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Deoxygenation in the oxygen minimum zone of the eastern tropical North Atlantic

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[1] Observations and model results both indicate increasing oxygen minimum zones (OMZ) in the tropical oceans. Here we report on record low dissolved oxygen minimum concentrations in the eastern tropical North Atlantic in fall of 2008, with less than 40 μmol kg^{-1} in the core of the OMZ. There we find a deoxygenation rate of ~0.5 μmol kg^{-1} a^{-1} during the last decades on two repeat sections at 7.5 and 11°N. The potential temperature and salinity in the surface and central water layers increased on both sections compared to previous observations. However, in contrast to the oxygen decrease in the core of the OMZ, increasing oxygen concentrations were observed in the central water layer above the OMZ. The observed deoxygenation was thus restricted to the core of the oxygen minimum layer. It remains unclear whether the vertical expansion of the oxygen minimum represents a long time trend or decadal variations. **Citation:** Stramma, L., M. Visbeck, P. Brandt, T. Tanhua, and D. Wallace (2009), Deoxygenation in the oxygen minimum zone of the eastern tropical North Atlantic, *Geophys. Res. Lett.*, *36*, L20607, doi:10.1029/2009GL039593.

1. Introduction

[2] Century long integrations of a biogeochemical climate model under global warming conditions predict an overall decline in oceanic dissolved oxygen concentration and expansion of the mid-depth oxygen minimum zones [*Bopp et al.*, 2002; *Oschlies et al.*, 2008]. Predicted oxygen changes in the thermocline waters result largely from solubility changes in the upstream source waters, whereas changes in the deeper water result mainly from decreased interior advection and ongoing oxygen consumption by remineralization of sinking particulate organic matter [*Matear and Hirst*, 2003]. In addition, the marine carbon pump is affected by oceanic acidification in that lower calcification rates leads to slower sinking of biological material (i.e., reduced ballast) which in turn may lead to decreasing oxygen concentrations in the oxygen minimum layer [*Hofmann and Schellnhuber*, 2009]. Long-term oxygen changes have been observed and reported for a few locations in the subpolar and subtropical regions [*Whitney et al.*, 2007]. Layers with particularly low oxygen concentrations known as oxygen minimum zones (OMZ) are located in the eastern tropical oceans at depth of 200 to 700 m depth [e.g., *Karstensen et al.*, 2008]. Decreasing dissolved oxygen concentrations might have dramatic consequences for microbial and chemical cycling of nutrients as well as for the ecosystem in the open ocean. For example, shoaling of the tropical OMZ restricts the distribution of tropical pelagic fishes by compressing their habitat within the oxygenated surface layer [*Prince and Goodyear*, 2006]. When the expanding OMZ reaches the shelf areas we can expect significant changes in animal populations, with altered activity, changed vertical migration depth and an overall reduced biodiversity associated with avoidance, mortality, or lowered growth and reproductivity rates of hypoxia-sensitive taxa [*Vaquer-Sunyer and Duarte*, 2008]. Tropical ocean data are too sparse for a complete space and time analysis of oxygen distribution. However, vertical expansion of oxygen minimum zones in selected tropical oceans regions have been reported [*Stramma et al.*, 2008b]. Here new data from a ship survey in the eastern tropical North Atlantic during November and December 2008 is analyzed to detect OMZ changes in comparison to historical data.

2. Data Set

[3] Historical hydrographic data from the Hydrobase2 data set (R. Curry, Hydrobase2, 2008, http://www.whoi.edu/science/PO/hydrobase/) was used for studying the oxygen minimum distribution in the depth range 300 to 600 m. The sources for those data are the World Ocean Database 2001 [e.g., *Boyer et al.*, 2006] as well as data from other programs, e.g. from the World Ocean Circulation Experiment (WOCE).

[4] The cruise with the German research ship RV Merian from 31 October 2008 from the Azores to 5 December 2008 to the Cape Verde Islands in the tropical eastern Atlantic was designated as a tracer survey of a tracer deployed during an earlier cruise in April 2008. The tracer had been deployed at 8°N 23°W at a density of $\sigma_\theta = 26.85$ kgm^{-3}, which is located in the upper part of the OMZ. The tracer survey was combined with a survey of the OMZ and resulted in a detailed station grid with a total of 225 CTD-stations.

[5] During the whole cruise a Seabird SBE 9 CTD rosette system has been used. The CTD system was equipped with one Digiquartz pressure sensor and double sensor packages for temperature, conductivity and oxygen. The calibration of the conductivity sensor for the CTD salinity resulted in a salinity accuracy of 0.0024.

