climate change SUPPLEMENTARY INFORMATION
DOI: 10.1038/NCLIMATE1304

Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes

Dissolved oxygen presentation

On our recent cruises, we measured DO using the classical Winkler titration method, which was similar to that used in earlier studies. Hence, no method-related differences influenced our comparisons between recent and older data sets. Using the common unit mL L^{-1} to describe DO levels, the precision of the DO measurement was 0.03 mL L^{-1}, decreasing by about 25% for oxygen contents below 2 mL L^{-1} [32]. For converting to other DO units: µmol L^{-1} = 44.66 mL L^{-1}; µmol kg^{-1} = 44.66 mL $L^{-1}(\rho^{-1})$, where ρ is the density of sea water; and, mg L^{-1} = mL L^{-1}/0.7.

The hydrographic data sets

The basic data set of the computation was the freely available HydroBase-2 (presently the web-page is rewritten to HydroBase-3)[33] software and data set. HydroBase is a tool for climatological analysis of oceanographic properties. Building upon isopycnal averaging techniques developed for a North Atlantic climatology[34], it provides a flexible means of producing and analyzing datasets customized to investigators' research needs. The original version of HydroBase was revamped for version 2, e.g. the software was totally rewritten to conform to ANSI standards, many new functions and features were added and the database was updated to incorporate the substantial data set acquired during the World Ocean Circulation Experiment (WOCE).

The HydroBase-2 quality controlled data set as of 10 October 2008 was supplement with data collected during several recent cruises in the tropical northeastern Atlantic (Table S1, Figure S1). These cruises were made primarily within the large multidisciplinary project 'climate – biogeochemistry interactions in the tropical ocean' to investigate the oxygen minimum zone in the tropical northeastern Atlantic. The cruises were directed at a spatial survey to investigate the spreading of a tracer released in the OMZ in April 2008, or, on repeated surveys of the OMZ along 23°W.

Expanding oxygen minimum zones

The expansion of oxygen minimum zones in tropical regions is visible in plots of vertical mean annual oxygen profiles versus depth[3]. As the rates of change in Figure 2 do not provide information about the stability of the changes, we present two examples of the ongoing deoxygenation in the eastern tropical North Atlantic (ETNA). To reduce the influence of spatial variability we reduced the area to 2°x2° squares. In addition to the cruises listed in Table S1, a RV Meteor cruise covered the ETNA in October and November 2010. The 2010 CTD-oxygen profile calibrations are still not finalized however, we used the preliminary data set to extend the time series to the end of 2010. Annual mean oxygen profiles were derived and objectively mapped using correlation scales of 1 year and 50 m.

An area 12-14°N, 22-24°W south of the Cape Verde Islands (Figure S2a,b), and an area 6-8°N, 16-18°W south of the eastern side of the OMZ were selected (Figure S2c,d). The time series for the vertical oxygen profiles indicated the vertical expansion of the low oxygen layer, despite the large gaps in time for which no oxygen profiles were available in the selected region. For the area 12-14°N, 22-24°W the trend (Figure S2b) resulted in -0.010 +/- 0.004 mL L^{-1} yr^{-1} and was significantly different from zero at the 95% confidence level. The variance explained by the linear trend is 63%. For the area 6-8°N, 16-18°W the trend (Figure 2d) resulted in -0.009 +/- 0.003 mL L^{-1} yr^{-1} and was also significantly different from zero at the 95% confidence level. The variance explained by the linear trend was 85%. Although the data did not provide information on the future, the two examples clearly document an ongoing deoxygenation process that lasted at least until the end of 2010. Our results do not allow for a clear differentiation between multi-decadal variability and long-term global change.

