Biogeosciences Discuss., 11, 17391–17411, 2014
www.biogeosciences-discuss.net/11/17391/2014/
doi:10.5194/bgd-11-17391-2014
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Biogeosciences
Discussions
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This discussion paper is/has been under review for the journal Biogeosciences (BG).
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Open ocean dead-zone in the tropical North Atlantic Ocean

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Received: 3 November 2014 – Accepted: 13 November 2014 – Published: 12 December 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The intermittent appearances of low oxygen environments are a particular thread for marine ecosystems. Here we present first observations of unexpected low (< 2 μmol kg^{-1}) oxygen environments in the open waters of the eastern tropical North Atlantic, a region where typically oxygen concentration does not fall below 40 μmol kg^{-1}. The low oxygen zones are created just below the mixed-layer, in the euphotic zone of high productive cyclonic and anticyclonic-modewater eddies. A dynamic boundary is created from the large swirl-velocity against the weak background flow. Hydrographic properties within the eddies are kept constant over periods of several months, while net respiration is elevated by a factor of 3 to 5 reducing the oxygen content. We repeatedly observed low oxygen eddies in the region. The direct impact on the ecosystem is evident from anomalous backscatter behaviour. Satellite derived global eddy statistics do not allow to estimate the large-scale impact of the eddies because their vertical structure (mixed-layer depth, euphotic depth) play a key role in creating the low oxygen environment.

1 Introduction

The concentration of dissolved oxygen (DO) in seawater is of critical importance to almost all marine life and oceanic biogeochemical cycling (Wilding, 1939; Diaz and Rosenberg, 2008; Vaquer-Sunyer and Duarte, 2008; Wright et al., 2012; Kalvelage et al., 2011). Local DO concentrations are the result of a delicate balance between oxygen supply and consumption and eventually regions of extreme low oxygen content are created: at the microscale at particle boundaries (Alldredge and Cohen, 1987), at the mesoscale as coastal dead-zones (Diaz and Rosenberg, 2008) or at the large scale such as eastern boundary Oxygen Minimum Zones (OMZ) (Luyten et al., 1983; Karstensen et al., 2008). Understanding processes that control the

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DO supply/consumption balance, and any possible alterations over time, remain a challenge of current research.

Critical DO concentration thresholds have been identified, which lead to major reorganizations of the marine ecosystems (Vaquer-Sunyer and Duarte, 2008; Wright et al., 2012; Kalvelage et al., 2011). For higher trophic levels, such as fish, the impact of a certain DO levels on metabolism and as such fitness, is species dependent (Wilding, 1939). Nevertheless, for DO below 20 μmol kg^{-1} ("severe hypoxia") mass mortality of fish has been reported (Diaz and Rosenberg, 2008). Also triggered by severe hypoxia DO levels, microbes begin to convert nitrite and ammonium to nitrogen gas, and this remove fixed nitrogen from the water which in turn limits primary productivity (Wright et al., 2012; Kalvelage et al., 2011). A next distinct DO threshold is for concentrations below about 5 μmol kg^{-1} when microbes begin to utilize nitrate (and other nitrogen species) as terminal electron acceptors in anaerobic respiration ("denitrification") (Wright et al., 2012; Kalvelage et al., 2011). Finally, when DO reach concentrations around 1 μmol kg^{-1} ("anoxia"), only specifically adapted microbes can exist (Wright et al., 2012).

The pelagic zones of the eastern tropical North Atlantic OMZ are considered to be "hypoxic", with minimal DO of hardly below 40 μmol kg^{-1} (Stramma et al., 2009; Karstensen et al., 2008). As such it is assumed that the DO levels pose on the regional ecosystem some limitation in biodiversity primarily through avoidance and maybe an increased mortality (Vaquer-Sunyer and Duarte, 2008). The region is thus very much in contrast to the major OMZs in the eastern North and South Pacific Ocean and the northern Indian Ocean where DO concentrations pass all DO thresholds outlined above, and as such specifically adapted ecosystems must exists.

However, here we report on recent observations of extreme low DO, characterizing severe hypoxia and even anoxia with horizontal scales of about 100 km and vertical scales of about 100 m, exists in the eastern tropical North Atlantic.

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2 Data and methods

2.1 Moored oxygen sensors

DO time series were acquired at the Cape Verde Ocean Observatory (CVOO) mooring. CVOO is located in the eastern tropical North Atlantic, about 100 km northeast of the Cape Verde Island Sao Vicente (17°35′ N, 24°15′ W) and approximately 800 km from the Mauritanian coast (Fig. 1). Since 2006 the observatory is equipped with oxygen optodes, while since the beginning of 2008 at least one optode was installed in the upper 60 m of the water colmn.

