

Authors' response on manuscript "Decadal oxygen change in the eastern tropical North Atlantic"

Johannes Hahn¹, Peter Brandt¹, Sunke Schmidt¹, Gerd Krahmann¹

¹GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany

Correspondence to: Johannes Hahn (jhahn@geomar.de)

Dear Editor,

we would like to thank you and the two anonymous reviewers for the positive, but thorough evaluation of the manuscript. We appreciate the fruitful comments, which help to improve the manuscript. We have structured our response to the referees' comments as follows: The individual comments from the referees are given in black and are directly followed by the authors' response (AR) given in blue color. The AR not only contains the answer to the reviewer's comment, but also contains a brief description about what was changed in the manuscript (→ '*manuscript changes*'). All figures given in this authors' response letter are referenced with AR-Fig. ##. All figures from the manuscript that are referred to in the authors' response letter are referenced with Fig. ## (or with 'former Fig. ##' when referring to figures in the published discussion paper).

Anonymous Referee #1

Review of the manuscript os-2016-102 Decadal oxygen change in the eastern tropical North Atlantic Johannes Hahn et al.

The manuscript presents an study on decadal variability of Eastern North Tropical Atlantic (ETNA) Oxygen Minimum Zone (OMZ) from in situ measurement (including mooring and repeated shipboard section). The authors show decadal negative trend of dissolved oxygen (DO) within the upper OMZ (200-400 m), while increase of DO is shown within lower OMZ layer (400-1000 m). This is attributed to a southward shift of the wind-driven zonal circulation in the North Tropical Atlantic, which supplies the ETNA in oxygen enriched water including South Atlantic subtropical Waters. Isopycnal salinity/spiciness is also used as proxy to infer DO concentration variability (negative correlation in the ETNA) in the broader context of the upper South and Tropical Atlantic circulation.

The manuscript presents an interesting multi-sensor approach to document the variability of last decade of the ETNA OMZ. This is a valuable contribution to better understand the complex variability and dynamics of the DO in this region, which has been intensively investigated since ten years by this group. However, the manuscript is a little bit too long and lack of concision. Some Figures are poor and not easy to read (that make them not

35 convincing). Also some supplementary analyses could be valuable to strengthen the results (oxygen and salinity transports).

Suggestion of the reviewer: moderate revision.

40 AR: Thank you very much for the general statement and the positive evaluation of the manuscript. According to the reviewer's comments, we generally did the following changes in the manuscript:

i) We calculated a rough estimate of the lateral advective oxygen supply as well as its temporal change. Even though this is only a qualitative estimate, the vertical profile generally agreed with our results in the oxygen budget. We used this result to strengthen our argumentation that changes in the lateral advective oxygen supply may have substantially contributed to the observed decadal oxygen changes.

ii) We removed detailed descriptions of data analysis methods from Sect. 3 and included them in Sect. 2 in order to improve the readability and comprehensibility of Sect. 3.

50 iii) We reordered the figures in the result section Sect. 3.2 in order to improve the structure and the flow in the manuscript (Fig. 3 – Fig. 9). The text in Sect. 3.2 was restructured and edited according to the figure order. Some figures, that were poor in content or not easy to read, were removed or edited/regrouped, in particular a better view on the comparison of shipboard and moored observations and float observations.

iv) We included a schematic (Fig. 15) in order to illustrate oxygen and ventilation changes and the associated upward migration of the ETNA OMZ.

55 In the following specific answers to all reviewer's comments are given including according changes in the manuscript.

Comments/Questions:

1.108: typo : 'Theta-S'

AR: Done. Changed to ' θ -S'.