Electronic Tagging Methods

In-water tagging techniques[35] and associated equipment described previously[8,9,36] were used for this study. Pop-up satellite archival tags (PSATs, Fig. 1) were programmed to transmit summarized data of depth, temperature and light. The light data were initially processed using the global positioning software WC-AMP (Wildlife Computers) to derive light-level based geolocations. We then applied a sea-surface temperature-corrected Kalman filter[37,38] and a custom bathymetry filter to refine the final movement track, based on 2 x 2 minute grid ETOP02 bathymetry[39] data and the daily maximum depth from the PSAT[9]. Wildlife Computers (www.wildlidfecomputers.com, Redmond, WA, USA) PSAT models PAT 3 and 4 were deployed on blue marlin to monitor horizontal and vertical habitat in the western North Atlantic and eastern Tropical Atlantic. The three blue marlin featured in Figure 3 were tagged off Long Island, Bahamas in the WNA (2003) and the Cape Verde Islands in the ETA (2004). The data on maximum daily depth was taken directly from PSAT depth/temperature (PDT) records for each binning interval for all 47 Atlantic blue marlin deployments (Fig. 3a). The tag information for the three blue marlin featured in Fig. 3b-f, as well as all blue marlin deployments are summarized in Table S2.

Supplementary References

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Supplementary Tables:

Table S1. Datasets used to compute oxygen changes.

Dataset	Comments
Hydrobase QC Dataset[33]	Online version October 2008.
Cruises:	
Meteor 47/1	April 2000 23°W
Meteor 55	October/November 2002 tropical North Atlantic bottle data
Meteor 68/2	June/July 2006 tropical and equatorial Atlantic
Meteor 68/3	July/August 2006 off Africa
Atalante	February 2008 off Africa
Atalante	March 2008 23°W section
Merian 8/1	April 2008 tropical northeast Atlantic
Merian 10/1	November/December 2008 tropical northeast Atlantic
Meteor 80/1	October/November 2009 23°W section
Meteor 80/2	November/December 2009 tropical northeast Atlantic

Table S2. Summary of pop-up satellite archival tag information for 47 blue marlin deployed in the western North Atlantic (WNA) and eastern tropical Atlantic (ETA) zones during 2002-2004 including: PSAT number (PTT), date deployed, days-at-large (DAL), linear displacement, release zone, release location, and pop-up location.

No.	PTT	Date deployed	DAL	Displacement (nm)	Release zone	Release location	Pop-up location
1	22870	9 Jun 02	36	499	WNA	28.71N-78.89W	36.27N-74.76W
2	23548	11 Jun 02	33	490	WNA	28.76N-78.79W	35.99N-74.37W