Oxygen measurements at the CVOO mooring were done with AADI Aanderaa oxygen optodes (type 3830). A calibration was done against CTD/oxygen sensor (Sea-Bird Electronics 43 Clark electrode) data for the deployment period from 2009 to 2014 before and after the deployment phase. For each optode, 17 independent calibration points were obtained, choosing locations with weak vertical oxygen gradient. A lab calibration at zero oxygen concentration was also performed by submerging the optodes into a sodium sulfite solution. All calibration points were used to derive a final calibration equation, while the chemically forced (and thus more precise) zero oxygen calibration was weighted three times higher than the CTD/oxygen cast references. The difference between calibration point observations and calibrated optode suggests an overall rms error of 3 $\mu mol\,kg^{-1}$. Comparison of the chemically forced zero oxygen phase data and the phase readings during the anoxic event suggests a higher accuracy of about 1 $\mu mol\,kg^{-1}$. Pressure and salinity variability was corrected according to the AADI manual.

2.2 Argo float

Data from a PROVOR Profiling Argo Float (WMO 6900632; Martec Inc., France), equipped with a standard CTD (SBE 41CP; Sea-Bird Electronics, Bellevue, USA), an oxygen optode (3830; Aanderaa Data Instruments, Bergen, Norway) and a transmissometer (CRV5; WETLabs, Philomath, USA) was used. The float was programmed to conduct every 5th day a vertical profile between 400 db and the surface with a vertical resolution of 5 db. Transmitted DO concentrations were corrected for salinity effects and a pressure correction of 4 % per 1000 db was applied to the data. After deployment, a ship-borne CTD cast that included measurements for DO (Winkler Titration and a Sea-Bird SBE 43 Clark Electrode), was conducted next to the deployment location and used for post offset correction of float-based DO measurements. Transmissometer data was obtained in units of m^{-1} (beam attenuation coefficient) based on the factory calibration. Biofouling within the optical path was accounted for by subsequently subtracting each profile's minimum beam attenuation value from the respective profile data.

2.3 Eddy tracking

For detecting and tracking eddy-like structures from the daily merged SLA data, an algorithm based on the Okubo–Weiß method was applied. The method is robust and widely used to detect eddies in satellite data as well as on numerical model output (Chelton et al., 2007; Sangrà et al., 2009). Analysing the contribution of relative vorticity on the strain tensor, an eddy is defined as a region of negative W (vorticity dominates over strain) surrounded by a region of positive W (strain dominates over vorticity). We applied a threshold of $W_0 = -2 \times 10^{-12}\,s^{-2}$ as our eddy detection limit. Moreover, we considered that the detected area has a circular area-equivalent with a radius larger than 40 km and must be detectable for at least 7 days. An eddy trajectory is derived by following the centre of individual W_0 areas in SLA maps from 1 day (maximum 10 km) up to 3 weeks (maximum distance 60 km).

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3 Results

3.1 Open ocean low oxygen events from moored observation

The first data sets we report is DO time series from CVOO mooring available from 2006 until 2014 (Fig. 2). The time series from the instruments installed shallower than 60 m depth typically shows short term variability of 50 $\mu mol\,kg^{-1}$ around the saturation. However, exceptional low oxygen events are observed during boreal winter 2007, 2010, 2011, and 2012.

The most intense event was recorded at the mooring site over a period of about 1 month, in February 2010 (CVOO2010; Fig. 3a) with DO concentrations close to zero (DO < 2 $\mu mol\,kg^{-1}$) at shallow depth (42 m optode), where typical DO is within 10 % of saturation (> 200 $\mu mol\,kg^{-1}$). At a second sensor, installed at nominal 170 m, showed a more moderate DO decreased from the typical 100 $\mu mol\,kg^{-1}$ to less than 30 $\mu mol\,kg^{-1}$ during the event. Inspecting the hydrography and currents from other moored instruments we found that the low DO event was accompanied by a lens of cold and less saline (Fig. 3b) water and a strong and reversing meridional flow (Fig. 3c). The temporal evolution of the isopycnals (surfaces of constant water density) indicates that an anticyclonic-modewater eddy has passed through the mooring and contained the extreme low DO concentrations.