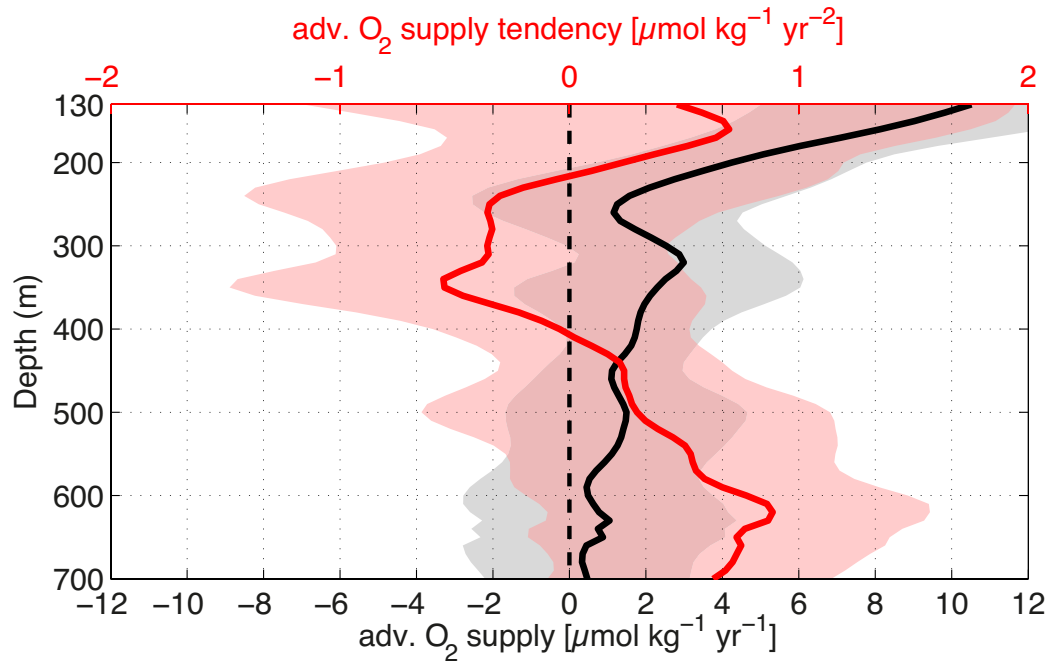
60 1.217: The advection which is the key mechanism is estimated as residual. Is it possible (why if not) to make an estimate of such a term from data at hand? (see comment below)

65 AR: It is quite a challenge to derive a consistent and quantitative estimate of the advective supply solely based on observations. Such an estimate would be only reasonable, if all surfaces (sections) of a well-defined 'ocean box' were measured quasi simultaneously (e.g. as a combination of repeat ship sections and moored observations complemented by other measurement platforms such as floats or gliders) in order to determine all influxes/outfluxes

to/from this box. This cannot be achieved with the existing data set available for this study. However, we followed the reviewer's suggestion and qualitatively estimated the advective supply and its tendency directly from observations in order to strengthen our discussion about the physical drivers of the decadal oxygen change.

For this rather qualitative estimate, we defined a box between 23°W and 15°W and between 6°N and 14°N. We assumed a balanced mass flux through the 23°W section, whereas fluxes through all other boundaries are negligible. This is a very strong assumption, but nevertheless we believe that this represents the effect of the mean current field in this regime to first order of magnitude.

The lateral advective oxygen supply was estimated by calculating the integral of eastward and westward fluxes through 23°W and subsequently dividing the result by the volume of the assumed box as given above. Indeed, the vertical structure of the mean lateral advective oxygen supply as well as of its decadal change (AR-Fig. 1) is qualitatively in agreement with the oxygen budget terms (vertical structure of the residual supply and decadal oxygen change, respectively).



AR-Fig. 1: Vertical profiles of the mean zonal advective oxygen supply across 23°W (black) and the lateral advective oxygen supply tendency (red) calculated from shipboard observations along 23°W and referred to the box regime 23°W-15°W and 6°N-14°N. Gray shading defines double the standard deviation of the advective oxygen supply and red shading is the 95% confidence band of the advective oxygen supply tendency. (This figure is now Fig. 14 in the manuscript)

Manuscript changes: We have included a passage with a detailed description about the qualitative estimate of the advective oxygen supply and its respective trend in the manuscript's discussion section (ll. 1206–1239). We also included figure AR-Fig. 1 (Fig. 14 in the manuscript) and we embedded a qualitative discussion of the results.

Section 3.2: This section could be more effective if restructured : The observations of interannual variability and decadal trend need to be first introduced (Fig. 3-4-5-8-9), then mechanism of passive advection and correlation with spiciness should be discussed (Fig. 6-7-10-11).

AR: We have reordered the figures following the reviewer's suggestion. Moreover, the presentation of the time series was simplified to improve comprehensibility (Fig. 3 – 5).

Manuscript changes: The order of the figures was restructured as given in the following. The manuscript (mainly Sect. 3.2) was changed accordingly to the figure order.

1) We changed the figures of the mooring time series (former Fig. 3, 4, 5). Now: Fig. 5, 4 and 3. Instead, we plotted time series as averages over two depth regimes (200m-400m and 500m-800m) in order to improve the presentation and comparison of shipboard and moored observations. We also included the trend estimate from moored and shipboard observations together and removed the figure with vertical profiles of the decadal trend (former Fig. 8). The latter change was done according to a specific comment by reviewer 2.