[6] The oxygen sensor on the CTD was calibrated versus oxygen concentrations determined by Winkler titrations. One standard deviation of the oxygen concentration determined from the titration is 0.3 μmol kg^{-1} based of 80 duplicate measurements. The standard solution for the titration was found to be accurate to better than 0.27% based on comparison to two independent reference materials; from

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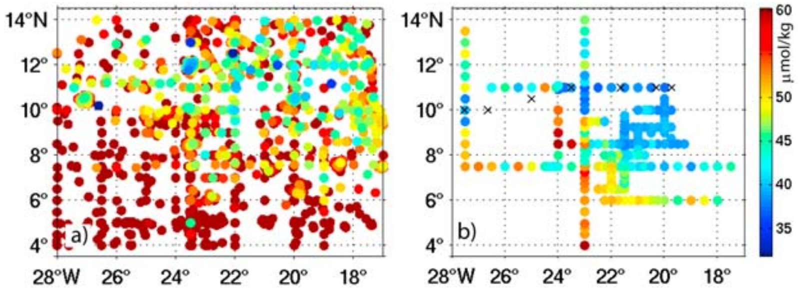

Figure 1. Distribution of the lowest oxygen minimum values in μmol kg^{-1} in the oxygen minimum layer at 300 to 600 m depth from (a) all data in Hydrobase2 database for oxygen measurements made before the year 2000 (lower values plotted over higher values) and (b) cruise MSM10/1 CTD stations in November and December 2008. The CTD locations of the RV Meteor cruise 55 in November 2002 are added as black crosses in Figure 1b.

WAKO inc. (USA) and Bjerknes Center in Bergen. Furthermore, oxygen concentrations in deep water samples were compared to all relevant historical cruises in both the Global Ocean Data Analysis Project (GLODAP) and CARINA databases, as well as more recent data, and no systematic bias could be detected. Our oxygen data are consistent with both GLODAP and CARINA to within 1.3% based on the weighted mean of the absolute offset for 12 crossover comparisons. The CTD oxygen sensor calibration resulted in an estimated accuracy of 0.8 μmol kg^{-1} when one third of the data with largest deviation compared to the titration were removed.

[7] For a direct comparison two historical cruise sections were selected in the investigation area. A zonal section with the RV Meteor (M55) crossing the Atlantic at about 10°N in the western and central part and at 11°N in the eastern part was carried out within the Surface Ocean Lower Atmosphere Study (SOLAS) program in October and November 2002 [*Wallace and Bange*, 2004]. The bottle oxygen data of this cruise are believed to have high quality. The CTD casts were made only to about 600 m depth and represent a reliable data set. As can be seen in Figure 1b, west of 24°W the 2008 stations are not exactly at the positions of the 2002 section.

[8] A section located to the south of the centre of the OMZ at 7°30′N was measured within the international WOCE project in February/March 1993 [*Arhan et al.*, 1998]. This section was carried out in March 1993 on RV Atalante, and the resulting oxygen data set is of high quality, *Gouretski and Jancke* [2000] suggest only an insignificant upward adjustment of the oxygen values with 0.45 μmol kg^{-1}. Here the March 1993 cruise will be compared to the part reoccupied in November 2008.

3. Changes in the OMZ

3.1. Spatial Oxygen Minimum Distribution

[9] The geographical area measured in late 2008 covered the OMZ south of the Cape Verde Islands between 4°N and 14°N, 17°W to 28°W. This area was selected for a direct comparison of the new and historical data. The lowest oxygen values in the Hydrobase2 data set recorded before the year 2000 show mainly values in the range 55 to 60 μmol kg^{-1} (Figure 1a), with oxygen minimum values north of 9°N between 40 and 50 μmol kg^{-1}, especially near the African continent. The large scale horizontal distribution of the lowest oxygen value within the OMZ as measured with the CTD oxygen sensor during cruise MSM10/1 in November–December 2008 (Figure 1b) shows the expected distribution of higher oxygen values in the region of the eastward North Equatorial Under- und Countercurrents at 4 to 9°N. These currents supply oxygen richer water to the OMZ [*Stramma et al.*, 2008a], while in the so called Guinea Dome region [e.g., *Siedler et al.*, 1992] and in the station closest to the African continent the lowest oxygen minimum values were observed. The density range where the oxygen minimum was reached is σ_θ = 26.74–27.14 kg m^{-3} with a mean pressure of 423 dbar. The minimum oxygen values measured in November 2008 are lower than previously observed in this area, reaching record low values of less than 40 μmol kg^{-1}, at several locations at and south of 11°N.