Anticyclonic-modewater eddies, also called intrathermocline eddies, are associated with downward/upward bended isopycnals below/above a subsurface velocity maximum (Kostianoy and Belkin, 1989). The transition between up and downward bended isopycnals form a lens (or mode) of a specific water mass. In our observations the mode has a height of about 50 m and is also centred at about 50 m depth and, as a consequence, the surface mixed-layer shoaled from a thickness of about 50–60 m before (and after) the eddy passage to less than 20 m during the passage. Anticyclonic-modewater eddies have been reported before to be associated with specific ecosystem responses, such as high primary productivity presumably due to

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eddy-wind interaction (McGillicuddy et al., 2007) while controversy about the governing processes exists (Mahadevan et al., 2008).

Earlier DO record from CVOO revealed that in February 2007 (CVOO2007), almost exactly 3 years before the 2010 event, a single oxygen sensor installed at 120 m (nominal) depth also recorded very low DO concentrations, down to about 15 µmol kg^{-1}. This low oxygen event was again associated with the passage of an anticyclonic-modewater eddy.

3.2 Open ocean low oxygen events in Argo float data

One further North Atlantic "severe hypoxia" event was detected within a cyclonic eddy and surveyed with an Argo type float (Fig. 4a and b) that operated from mid February 2008 until the end of May 2009. After launch, the float remained in the Mauritanian upwelling region until, by the end of May 2008, it begun to move in west-northwest directions (Fig. 1). The float trajectory already indicated that it was trapped in a cyclonic eddy, as confirmed by a more detailed analysis presented below. In parallel to the westward propagation into the open waters a decrease in DO was seen at all depth and that lasted until mid-December 2008. During that period, lowest DO (about 14 µmol kg^{-1}) was always observed close to the mixed-layer base which, however, successively deepened. After December 2008 the DO increased again (Fig. 4b), accompanied by drastic changes in temperature (not shown here) and salinity (Fig. 4a). It turned out from the eddy trajectory analysis below, that the float was still inside the eddy but the changes in the water properties indicate that the eddy lost its isolated character.

3.3 Propagation of oxygen anomalies

Making use of sea-level anomaly (SLA) maps, all three low oxygen observations (CVOO2007, Argo2008, CVOO2010) could be associated with individual nonlinear mesoscale eddies (Chelton et al., 2011). The two eddies observed at CVOO rotated in an anticyclonic way (as also seen in the CVOO mooring data), the Argo2008 eddy was a cyclonic eddy. Considering the along path characteristics from concurrent SLA maps, all three eddies had roughly similar diameters (about 130 km) and propagated westward with speed of about $7\,\mathrm{cm\,s^{-1}}$. As such they can be categorized as "typical" for this latitude range (Chelton et al., 2011; Chaigneau et al., 2009). The SLA across the eddy radius was rather weak with an amplitude of 1.5 (±1.5) cm (negative for the cyclone, positive for the anticyclones). The SLA anomaly translates to maximum geostrophic surface currents of about 0.05–$0.10\,\mathrm{m\,s^{-1}}$, which is slow when compared with global eddies characteristics (Chelton et al., 2011; Risien and Chelton, 2008). Moreover, such a slow surface geostrophic current reflect only 10–20 % of the oberserved interior maximal swirl velocity, at least for the anticyclonic-modewater eddies (Fig. 3c). All three eddies had a similar region of origin at about 18° N/16.5° W. The cyclone was formed in May 2008 (the float entered the eddy core about one month later), and the two anticyclonic-modewater eddies in July 2006 and 2009, respectively.

Cyclonic eddies as well as anticyclonic-modewater eddies have been shown to be vital for the oceanic productivity (Chelton et al., 2011; McGillicuddy et al., 2007). Cloud free/partial cloud conditions are rare in the region, but selected satellite derived surface chlorophyll images clearly show such productivity events (Fig. 5), covering almost the whole diameter of the eddies.

3.4 Isolation and respiration

In July 2006 the research vessel *METEOR* operated close to the coast and surveyed by chance the CVOO2007 eddy, shortly after it left the Mauritanian upwelling region (Fig. 6). Comparing the ships survey data from 2006 with the mooring survey data from 2007 reveals that the core of the eddy remained unchanged in temperature and salinity over a period of seven months, and after propagating more than 650 km westward. Moreover, the water within the eddy shows distinct South Atlantic Central Water characteristics, typical found in the Mauritanian upwelling region.