2) We kept former Fig. 9 (trend estimates from shipboard observations), but we included an additional subpanel with an estimate of the salinity trend based on float observations. Now: Fig. 6.

3) We removed former Fig. 10 (correlation of oxygen and salinity trend) and included a table with oxygen and salinity trends for different boxes averaged over latitude and depth. Now: Table 3. This shall improve the structure and the thread of the manuscript.

4) We kept former Fig. 7, as this helps to better understand the correlation of oxygen and salinity as well as the relation of the respective trends (given in Fig. 6 and Table 3). Now: Fig. 7.

5) We kept former Fig. 11 showing the salinity trends from float observations at density surfaces 26.8 and 27.2. Now: Fig. 8.

6) We kept former Fig. 6 about the OMZ location. Now: Fig. 9.

1.296-298: The DO increase of the lower layer may be barely significant. Figures 3 and 4 does not show such a tendency.

AR: The combination of moored and shipboard observations shall generally give an overview about the existing data set. Indeed, there is a lot of variability existing on different time scales which makes it challenging in ad-hoc interpreting the time series. However, particularly for 11°N (as well as for 8°N) the combined presentation of both data sets strengthens our argumentation, since moored observations show negative oxygen anomalies in the upper OMZ layer (above 400 m) and positive oxygen anomalies in the lower OMZ layer (below

400 m). The now plotted depth average of the time series over the upper and the lower depth layer shall provide a more detailed view on the time scales existing in the time series (Fig. 3 to 5).

Most striking is the meridional section of the decadal oxygen change based on shipboard observations, where a significant average oxygen decrease ($5.9 \pm 3.5 \mu\text{mol kg}^{-1} \text{decade}^{-1}$) was found in the upper layer between 200 and 400 m and a significant average oxygen increase ($4.0 \pm 1.6 \mu\text{mol kg}^{-1} \text{decade}^{-1}$) was found in the lower layer between 400 and 1000 m, both as an average between 6°N and 14°N . The spatially coherent structures in both depth layers further strengthen the robustness of this estimate.

We agree with the reviewer's argumentation, that shipboard and moored observations at 5°N , 23°W don't show a decadal oxygen change in the respective two depth layers. Here, intraseasonal, seasonal and interannual variability plays an important role, likely driven by tropical instability waves as well as variability in the zonal currents (NECC/NEUC).

Manuscript changes: We have rewritten the passage in the manuscript about oxygen time series and the decadal oxygen tendency from shipboard observations (ll. 473-481). Now, depth averaged time series are shown in the manuscript (Fig. 3 to Fig. 5), also according to a suggestion from reviewer 2. In ll. 482-612, significant oxygen tendencies with confidence intervals are given (i) as an average between 6°N and 14°N and (ii) as box averages (table 3). The decadal salinity tendency was additionally calculated from float observations along 23°W (Fig. 6c) in order to make this estimate more robust. The text passage was adapted accordingly in ll. 613-618.

Fig.3-5: is it possible to group this figures to allow an better overview of the ship and mooring data set at hand. Also, please improve this figure to make them more read- able (plot the time series in row panels for example to elongate them and improve the readability). Why it is it the mean isopycnal that is represented on the right panels and not the full isopycnal depth time series? Also, It seems that the seasonal to interannual variability may be important : discontinuity between mooring measurements and shipboard sections are questionable. Please better comment this point.

AR: Fig. 3, 4 and 5 were completely renewed. Instead showing the full depth range, depth averages of oxygen and salinity anomaly time series were plotted for two depth layers (200-400m and 500-800m). The anomaly time series were evaluated on isopycnal surfaces in order to remove the effect of isopycnal heave. For a more intuitive representation, we converted the results back onto depth grid and calculated the depth average. Thus, a particular depth can be associated as the mean depth for a specific isopycnal surface. The mean depth of the two depth layers corresponds to the isopycnals 26.8 and 27.2.