[10] Specifically, no oxygen values lower than 40 μmol kg^{-1} are recorded in the eastern tropical North Atlantic in GLODAP bottle data set [*Karstensen et al.*, 2008], and in the older bottle data in Hydrobase2 only a few values below 40 μmol kg^{-1} exist and these were measured north of 10°N. Due to the wide vertical spacing of bottle samples in Hydrobase2 database the data do not resolve the oxygen minimum well, and hence may be biased to much higher values. However, the Hydrobase2 data include also CTD data for the more recent period. The fact that both the Hydrobase2 and GLODAP oxygen concentrations are generally higher than in November 2008 shows that the oxygen minimum values reached record low oxygen concentrations in November 2008.

3.2. Comparison With Former Cruises

[11] To facilitate a direct comparison to historical data we repeated a part of a cruise carried out in March 1993 along 7.5°N (Figure 2a). The isopycnal σ_θ = 27.1 kgm^{-3} marks the boundary between the South Atlantic Central Water (SACW) and the Antarctic Intermediate Water (AAIW). Low oxygen concentrations are encountered in both water masses with the minimum in the lower reaches of the SACW. Whereas in March 1993 the 60 μmol kg^{-1} contour forms the lowest large-scale contour, in November 2008 (Figure 2b) wide regions east of 27°W fall within the 50 μmol kg^{-1} contour, and the oxygen values fall below 40 μmol kg^{-1} at two locations (20°W and 19°W). Only at

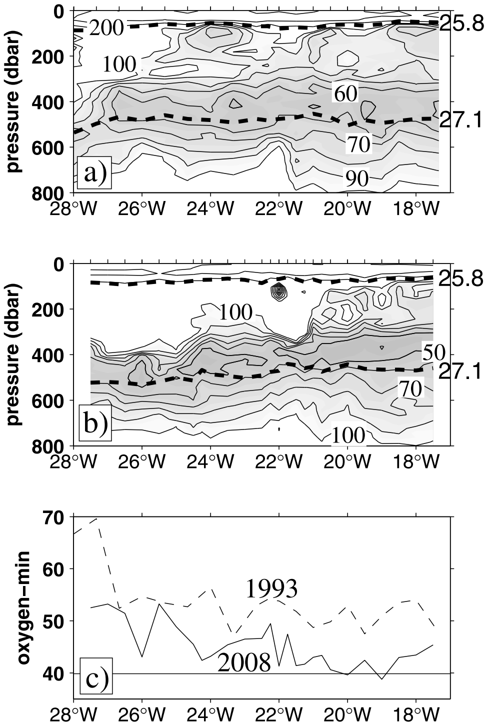

Figure 2. Dissolved oxygen section along 7.5°N with 10 μmol kg^{-1} contour intervals below 100 μmol kg^{-1} and 50 μmol kg^{-1} contour intervals for oxygen larger than 100 μmol kg^{-1} for (a) March 1993 cruise and (b) data from November 2008. The isopycnals σ_θ = 25.8 and 27.1 kg m^{-3} are included as dashed lines which mark the boundaries between Tropical Surface Water and the South Atlantic Central Water (SACW) and between the SACW and the Antarctic Intermediate Water. (c) The lowest oxygen values reached in the depth range 300 to 600 m for March 1993 (dashed line) and November 2008 (solid line) with 40 μmol kg^{-1} marked as line.

19°W, however, the minimum is strong enough to be noticeable on the contour plot (Figure 2b).

[12] The lowest oxygen values reached in the CTD-sections between 300 m and 600 m depth at 7.5°N (Figure 2c) shows that except for 2 locations with similar minima at the western part of the section, the lowest oxygen concentrations the OMZ in November 2008 are 8.1 μmol kg^{-1} lower than in 1993, 15 years earlier. Although the lowest oxygen values are expected close to the coast, at 7.5°N there is only a weak oxygen decrease in the minima east of 26°W.

[13] For the November 2002 data along 10–11°N a less-pronounced oxygen minimum at the base of the thermocline at 60 to 150 m depth in the eastern Atlantic was described by *Wallace and Bange* [2004], which may be caused by enhanced remineralization in a region with high biological productivity and a shallow mixed layer. During this cruise, one oxygen concentration of 40.3 μmol kg^{-1} was observed at 9°18′N, 19°00′W at 400 m depth.