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For the anticyclonic-modewater eddies (CVOO2007, CVOO2010) the direct velocity observations show that just below the mixed-layer base the ratio (α) of swirl velocity to translation speed, which is a proxy for the nonlinearity (and coherence) of eddies (Chelton et al., 2011), is at maximum ($\alpha > 9$). Note, at this depth not only highest swirl velocities but minimal DO concentrations are found. No direct swirl velocity observation exists for cyclone surveyed by the Argo2008 but composite density profiles, recorded when the float entered the eddy (May/June 2008) and when it left the eddy (March/April 2009), were used to derive geostrophic current profiles (see Chaigneau et al., 2011). As we do not have a proper reference velocity the absolute value for the α, and as such for the intensity of the isolation, cannot be calculated. However, we observe a fundamental change in the velocity shear profile, from a rotation with nearly constant velocity from just below the mixed-layer (30 m) at the beginning of the survey to a profile with a distinct peak in swirl velocity below 100 m depth at the end of the float survey. Such a change in the flow structure indicate that the maximum α moved to deeper levels, and the eddy lost its isolated character at shallow depth, which in turn may explain the strong change in hydrographic properties (and the oxygen increase) as lateral exchange with surrounding waters could take place at this stage of the eddies life-time (Fig. 4).

From differences in DO concentrations between concurrent Argo float profiles, an apparent oxygen utilization rate (aOUR) profile was estimated (Fig. 4c). Only profiles where DO decreased (May to mid-December 2008) were considered (isolated eddy). In order to take the successive deepening of isopycnals over time into account (e.g. Fig. 4a, contours) the aOUR was calculated in density classes and subsequently projected back to depth, using the mean vertical density profile. The aOUR is highest, more than 0.15 μmol kg^{-1} day^{-1}, just below the mixed-layer and level out to about 0.05 μmol kg^{-1} day^{-1} between 120 m and the maximum depth the float surveyed (400 m). These rates are 3 to 5 times higher than typical rates for the thermocline (Jenkins, 1982; Karstensen et al., 2008) but as the calculations do not consider any lateral oxygen supply (which should be minimal given the constancy of the hydrographic

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properties), the rates can be seen as lower bounds for the respiration inside of the eddy. The relative particle load, as observed with the transmissometer (not shown), is at maximum just at the base of the mixed-layer. However, the minimal DO is observed about 5 m below that particle maximum and which indicates that the net oxygen respiration is related to the sinking particles.

For the anticyclonic-modewater eddies a net DO respiration can only be derived for the CVOO2007 eddy and for one depth only. This eddy was surveyed twice, off Mauritania by RV *METEOR* and 7 month later at the CVOO mooring site. Between these two surveys the DO concentrations at the 120 m depth level (only depth with DO instrument at CVOO2007) changed by more than 50 µmol kg^{-1}. Such a change translate to an aOUR of 0.25 µmol kg^{-1} day^{-1} and which is even higher than in the cyclonic eddy and suggests that the productivity (and subsequently oxygen drawdown through sinking particles) is more intense in anticyclonic-modewater eddies then in cyclonic eddies.

4 Discussion

Here we have reported first observations of open ocean dead-zones in the tropical Northeast Atlantic. We could show their evolution, from their generation near the Northwest African shelf to the westward propagation into the open ocean during which extrem low-oxygen environments developed just below the mixed layer. To estimate the impact of the eddies on the large-scale ocean at least their intensity and occurrence must be known. While methods for eddy surface detection from SLA maps are rather well established (Chelton et al., 2007, 2011; Chaigneau et al., 2009), concurrent details on the vertical stratification are required to detect the dead-zone eddies. A possibility has been outlined using Argo float data in parallel to SLA data (Chaigneau et al., 2009) to map the large-scale mean hydrographic eddy (cyclone, anticyclone) structures. Nevertheless, for a dead-zone detection the DO cencentration is required as well and which is so far not a routinely measured with floats.

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There is clearly a local impact of dead-zone eddies on the ecosystem. During the passage of the anticyclonic-modewater eddies at the CVOO we observed in the target strength data that acoustic back scatterers, such as zooplankter, stopped their diurnal migration cycle (Fig. 7). Such an absence of the vertical migration is indicative for zooplankter in the major OMZ regions (Ayon et al., 2008). While in the open ocean mobile organisms may escape from the dead-zone other organisms, such as the wide range of prokaryotes, may need to adapt to the environment in order to survive. In that sense the dead-zone eddies can be seen as gigantic natural laboratories where an extreme environment is created in a relative short period of time (a few month). As such these features may open new way in investigating the adaptation techniques of organisms to low DO environments.