Intraseasonal to interannual variability becomes more important at the southern rim of the OMZ (we stated this in more detail in ll. 473-481 of the manuscript). Particularly at 5°N , no significant decadal changes in oxygen or salinity could be generally observed and

intraseasonal to interannual variability is dominant, likely driven by tropical instability waves as well as variability in the zonal currents (NECC/NEUC). This can be directly seen in the mooring time series of oxygen anomaly and salinity anomaly, where dominant time scales of positive and negative anomalies are between a month and several years. The strong inconsistency between estimates of decadal change in salinity from shipboard observations on the one hand (former Fig. 9b) and a combination of moored and shipboard observations on the other hand (former Fig. 8b) was mainly in the upper 200m. We revisited again the salinity time series at 100m for the last mooring period of the 5°N mooring. Indeed, the corresponding sensor likely had a bad conductivity cell after about 1/5 of the mooring period. This data was removed. Note that at 5°N, salinity fluctuations on a time scale of about the whole decade could be observed at depths between 100 and 300 m.

At 8°N and 11°N, intraseasonal to interannual variability is less pronounced compared to 5°N as can be directly seen from moored observations. Decadal changes become more important. Thus, estimates of decadal changes become more robust. However, moored observations at 8°N and 11°N are too short to use them alone for an estimate of decadal changes in oxygen and salinity. Shipboard observations provide a reasonable alternative to estimate decadal changes due to the reduced variability on intraseasonal to interannual time scales.

Manuscript changes: Fig. 3, 4 and 5 were completely changed and all time series anomalies were plotted as depth averages for two depth layers (200-400m and 500-800m). However, the time series anomalies were calculated in density space. More details about the time series were given in ll. 473-481.

l. 308-309: Maybe introduce that the ventilation process by passive tracer circulation appear to be a significant mechanism in the lower layer of OMZ. However, I would first introduce the Fig. 8 and 9 before trying to correlate between S and DO. Indeed, it seems that the link between spiciness and DO less robust, than the observed trends of both S and DO (Fig. 7 and 10), and need to be discussed in the larger context of the STC along with the Fig. 11.

AR: If the reviewer meant that dissolved oxygen and salinity are not robustly correlated in the upper 200-300m of the water column as well as around the OMZ core, we agree. However, at depth of the lower Central Water and Intermediate Water, both variables correlate well south of the OMZ core with an average slope of about $\frac{\partial O_2}{\partial S} = -255 \pm 140 \mu\text{mol/kg}$ (we additionally stated this in the manuscript in l. 623). A qualitatively similar relation is also shown for the oxygen vs. salinity trend south of the OMZ core. Close to the OMZ core, oxygen vs. salinity correlation is not given at all. However, as mentioned already in the manuscript, a direct relation among salinity changes and water mass or circulation changes cannot be drawn.

Manuscript changes: We included one sentence in the beginning of the respective paragraph to make clear, that oxygen and salinity changes are analyzed in order to study the effect of physical ventilation processes (ll. 619-620).

We followed the reviewer's suggestion and reordered former Fig. 6 to 10. Former Fig. 9 (now: Fig. 6) is introduced before former Fig. 6, 7 and 10. Former Fig. 8 and 10 were removed. A detailed overview about the figure order is given in the response to the reviewer's 3rd comment.

205 We included a quantitative estimate of the slope $\frac{\partial O_2}{\partial S} = -255 \pm 140 \text{ } \mu\text{mol/kg}$ in the manuscript in l. 623 in order to underline the significant correlation of oxygen and salinity south of the OMZ core and below the deep oxycline.

210 There were already described several remote processes, which might have lead to salinity changes in the eastern tropical North Atlantic (see ll. 990–996 in the manuscript). In addition, we included a paragraph in Sect. 4.2 in order to state the potential impact of these processes on oxygen changes in the ETNA (ll. 1003-1074).

Fig. 8-9: Try to group these figures

215 AR/Manuscript changes: Former Fig. 8 was removed and instead, the trends were included in the depth averages of oxygen and salinity anomaly time series (Fig. 3, 4, 5) - according also to reviewer 2). Former Fig. 9 (Now: Fig. 6) was kept, but an additional subpanel was included showing the estimate of the decadal salinity change from float observations.

220 1.372-380: This is a striking results of the paper. It would be more convincing if DO and S transport were calculated. Also divergence of these transports between 23°W and African coast (if a good assumption) could help to estimate the variability of zonal advection of DO and S ?

AR: We followed the reviewer's suggestion and qualitatively estimated the oxygen flux divergence (oxygen supply) due to zonal advection. As this point was already mentioned earlier by the reviewer, details are given above in the response to the reviewer's 2nd comment.