[14] The comparison between the 11°N section in November 2002 and November 2008 again reveals the lower dissolved oxygen values in the OMZ core layer in 2008 (Figure 3) despite the two repeats being separated by only 6 years. While in November 2002 the 50 μmol kg^{-1} contour forms the lowest large-scale isoline contour (Figure 3a), in November 2008 (Figure 3b) most of the area east of 24°W drops below 40 μmol kg^{-1}. The values below 40 μmol kg^{-1} are best visible in the comparison of the lowest values found between 300 m and 600 m depth (Figure 3c) with a decrease compared to the 2002 data of 2.7 μmol kg^{-1}. The smaller oxygen difference at 11°N compared to 7.5°N is consistent with the shorter time difference between the 2 cruises, but also affected by one high oxygen value in November 2008 at 24°30′W (Figure 3c) and possibly by the different station positions west of 24°W.

[15] While on both sections at 7.5°N and 11°N the oxygen in the core of the OMZ decreased, there is at the same time an increase of oxygen in large regions of the upper central water. Computing the differences on depth surfaces on the 7.5°N section between 2008 and 1993 resulted in an increase in potential temperature and salinity in the depth range 100 to 350 m depth east of 22°W and down to 800 m west of 22°W (Figures 4a and 4b). A similar increase for temperature and salinity had been observed for a meridional section in the central Atlantic between the time periods 1985 to 1999 and 1955 to 1969 [*Curry et al.*, 2003]. The increase in potential temperature is in agreement with increasing warming of the ocean [*Levitus et al.*, 2000]

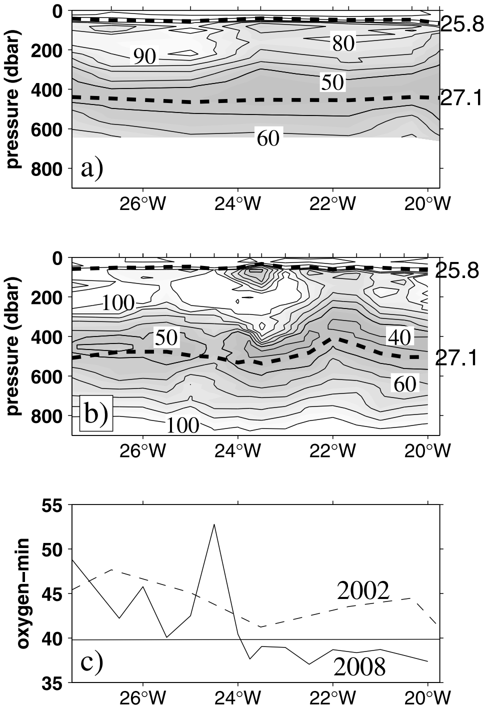

Figure 3. Dissolved oxygen section along about 11°N with 10 μmol kg^{-1} contour intervals below 100 μmol kg^{-1} and 50 μmol kg^{-1} contour intervals for oxygen in excess of 100 μmol kg^{-1} for (a) RV Meteor cruise in November 2002 and (b) data from November 2008. As in Figure 2 the isopycnals σ_θ = 25.8 and 27.1 kg m^{-3} are included. (c) The lowest oxygen values reached in the depth range 300 to 600 m for November 2002 (dashed line) and November 2008 (solid line) with 40 μmol kg^{-1} marked as line.