It is worth considering the possible interaction of a dead-zone eddy with an island (e.g. Cape Verdes Islands archipelago). Given the shallow depth the low DO is located, a sudden flooding of a coastal areas with low DO waters will have a dramatic impact on the local ecosystems, and sudden fish or crustacean death may occur. In retrospective, such eddy/island interactions may explain such events that have been reported in the past (O. Melicio, personal communication, National Fisheries Institute INDP, Mindelo, Sao Vicente, Cape Verde Island).

5 Conclusions

Differences in the eddy dynamics among cyclones and anticyclonic-modewater eddies can explain differences between the intensity and lifetime of their respective dead-zones. For example the generation of up- and downwelling within eddies through interaction with the overlying wind field (McGillicuddy et al., 2007; Mahadevan et al., 2008) can generate anomalous shallow (deep) mixed-layers in the anticyclonic-modewater (cyclonic) eddies which in turn may influence productivity, export and respiration efficiency (Klein and Lapeyre, 2009; Lévy et al., 2012). Further observational and modeling studies are required that focus on the submesoscale

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dynamics and on the biogeochemical cycling and ecosystem response within the eddies and their potential impact on large-scale marine ecosystem (Klein and Lapeyre, 2009; Lévy et al., 2012).

In principle open ocean dead-zones in mesoscale eddies may be created in all oceanic regions characterized through a sluggish background flow. Primary sites are the eastern boundary shadow zones (Luyten et al., 1983). Given the much lower oxygen levels of the major OMZs in the Pacific or the Indian Ocean, the dead-zones in those regions will not appear in DO anomalies but in other biogeochemical extremes, such as an anomalous nitrogen isotope composition (Altabet et al., 2012).

One may wonder why dead-zone eddies have not been discovered before? Besides the undersampling of the tropical eastern North Atlantic in the past, there is the likelihood that such low oxygen concentrations were disregarded as "outliers" in the data sets. In fact we interpreted the low oxygen at CVOO2007 first as an outlier related to an instrumental error and only the more recent events recorded with the double sensor package at CVOO2010, and combined with sophisticated optode calibration procedures, gave us confidence that our observations were real.

Acknowledgements. Financial support is acknowledged from: the European Commission for FP7 GROOM (284321), FP7 CARBOOCEAN (264879), FP7 CARBOCHANGE (264879), FP7 FixO3 (312463); the DFG for Collaborative Research Centre "SFB 754"; the BMBF for SOPRAN (03F0462A) and AWA (01DG12073E). CVOO is part of the OceanSITES network. SLA data was produced by Ssalto/Duacs and distributed by Aviso (www.aviso.oceanobs.com). MyOcean products have been used. Argo float data is available from Coriolis data centre (www.coriolis.eu.org).

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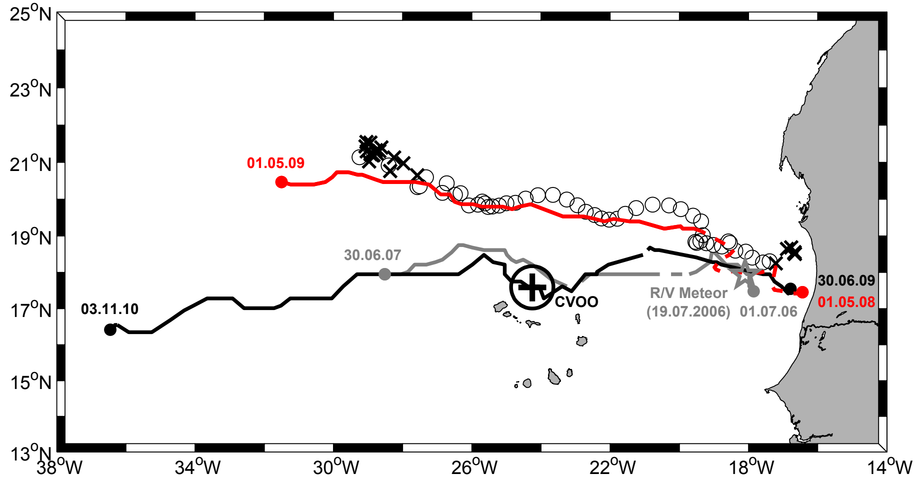

Figure 1. Overview map of the eastern tropical North Atlantic Oxygen Minimum Zone. The tracks of the two anticyclonic-modewater eddies (CVOO2007, grey line and CVOO2010, black line) observed at CVOO (plus sign; 17°35.39′ N, 24°15.12′ W) as well as the track of the cyclonic eddy (Argo2008, red line), surveyed with an Argo float are shown. The position (dots) and dates (label) of the first and last identification of the three eddies are given. The RV *METEOR* survey of the CVOO2007 (grey star) is labelled accordingly. For reference, the average footprint (circle at CVOO) is given. Positions of the Argo float profiles surveyed inside (white circles) as well as outside the cyclonic eddy radius (crosses) are shown.