225 The estimate of the zonal advection was solely based on oxygen. This was not done for salinity, since no salinity budget was calculated for the ETNA.

1.381-402: What is the driver of such meridionnal shift of the surface currents ? (wind curl?)

AR: Yes, we strongly suspect that changes in the large-scale wind stress curl may have driven (Sverdrup) circulation changes in the upper few hundred meters in the eastern tropical North Atlantic. The quantitative investigation of this mechanism goes beyond this study.

230 Manuscript changes: The suspected relation between (Sverdrup) circulation changes an the large-scale wind stress curl is pointed out at two defined positions in the manuscript. (i) ll. 1082-1083 (Sect. 4.2: discussion): here we specified our description with ',... wind-driven gyres of the tropical North Atlantic ...'. (ii) ll. 1293-1294 (Sect. 5: Summary and conclusion):

here we specifically included the speculation ,... - which are likely related to changes in the large-scale wind-stress curl - ...’

Anonymous Referee #2

The manuscript updates the observed decadal trend of Dissolved Oxygen (DO) of Eastern Tropical North Atlantic (ETNA) using both shipboard and moored measurements, as well as satellite Sea Surface Height (SSH) and Argo float profiles. The authors found that the most recent decadal trend is characterized by a dipole structure with decreasing DO in the 100-400m depth range and increasing trend below between 400m and 800m. This is in contrast to the previously identified multidecadal trend declining more uniformly from 100m to 800m. Results suggest that low frequency DO changes are more complicated than previously thought. Authors attribute the DO trend in the most recent decade to a southward shift of wind driven circulation in the upper layer and strengthening of Latitudinally Alternating Zonal Jets (LAZJ) in the deeper part. The study presents an interesting analysis of in situ measurements in the ETNA Oxygen Minimum Zone (OMZ) and should be publishable after addressing the following concerns. A minor revision is recommended.

Major Concern: The presentation is not easy to follow mainly because evidence shown in several of the figures are not robust and noisy. Some of the following specific comments may help to improve the manuscript.

AR: Thank you very much for the general statement and the positive evaluation of the manuscript. According to the reviewer’s comments, we generally did the following changes in the manuscript:

i) We improved the structure and the flow in the manuscript, particularly in the result section Sect. 3. Detailed descriptions of data analysis methods were removed from Sect. 3 and included in Sect. 2 in order to improve the readability and comprehensibility of Sect. 3. Some figures, that were poor in content or not easy to read, were removed (former Fig. 8 and 10), other figures were edited or regrouped (former Fig. 3 to 11). The text (particularly in Sect. 3.2) was restructured and edited according to the figure order.

ii) In particular, we completely renewed the figures about the mooring time series (former Fig. 3 to 5). These Figures (Now: Fig. 5, 4 and 3) show depth averages of the anomaly time series for two depth layers (200-400m and 500-800m) to improve the view on the consistency between moored and shipboard observations.

iii) We calculated a rough estimate of the lateral advective oxygen supply as well as its temporal change. Even though this is only a qualitative estimate, the vertical profile generally agreed with our results in the oxygen budget. We used this result to strengthen our argumentation that changes in the lateral advective oxygen supply may have substantially contributed to the observed decadal oxygen changes.

270 iv) We included a schematic (Fig. 15) in order to illustrate oxygen and ventilation changes and the associated upward migration of the ETNA OMZ.

In the following specific answers to all reviewer's comments are given including according changes in the manuscript.

Specifics:

275 1) Line 108: "q-S" typo here?