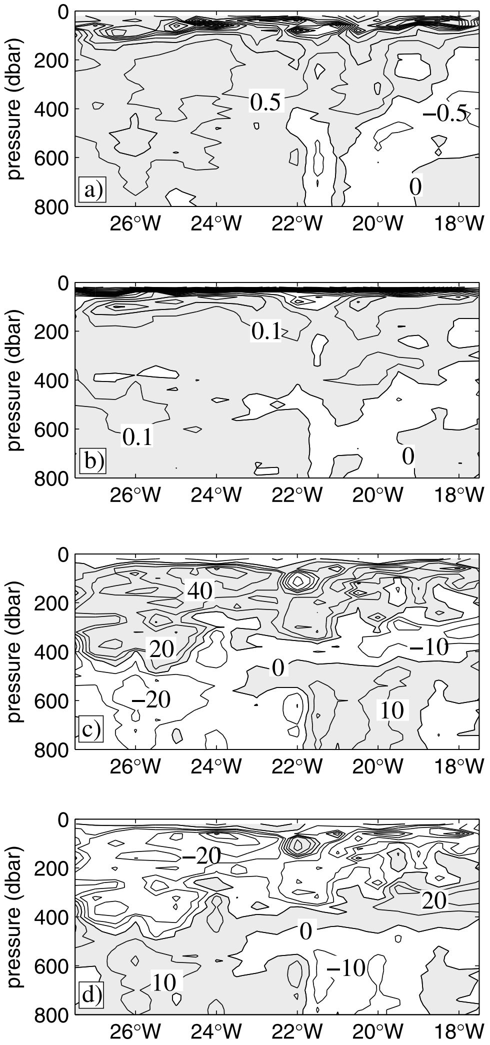

Figure 4. Differences between November 2008 and March 1993 for the section at 7.5°N for (a) potential temperature in °C (contour interval 0.5°C), (b) salinity (contour interval 0.1), (c) dissolved oxygen and (d) apparent oxygen utilization, Figures 4c and 4d both with 20 μmol kg^{-1} contour intervals as well as the -10 and +10 μmol kg^{-1} contours. The difference is calculated on depth surfaces.

although our result is just the difference between two realizations without any information on the short-term variability. The oxygen increased at 7.5°N between 1993 and 2008 in the layer 100 to 350 m and decreased in the OMZ minimum layer (Figure 4c). Thus, the oxygen difference patterns don't follow the changes in potential temperature and salinity and hence is not caused by temperature dependent oxygen solubility. The observed oxygen increase may be caused partly by higher oxygen in fall compared to spring due to seasonal variations of the ventilation by the North Equatorial Countercurrent (NECC) [*Stramma et al.*, 2008a]. Between 500 m and 800 m depth the oxygen increased east of 22°W while it decreased west of 22°W. The salinity and oxygen changes indicate increased/decreased AAIW fraction east/west of 22°W. The difference plot for apparent oxygen utilization, where the temperature and salinity dependence on oxygen solubility is accounted for (Figure 4d), resulted in a similar distribution at 7.5°N as the oxygen difference plot. At 11°N the temperature, salinity and oxygen differences are more patchy (not shown) probably due to strong eddy activity in November 2002 visible in altimeter data; they do however show a similar trend as at 7.5°N, of increasing potential temperature and salinity in the surface and central water layers and in oxygen mainly an increase in the central water layer and a decrease in the core layer of the OMZ.

4. Summary

[16] Our investigation of the OMZ in the tropical eastern North Atlantic reveals significant deoxygenation in the core of the OMZ. Record low oxygen concentrations of less than 40 μmol kg^{-1} were reached, and a direct comparison with earlier sections show that the oxygen minimum decreased by 8.1 μmol kg^{-1} over 15 years at 7.5°N and 2.7 μmol kg^{-1} over 6 years at 11°N. Both estimates are consistent with a deoxygenation rate of $\sim$0.5μmol kg^{-1} a^{-1} and if continued, the OMZ would go anoxic in less than 100 years. This cannot be expected but gives an idea of sensitivity. However, in our observations the oxygen content increased in the better-oxygenated upper part of the OMZ. Both potential temperature and salinity increased in these surface and central water layers, which can be partly explained by seasonal changes in the NECC at 7.5°N. *Curry et al.* [2003] suggest links to global warming and possible changes in the hydrologic cycle as the causes for the long-term observed temperature and salinity changes in the Atlantic. Similar trends in S, T and oxygen were found in modeled global warming scenarios [e.g., *Bopp et al.*, 2002; *Keeling and Garcia*, 2002; *Hofmann and Schellnhuber*, 2009]. While the reported record low oxygen minima are consistent with an expanding oxygen minimum zone as reported for the last 50 years for some tropical regions [*Stramma et al.*, 2008b] the increasing oxygen content in the upper central water layer is not consistent with the previously identified vertical expansion of the OMZ. Increasing oxygen is in part related to the seasonality in the SACW and horizontal shifts in the AAIW, but other processes not yet identified and focus of present research might be involved. The observed long-term oxygen time series [e.g., *Whitney et al.*, 2007; *Stramma et al.*, 2008b] showed phases with trend reversal, hence we should not assume a simple linear trend response in the future. The record low oxygen values reported here demonstrate the need for continuous future surveys of the changes of the water mass characteristics, especially changes in dissolved oxygen concentrations given the potentially profound impact of deoxygenation on ecosystems, fishery and microbiology.

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