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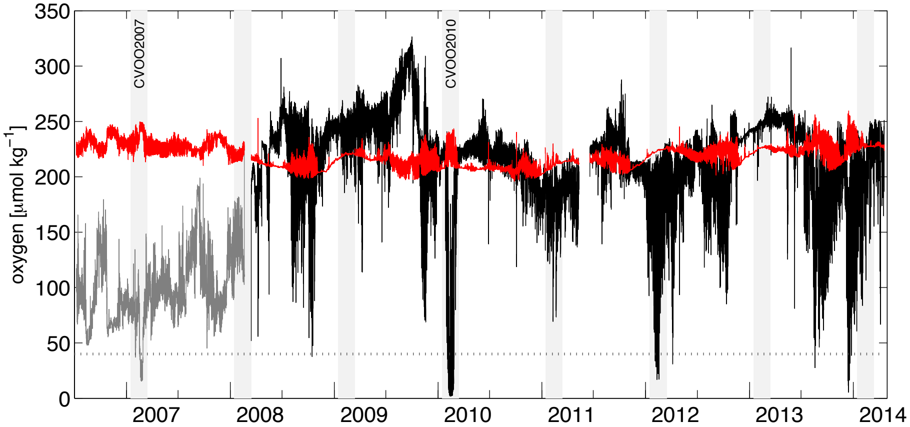

Figure 2. Time series of DO from the CVOO site at 40 to 60 m depth (black line) and first period at 140 m (grey line). The passage of the two anticyclonic-modewater eddies in February 2007 (CVOO2007) and February 2010 (CVOO2010) are labelled accordingly. The theoretical oxygen saturation (red line) is shown as well as the 40 μmol kg^{-1} threshold reported in the literature. The period from 15 January to 15 March for each year is indicated by grey shaded area.

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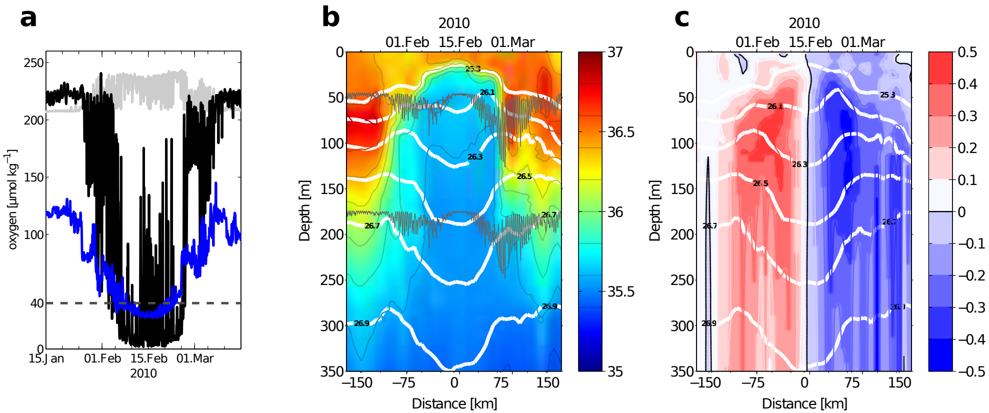

Figure 3. **(a)** Time series of DO from the two sensors available at nominal 42 m (black line) and 170 m depth (blue line). For reference, the oxygen saturation (grey line) as well as the 40 µmol kg^{-1} threshold from the literature (broken line) are shown. Corresponding time series of **(b)** salinity (in PSS-78) and **(c)** meridional flow (m s^{-1}) in the upper 350 m as observed during the CVOO2010 passage. The black lines in **(b)** indicate the varying depth of the oxygen sensors shown in **(a)**. Selected potential density anomaly surfaces are shown as white contours in (**b** and **c**) for reference and the time series data was converted into distance assuming an eddy translation speed of 7 cm s^{-1}.