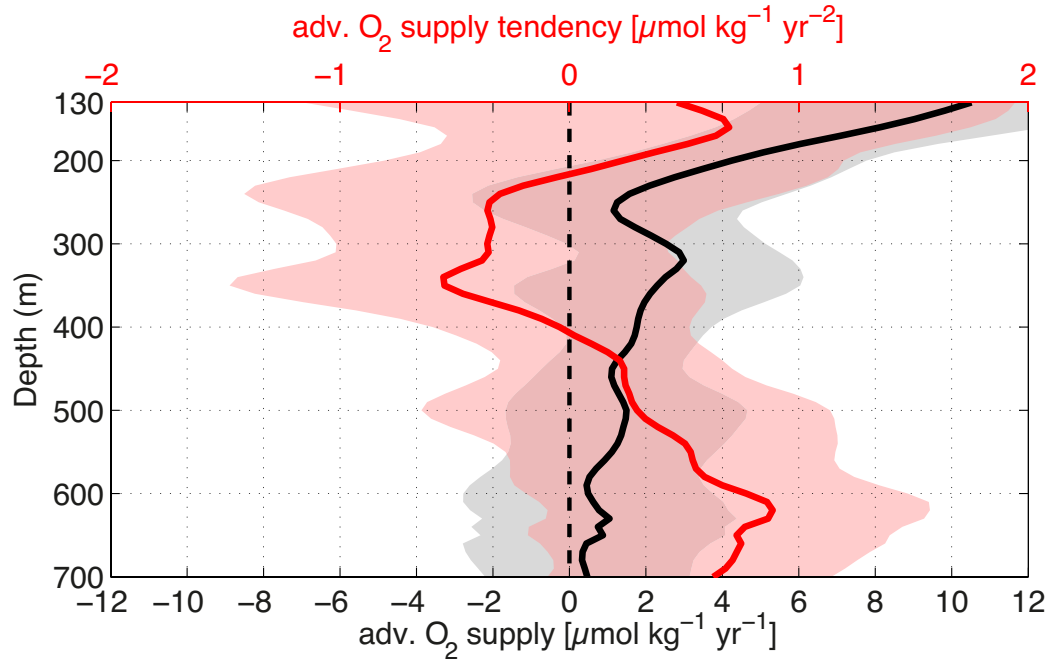
AR: Changed to ' θ -S'.

2) Line 230, residual term in eq.1, "[5] . . . composite of mean advection, zonal eddy diffusion as well as submesoscale processes": Mean advection shall be separately estimated by using the shipboard and mooring data.

280 AR: It is quite a challenge to derive a consistent and quantitative estimate of the advective supply solely based on observations. Such an estimate would be only reasonable, if all surfaces (sections) of a well-defined 'ocean box' were measured quasi simultaneously (e.g. as a combination of repeat ship sections and moored observations complemented by other measurement platforms such as floats or gliders) in order to determine all influxes/outfluxes to/from this box. This cannot be achieved with the existing data set available for this study.
285 However, we followed the reviewer's suggestion and qualitatively estimated the advective supply and its tendency directly from observations in order to strengthen our discussion about the physical drivers of the decadal oxygen change.

290 For this rather qualitative estimate, we defined a box between 23°W and 15°W and between 6°N and 14°N. We assumed a balanced mass flux through the 23°W section, whereas fluxes through all other boundaries are negligible. This is a very strong assumption, but nevertheless we believe that this represents the effect of the mean current field in this regime to first order of magnitude.

295 The lateral advective oxygen supply was estimated by calculating the integral of eastward and westward fluxes through 23°W and subsequently dividing the result by the volume of the assumed box as given above. Indeed, the vertical structure of the mean lateral advective oxygen supply as well as of its decadal change (AR-Fig. 1_2) is qualitatively in agreement with the oxygen budget terms (vertical structure of the residual supply and decadal oxygen change, respectively).



AR-Fig. 1_2: Vertical profiles of the mean lateral advective oxygen supply across 23°W (black) and the lateral advective oxygen supply tendency (red) calculated from shipboard observations along 23°W and referred to the box regime 23°W-15°W and 6°N-14°N. Gray shading defines double the standard deviation of the advective oxygen supply and red shading is the 95% confidence band of the advective oxygen supply tendency. (This figure is now Fig. 14 in the manuscript)

Manuscript changes: We have included a passage with a detailed description about the qualitative estimate of the advective oxygen supply and its respective trend in the manuscript's discussion section (ll. 1206–1239). We also included figure AR-Fig. 1_2 (Fig. 14 in the manuscript) and we embedded a qualitative discussion of the results.

3) Much of the significant changes, DO or salinity (S), are identified on density surfaces 26.8 and 27.2, but presented in difference-maps of two time periods (e.g., Fig.9). These two density surfaces happen to be the upper and lower bound of OMZ (Fig. 2). Even though isopycnal heaving has been ruled out as the main reason for observed variations, time series of moored DO and S, together with data points from shipboard measurements, shall be presented in the data section or 3.2 on these two density surfaces and 27.0 (corresponding to the center of OMZ).

AR/manuscript changes: We have calculated depth averages of the time series anomalies for two depth layers in order to explicitly show amplitude and time scales of oxygen and salinity fluctuations both from moored and shipboard observations. The two depth layers (i) 200-400m and (ii) 500-800m show the observed oxygen decrease in the upper layer and the oxygen increase in the lower layer. The depth averaged time series anomalies for the three mooring positions are shown in Fig. 3, 4 and 5 of the manuscript.