3	25999	14 Jun 02	45	747	WNA	23.93N-74.59W	17.41N-63.24W
4	22872	14 Jun 02	28	353	WNA	23.94N-74.61W	25.00N-68.26W
5	23077	21 Jun 02	19	71	WNA	23.79N-74.36W	24.93N-74.70W
6	23520	2 Jul 02	25	245	WNA	22.80N-74.35W	26.79N-73.41W
7	26005	6 Jul 02	13	72	WNA	22.82N-74.38W	22.70N-75.68W
8	26001	8 Jul 02	25	795	WNA	22.78N-74.39W	35.51N-70.16W
9	27825	12 Oct 02	29	566	WNA	18.71N-64.82W	15.56N-74.13W
10	26935	12 Oct 02	39	287	WNA	18.72N-64.83W	21.78N-60.92W
11	23205	13 Oct 02	38	1193	WNA	18.72N-64.82W	07.54N-47.90W
12	39334	14 Oct 02	43	229	WNA	18.85N-64.79W	22.44N-66.18W
13	41523	4 Jun 03	95	218	WNA	24.10N-75.25W	24.55N-71.29W
14	41524	4 Jun 03	82	319	WNA	24.10N-75.28W	19.03N-73.56W
15	41518	5 Jun 03	63	492	WNA	24.33N-72.53W	31.20N-77.59W
16	41520	5 Jun 03	63	825	WNA	24.10N-75.25W	36.85N-69.23W
17	23388	7 Jun 03	60	428	WNA	20.26N-72.47W	16.23N-66.27W
18	41521	7 Jun 03	61	176	WNA	24.10N-75.25W	22.25N-72.77W
19	41525	7 Jun 03	41	342	WNA	24.12N-75.27W	29.79N-75.85W
20	41526[a]	7 Jun 03	84	699	WNA	24.12N-75.30W	35.70N-73.83W
21	23389	8 Jun 03	61	406	WNA	20.25N-72.83W	16.02N-67.27W
22	23397	9 Jun 03	38	80	WNA	20.30N-72.62W	18.98N-72.85W
23	41522	9 Jun 03	10	80	WNA	24.08N-75.25W	24.98N-74.17W
24	41528	10 Jun 03	69	255	WNA	24.11N-75.28W	28.26N-74.28W
25	41516	11 Jun 03	57	212	WNA	24.05N-75.43W	27.25N-73.78W
26	41538	16 Jun 03	47	1125	WNA	21.99N-72.03W	14.29N-54.01W
27	41534	17 Jun 03	46	549	WNA	22.00N-72.07W	19.13N-62.78W
28	41539	18 Jun 03	74	92	WNA	21.99N-72.06W	20.62N-71.31W
29	41531	19 Jun 03	91	199	WNA	22.00N-72.06W	23.93N-69.12W
30	41530	26 Jun 03	7	91	WNA	22.85N-74.41W	24.36N-74.42W
31	41527	14 Jul 03	41	203	WNA	32.05N-65.03W	34.78N-67.43W
32	41537	24 Jul 03	45	498	WNA	32.13N-65.01W	36.11N-56.20W
33	41535	2 Sep 03	28	263	WNA	18.57N-66.22W	14.59N-64.29W
34	41540	3 Sep 03	7	57	WNA	18.57N-66.22W	19.06N-65.36W
35	42723	3 Sep 03	124	1397	WNA	18.53N-66.18W	03.08N-48.39W
36	42724	3 Sep 03	115	163	WNA	18.53N-66.18W	18.63N-63.32W
37	42722	3 Sep 03	39	1477	WNA	18.57N-66.22W	05.17N-45.06W
38	49773	9 May 04	21	154	ETA	16.98N-25.35W	14.43N-25.57W
39	49774[b]	10 May 04	47	756	ETA	16.92N-25.33W	28.41N-30.95W
40	49777	10 May 04	15	371	ETA	16.95N-25.38W	13.45N-30.66W
41	49775[c]	12 May 04	70	393	ETA	16.75N-25.10W	17.42N-18.28W
42	53733	14 Oct 04	4	15	ETA	07.90S-14.43W	08.10S-14.57W
43	53244	16 Oct 04	44	924	ETA	07.85S-14.40W	07.37N-16.78W
44	53245	19 Oct 04	36	390	ETA	07.90S-14.23W	02.85S-10.11W
45	53736	7 Nov 04	90	1373	ETA	07.00S-14.00W	26.78S-26.10W
46	53734	17 Nov 04	38	347	ETA	07.90S-14.43W	03.54N-10.60W
47	49778	12 May 04	56	161	ETA	16.75N-25.10W	17.68N-22.47W

