 analyst/ institute	Chief Scientist
				mean	standard deviation			
85	33RO19980123	x	0	0.98	0	**0.99**	C. Mordy	D. Bitterman, K. Lee
86	33RO20030604	x	0	1	0	**1**	C. Mordy, G. Johnson	J. Bullister, N. Gruber
87	33RO20050111	x	0	1.01	0	**1** (ATL+SO)	AOML/ U.Miami	R. Wanninkhof, S. Doney
89	33SW20010102	0	0	NC	NC	**NC**	Not available	A. Michaels/ D. Capone
90	33SW20030418	0	0	ND	ND	**ND**	Not available	D. Capone/ A. Subramaniam
91	34AR19970805	0	0	1	0	**NC**[b] (ATL+AMS)	T. Tanhua	H. Gronvall/ J. Launiainen
92	35A320010203	0	0	1	0.01	**1**	Not available	L. Prieur
93	35A320010322[c]	0	0	1.01	0	**1**	Not available	M. Bianchi
94	35LU19890509	0	0	0.99	0	**1**	F. Fraga	Not available
95	35LU19950909	0	0	1	0.01	**1**	P. Fournier, C. Oudot	Y. Gouriou
106	35TH19990712	0	0	1	0	**1**	Y. Gouriou	Y. Gouriou
107	35TH20010823[c]	0	0	1.01	0.01	**1**	Not available	J.C. Gascard
108	35TH20020611	x	0	1	0	**1**	P. Morin	H. Mercier
109	35TH20040604	x	0	1.01	0	**1**	P. Morin	T. Huck

Table 1. Continued.

#	expocode	Core	Ref	inversion method adjustment		recommend adjustment	O_2 analyst/ institute	Chief Scientist
				mean	standard deviation			
113	49NZ20031106	x	0	1	0	**1** (ATL+SO)	M. Aoyama, S. Watanabe	Y. Yoshikawa
125	58AA20010527	0	0	NC	NC	**1**[d] (ATL+AMS)	E. Falck	T. Johannessen
130	58JH19920712	0	0	1.01	0	**NC**[b] (ATL+AMS)	E. Falck	J. Blindheim, E. Buch
135	58JH19940723	0	0	1.01	0	**NC**[b] (ATL+AMS)	E. Falck	J. Blindheim
151	64PE19960618	0	0	1.01	0	**1**	P. Berkhout, M. Manuels	H.M. van Aken
152	64PE20000926	0	0	1.01	0	**1.01**	K. Bakker, D. Volkov	H.M. van Aken
153	64TR19890731	0	0	1	0	**1**	Not available	H. DeBaar
154	64TR19900417	0	0	1.01	0	**1**	I. Flameling, R. deVries, K. Bakker	H.G. Fransz
155	64TR19900701	x	0	1.03	0	**1.02**	M. Manuels, K. Bakker	H.M. van Aken
156	64TR19900714	0	0	1.02	0	**1.015**	M. Manuels, K. Bakker	H.M. van Aken
157	64TR19910408	x	0	1.01	0	**1.015**	H.M. van Aken	H.M. van Aken
158	67SL19881117	0	0	NC	NC	**NC**[e]	Not available	A. Rios

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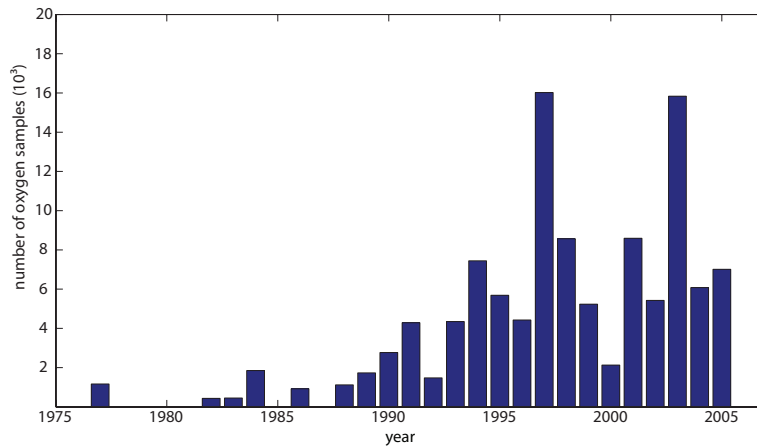Printer-friendly Version

Interactive Discussion

Table 1. Continued.