4) Line 300, “OMZ core . . . was estimated . . . by . . . center of 1%..”: How many data points, corresponding to the 1%, are used for estimating the position of OMZ core? Will using 5% of the data change the conclusion?

AR: The 1% area of lowest oxygen was calculated based on all ship sections, which were extracted in the latitude range 8°N–14°N and in the density (depth) range of about 27.0 – 27.06 kg m⁻³ (400m–460m). The 1% area corresponds to 8 data points. For a robustness check, we have redone the analysis by defining the 5% area (about 42 points per ship section) and we ended up with similar results, as shown in AR-Fig. 2.

Manuscript changes: We adapted the text (ll. 736–746) and the figure (now: Fig. 9) in the manuscript and now refer our analysis to the 5% area of lowest oxygen. We additionally stated that choosing the 1% area gave similar results. We didn’t mention explicitly the number of data points, since this is depending on the grid of the processed ship section data.

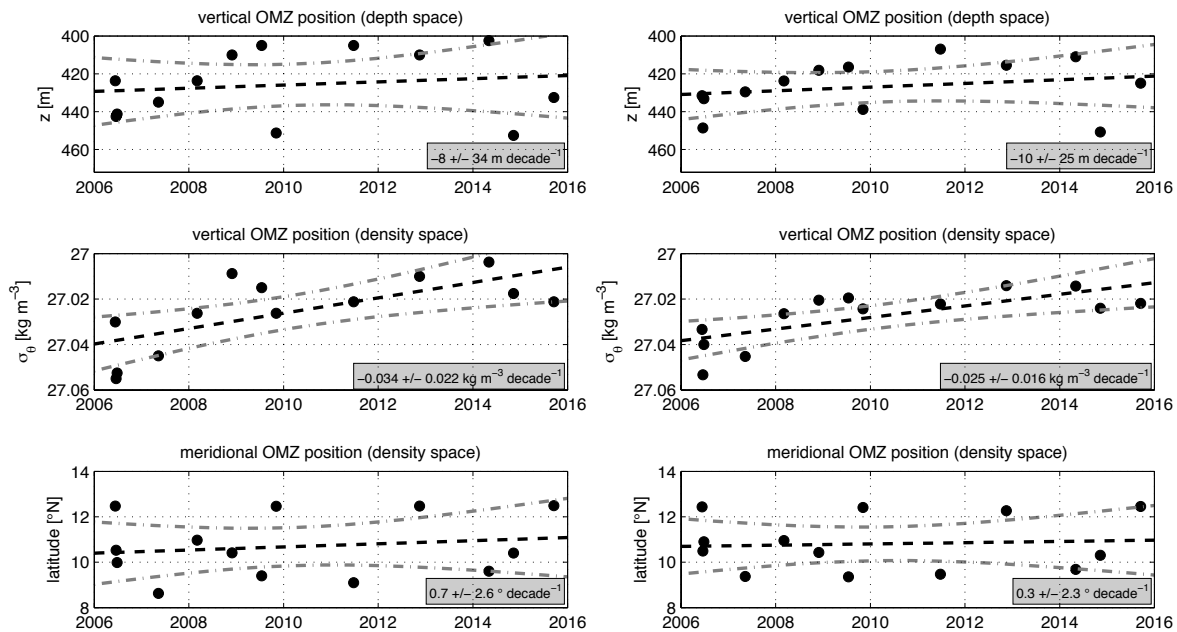


Fig. 2: Vertical and meridional migration of OMZ core. Left panels: former Fig. 6 from manuscript (i.e. 1% area of lowest oxygen between 8°N and 14°N). Right panels: new figure in manuscript (Fig. 9, i.e. 5% area of lowest oxygen was used).

5) Fig.7: How the moored timeseries data are represented by data points, every 90 days? The colored dots in the slope line can be confused with the data points. Consider using thin straight lines to show the linear fit?