[a] Specimen shown in Fig. 3b, d.
[b] Specimen shown in Fig. 3c, e.
[c] Specimen shown in Fig. 3c, f.

Supplementary Figures:

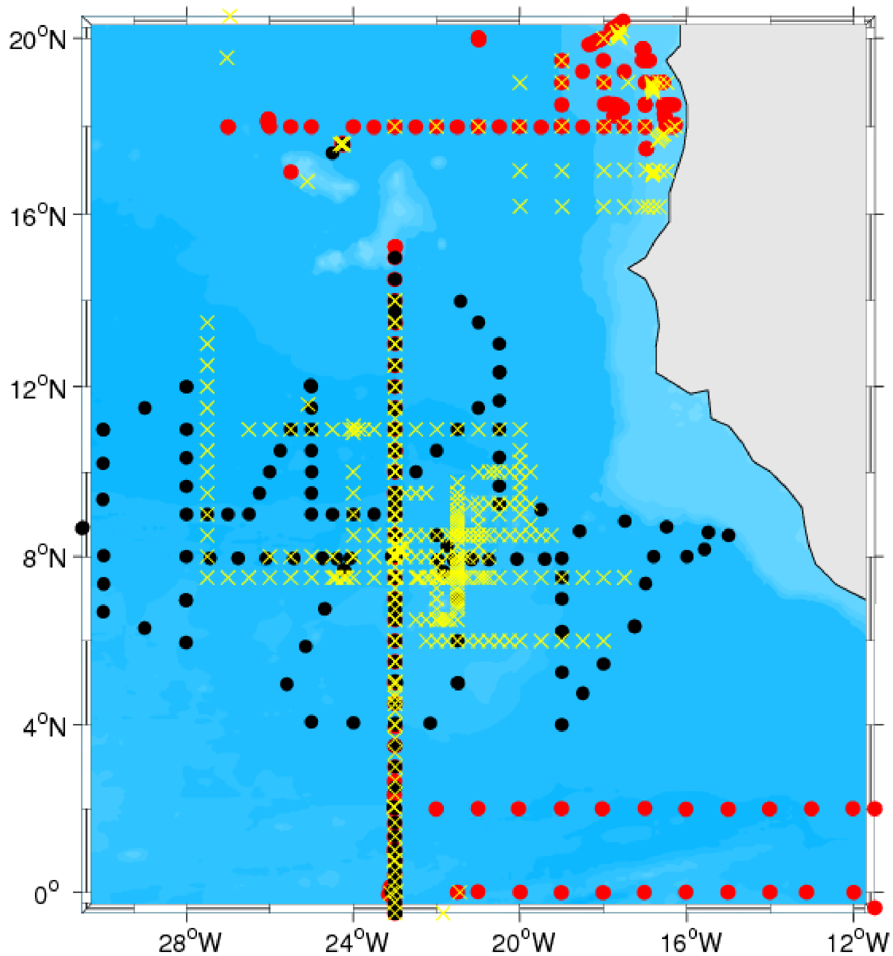

Figure S1 | Distribution of recent oxygen profile locations (see Table S1) sampled in 2006 (red dots), 2008 (yellow crosses) and 2009 (black dots) added to the HydroBase-2[33] data set.

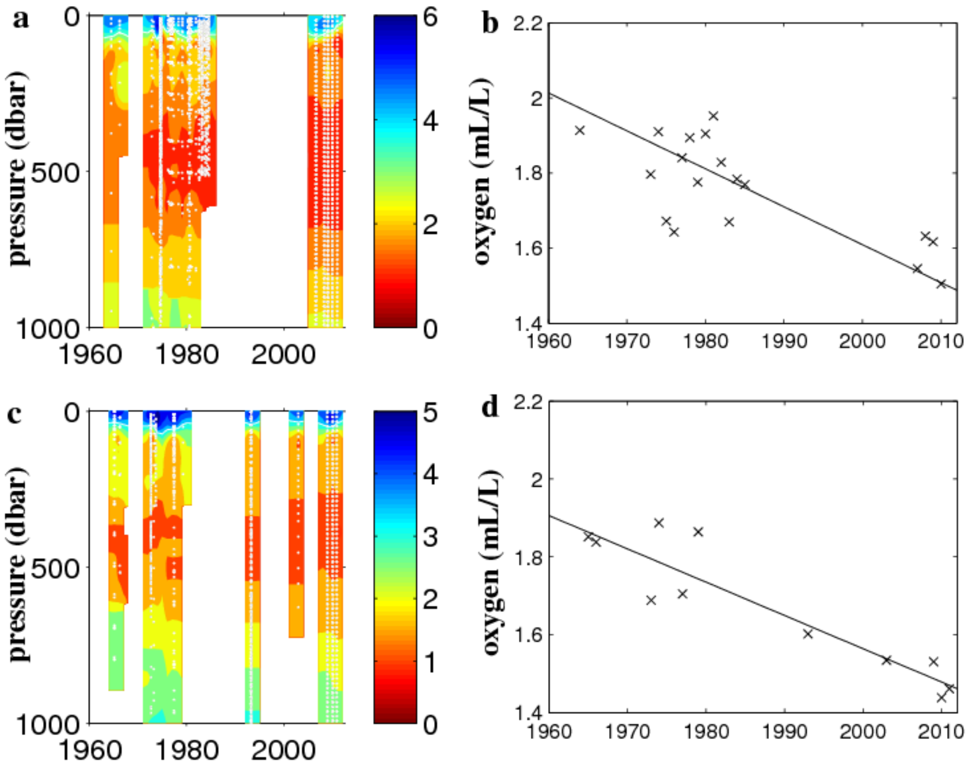

Figure S2 | Dissolved oxygen concentration maps versus time and time series of annual mean 50 to 500 m dissolved oxygen in (mL L^{-1}). Areas selected are **a, b,** 12-14°N, 22-24°W and **c, d,** 6-8°N, 16-18°W. Vertical sample locations are shown as white dots in **a,c**. Linear fits are shown as solid lines in **b,d**.