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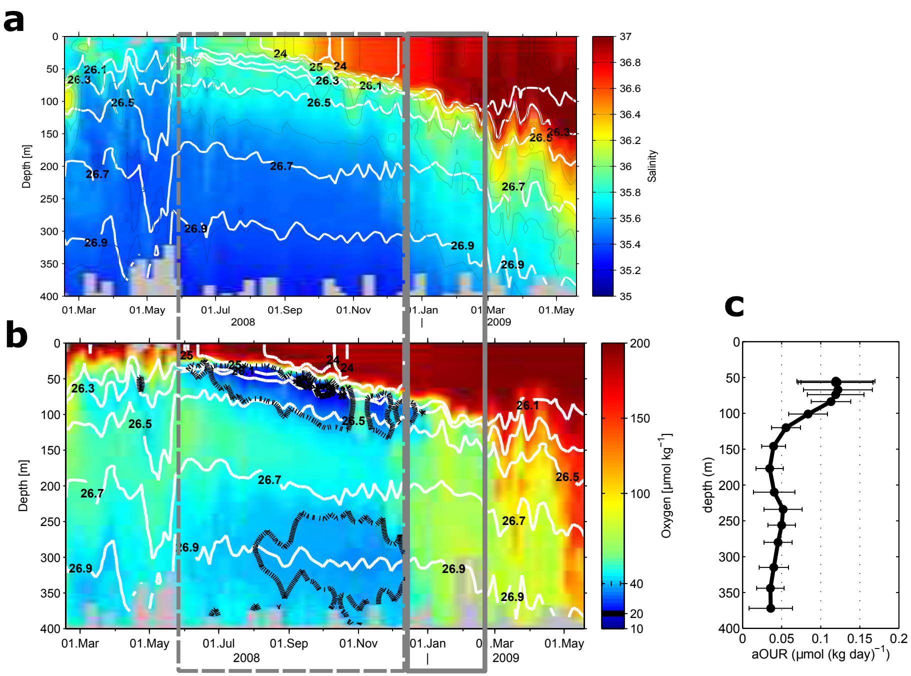

Figure 4. Time series of **(a)** salinity and **(b)** oxygen from profiling float data. The two neighbouring boxes indicate the period when the float was trapped in the cyclonic eddy separating the isolated period (left box) and the non-isolated period (right box). Potential density anomaly contours are shown as contour lines. **(c)** Vertical profile of the aOUR derived from successive dives during the period when the eddy was isolated.

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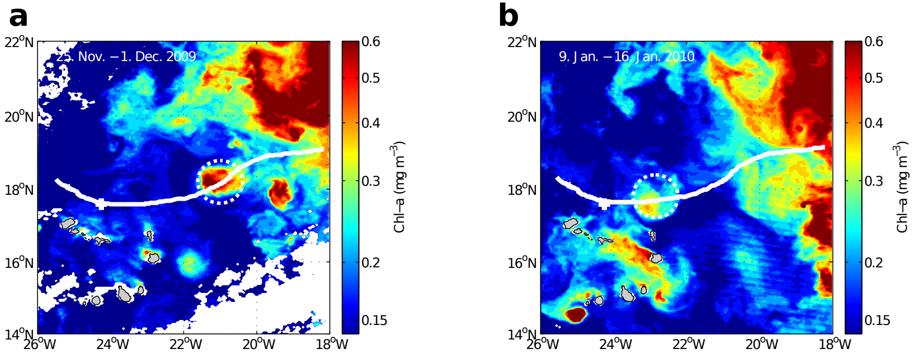

Figure 5. Surface chlorophyll concentration of the CVOO2010 anticyclone at two life stages approximately two month **(a)** and one month **(b)** before the centre of the anticyclone crossed the CVOO mooring. The SLA derived track of the anticyclone centre (compare Fig. 1) and the approximate diameter (130 km) are shown for reference. The white circle with a plus sign marks the CVOO position.