#	expocode	Core	Ref	inversion method adjustment		recommend adjustment	O$_2$ analyst/ institute	Chief Scientist
				mean	standard deviation			
159	74AB19900528	0	0	1.06	0.01	**flag**	Not available	Not available
160	74AB19910501	0	0	1	0	**1**	S. Hartman, R.Paylor	R. Pollard
161	74AB19910614	0	0	NC	NC	**NC**[e]	Not available	Not available
162	74AB19910712	0	0	1.06	0	**1.07**	Not available	Not available
164	74AB20050501	0	0	0.99	0	**0.94–1**[f]	S. Torres Valdes, T. Lesworth, R. Mather	E. McDonagh
165	74DI19890511	0	0	1.11	0	**flag**	Not available	Not available
166	74DI19890612	0	0	1.07	0	**flag**	Not available	Not available
167	74DI19890716	0	0	1.07	0	**flag**	Not available	Not available
168	74DI19900425	0	0	NC	NC	**NC**[e]	Not available	Not available
169	74DI19900515	0	0	ND	ND	**ND**	Not available	Not available
170	74DI19900612	0	0	ND	ND	**ND**	Not available	Not available
171	74DI19970807	x	0	0.98	0	**1**	S. Holley	S. Bacon
172	74DI19980423	x	0	1	0	**1**	Not available	D. S.-Wright
173	74DI20040404	x	0	1	0	**1**	R. Sanders	S. Cunningham
185	Irminger Sea T.S	0	0	NC	NC	**NC**	Not available	J. Olafsson

Table 1. Continued.

#	expocode	Core	Ref	inversion method adjustment		recommend adjustment	O$_2$ analyst/ institute	Chief Scientist
				mean	standard deviation			
187	OMEX1NA	0	0	1	0.01	**1**	Various	Various
188	OMEX2	0	0	1	0	**1**	Various	Various
*	29HE19920714	x	x	1	0	**1**	A. Cruzado	G. Parrilla
*	323019940104	x	x	1	0	**1** (ATL+SO)	X. A.-Salgado, D. Schuller	L. Mémery
*	316N19961102	x	x	1	0	**1**	Not available	K. Johnson
*	316N19970717	x	x	1	0	**1**	J. Jennings/ B. Sullivan	B. Pickart
*	316N19970815	x	x	1.01	0	**1**	A.A. Ross/ J. Arrington	T.M. Joyce
*	317519930704	x	x	1.02	0	**1.02**	Not available	R. Wanninkhof

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Interactive Discussion

CARINA oxygen data in the Atlantic Ocean
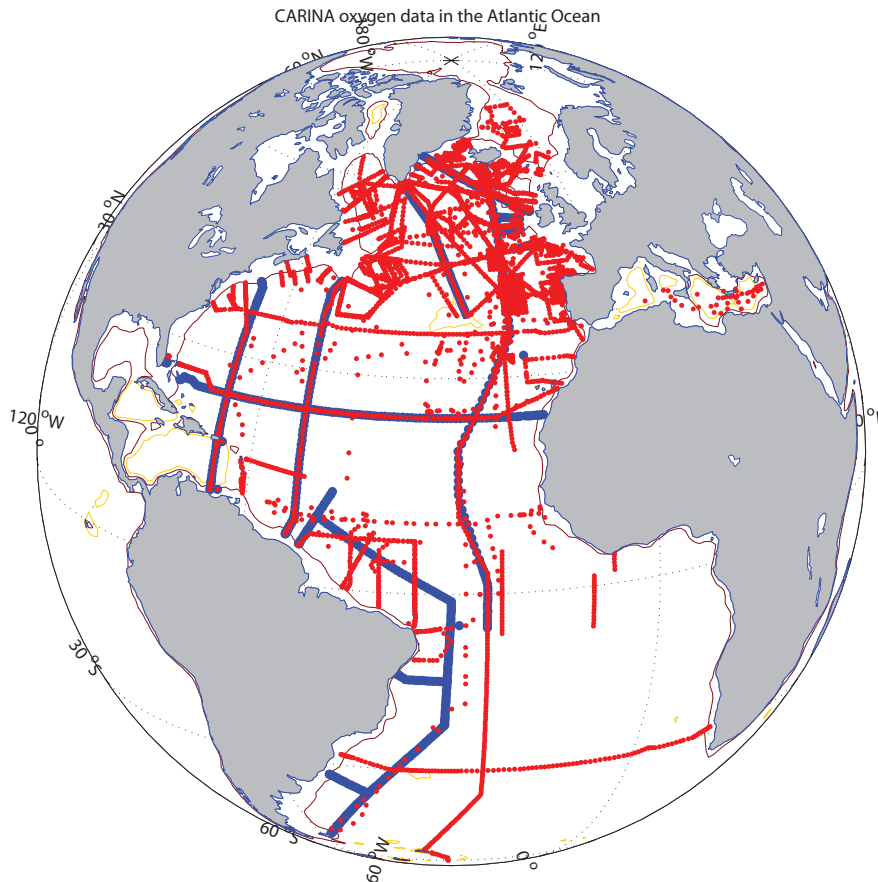
Fig. 1. Map of the CARINA database of the Atlantic region (CARINA-ATL), with the station positions of cruises with oxygen data. In red are the stations from the final CARINA-ATL database, in blue are the stations of the reference cruises.