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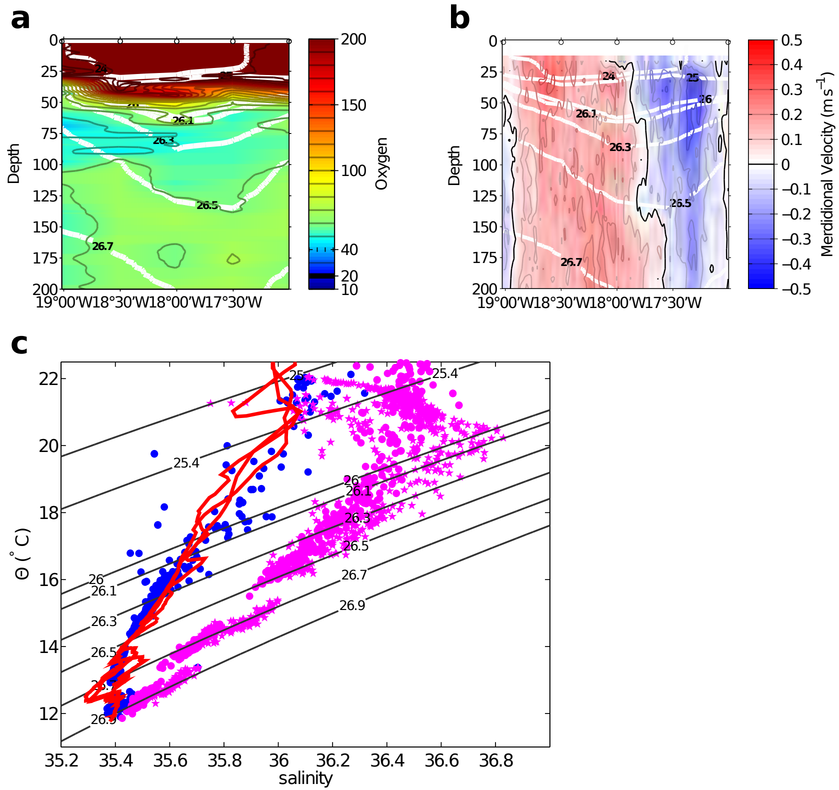

Figure 6. Vertical distribution of **(a)** oxygen (µmol kg^{-1}) and **(b)** meridional velocity (m s^{-1}) surveyed with RV *METEOR* (cruise M68/3) on the 18 July 2006, at 18° N and from 17 to 19° W (see Fig. 1 for position). **(c)** Hydrographic characteristics of the eddy core as observed with RV *METEOR* (red lines) and as observed 7 month later during the CVOO2007 passage (blue dots). For reference typical background conditions at CVOO are shown (magenta dots and stars).

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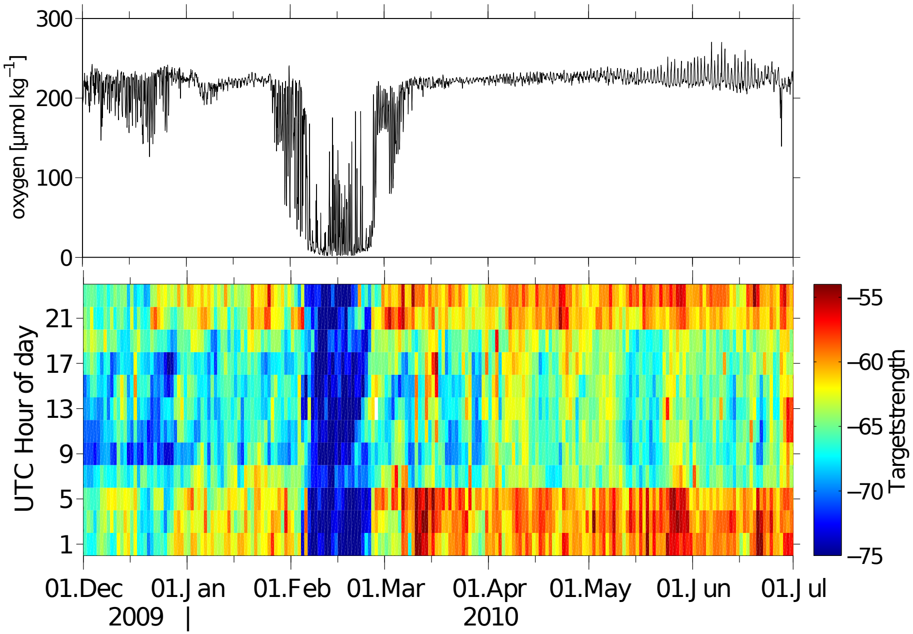

Figure 7. Time series of (upper) oxygen at nominal 45 m depth and (lower) target strength between 65 to 70 m depth calculated from the 300 kHz acoustic Doppler current profiler data at CVOO2010 plotted against hours of the day (in dB). Minimal target strength during all hours of day is seen during the passage of the anticyclonic-modewater eddy between 8 and 25 February 2010.

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