Fig. 2. Number of samples for oxygen by year in CARINA-ATL.
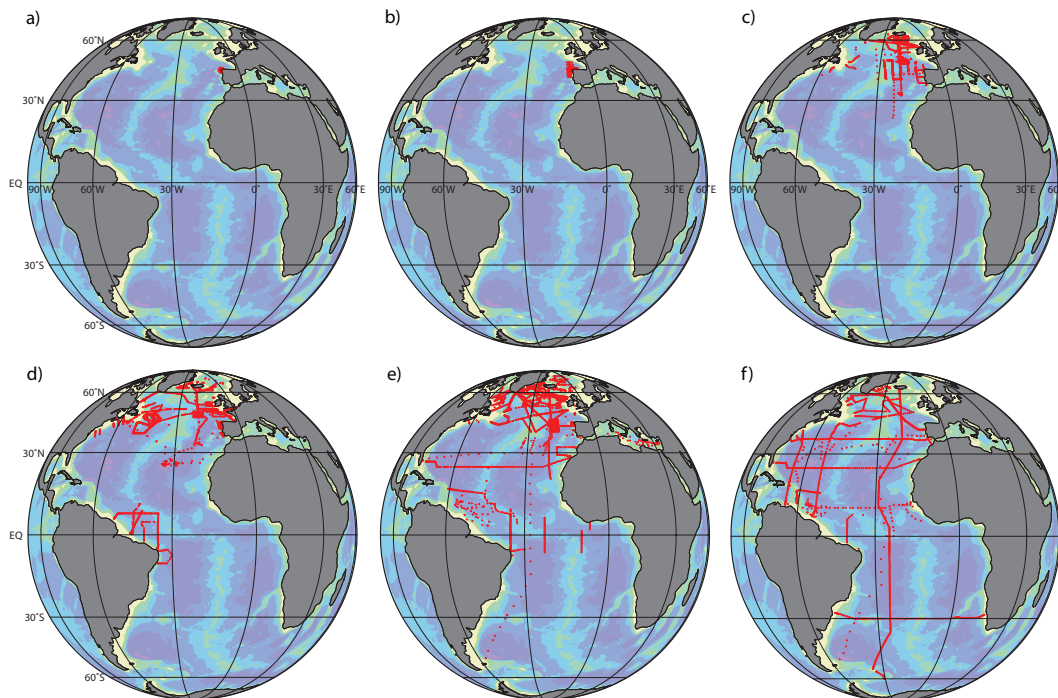
Fig. 3. Maps showing the temporal distribution (5 year intervals) of stations that have oxygen samples in the final product of CARINA-ATL (without the reference cruises): **(a)** 1977 to 1981; **(b)** 1982 to 1986; **(c)** 1987 to 1991; **(d)** 1992 to 1996; **(e)** 1997 to 2001, and **(f)** 2002 to 2007.
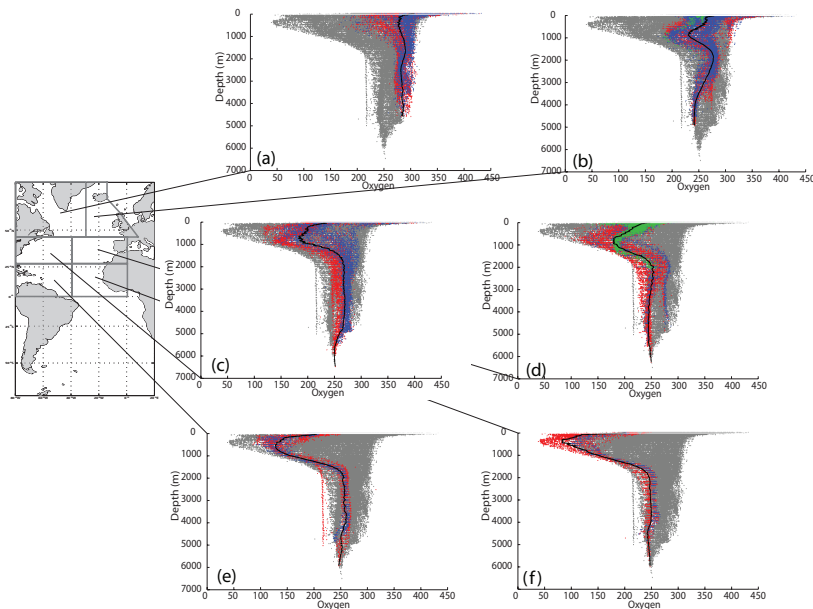
Fig. 4. Overview of the oxygen distribution in the database depicted as vertical profiles for 11 separate regions: **(a)** 70° N–46° N and 80° W–30° W, **(b)** 70° N–46° N and 30° W–20° E except the cruises in the Arctic Ocean north of 60° N, **(c)** 46° N–23° N and 80° W–40° W, **(d)** 46° N–23° N and 40° W–0° **(e)** 23° N–EQ and 80° W–40° W, **(f)** 23° N–EQ and 40° W–0° **(g)** Eq–23° S and 60° W–20° W, **(h)** Eq–23° S and 20° W–20° E **(i)** 23° S–46° S and 60° W–20° W, **(j)** 23° S–46° S and 20° W–20° E, **(k)** 46° S–70° S and 60° W–20° W. Shown in gray is the vertical distribution for the entire North Atlantic (a, b, c, d, e and f) and the entire South Atlantic (g, h, i, j and k) respectively. Shown in red is the vertical distribution in the area where the panel is located on the map from 1997 to 2007, in blue is the vertical distribution from 1987 to 1996 and in green is the vertical distribution from 1977 to 1986. The black line is the mean profile of the entire data in that area interpolated with a piecewise Cubic Hermite Interpolating scheme. Oxygen units are in μmol kg^{-1}
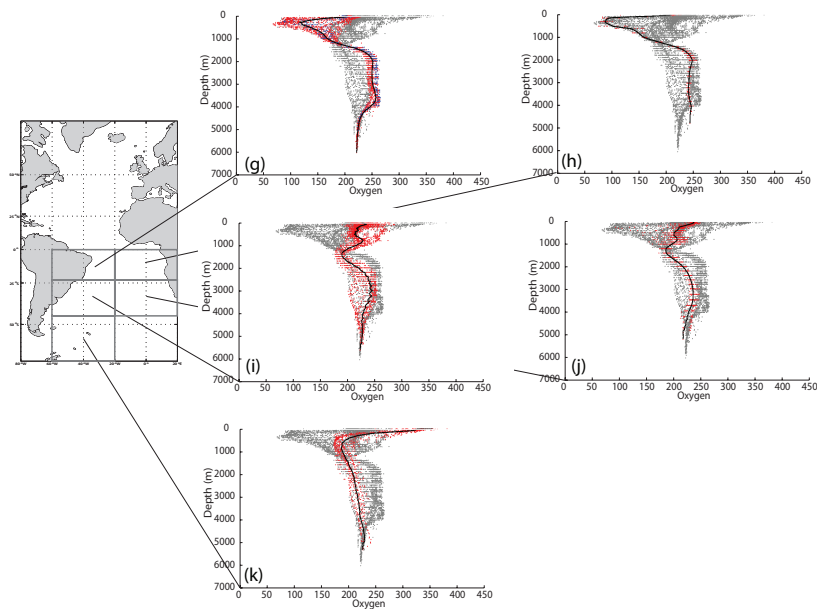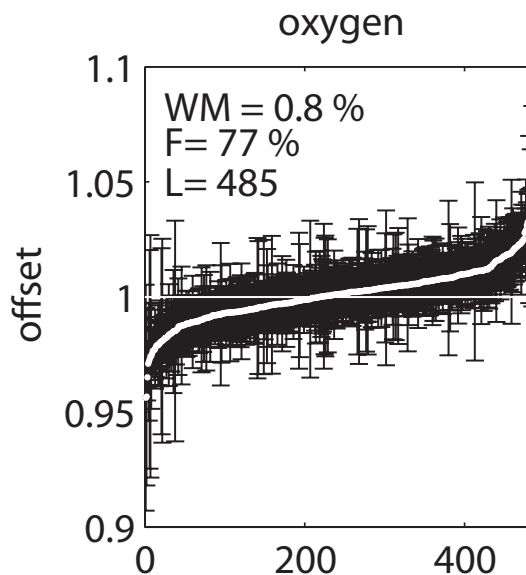
Fig. 4. Continued.

Fig. 5. Plot of the offsets calculated for each crossover in the final product of CARINA-ATL after adjustments have been applied. WL: the weighted mean of the offsets; F: the percentage of offsets indistinguishable from 1 within their uncertainty; L: the number of crossovers.
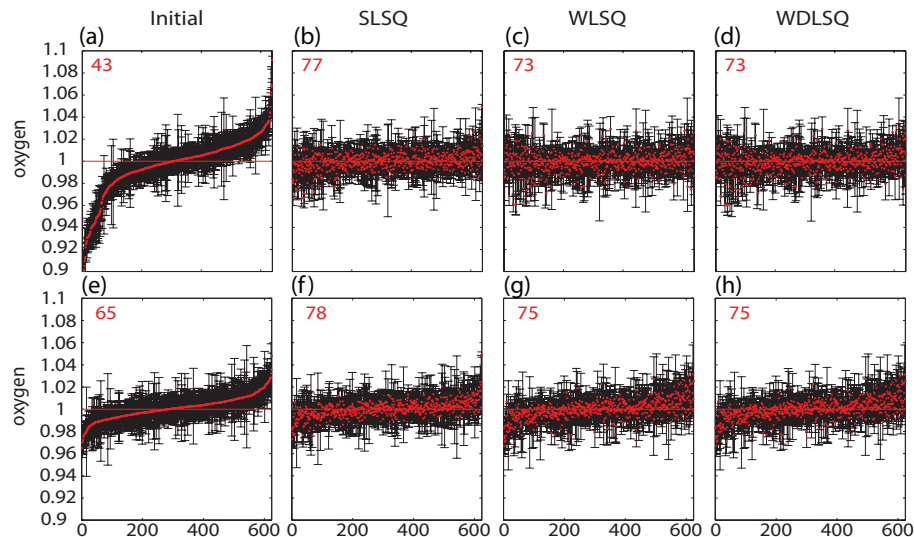
Fig. 6. Plot of the offsets for each crossover (red dots) and their uncertainties (black error bars). Here are included also the offsets from the reference cruises. The first row, i.e. **(a–d)** corresponds to the results before any suggested adjustment have been applied, while the second row, i.e. **(e–h)** corresponds to the results after the manually edited adjustments were applied. First column, i.e. (a) and (e), show the results from the offset analysis ordered by offset. The second, third, and forth columns depict the offsets after the inversions. (b) and (f) results from the Simple least Square method (SLSQ); (c) and (g) results from Weighted Least Square method (WLSQ); and (d) and (h) results from the Weighted Damped Least Square method (WDLSQ). The red numbers in the upper-left corner of each panel are the numbers of crossovers that are statistically indistinguishable from zero.
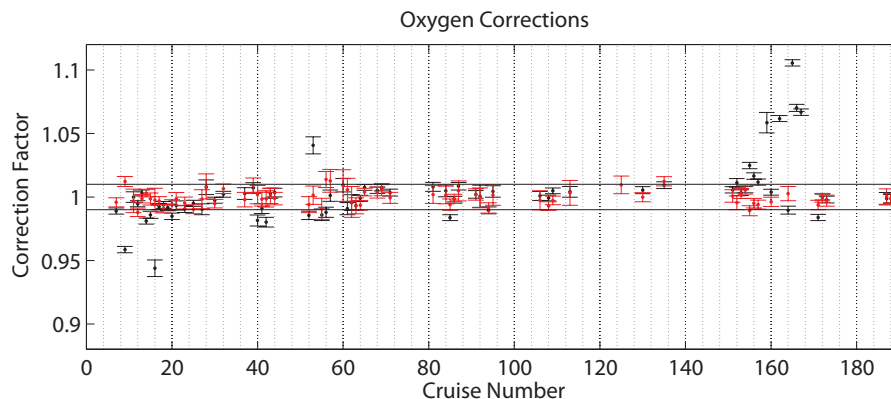
Oxygen Corrections

Fig. 7. Plot of the individual cruise corrections and their uncertainties based on the WDLSQ method (see Table 1). In black are the correction before any adjustment has been applied, i.e. the results from the first inversion of the offset results. In red are the corrections that the WDLSQ inversion suggests after the manually edited adjustments were applied to the oxygen data (see Table 1). The thin black lines represent the threshold of 1% of allowed adjustments. Cruises for which only red symbols are shown did not change their cruise adjustment from the initial to the second inversion. Cruises for which only black symbols are shown are those whose oxygen data have been flagged as bad and deleted in the adjusted database.