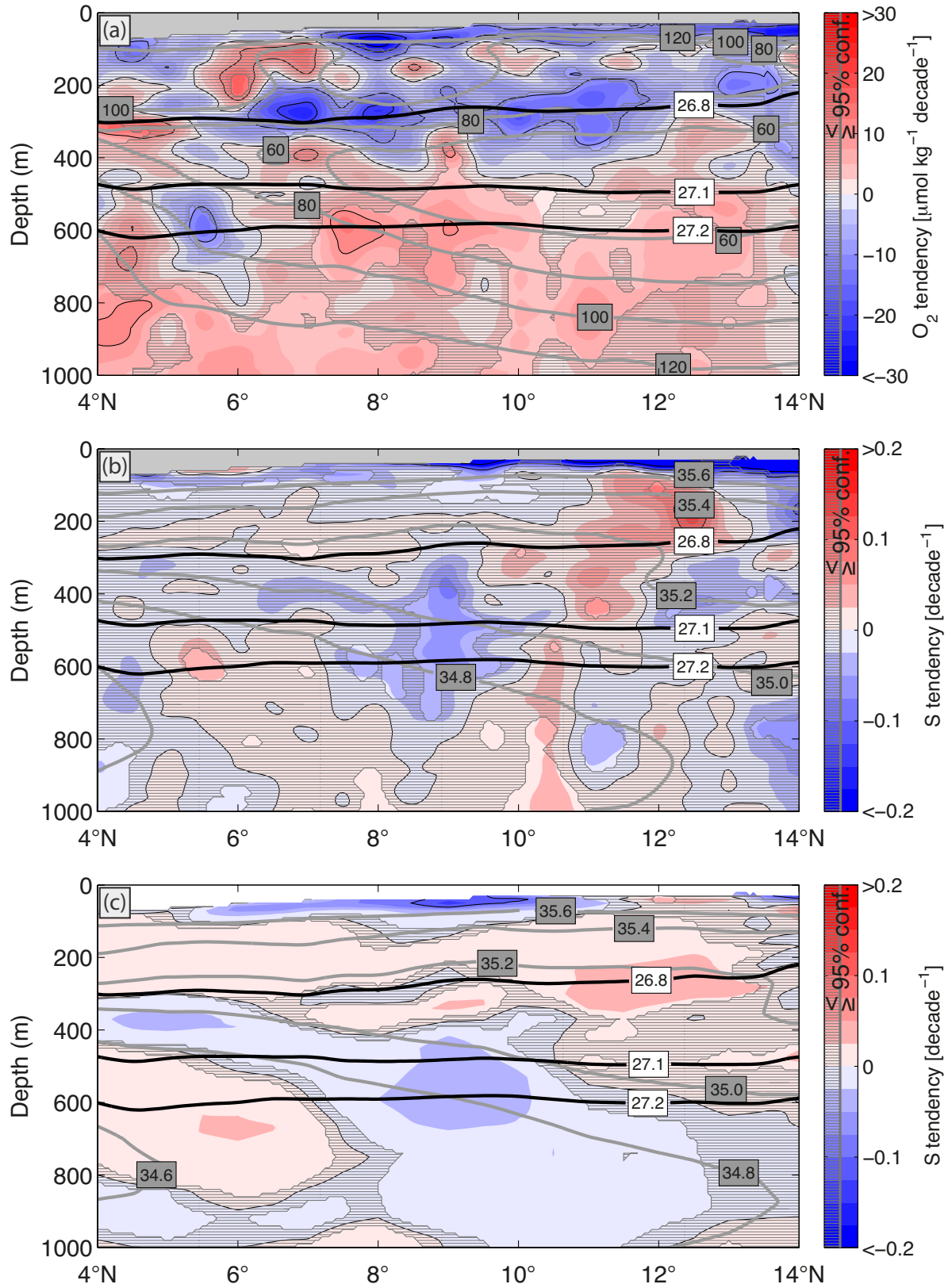
AR/manuscript changes: Yes, the data points shown in the scatter plot represent the 90 day median values of the mooring time series. However, according to both reviewers’ general statements, we decided to remove panels a to c, since they don’t substantially contribute to the main question/message (‘How do dissolved oxygen and salinity correlate?’) of corresponding paragraphs. The new figure is shown in Fig. 7 in the manuscript.

6) Fig.9b and Fig8b: Most of the S changes in Fig.9b are insignificant. There is also the large inconsistency between Fig.8b and Fig.9b at 5N. Why is so? Add another sub-figure based on Argo data? Fig.9a and b are noisy, not easy to identify the significant changes. Will smoothing help?

AR: We agree that most of the salinity changes estimated from shipboard observations (former Fig. 9b) are locally insignificant with respect to a 95% confidence interval. The results are very variable. We also see the inconsistency at 5°N between estimates from shipboard observations on the one hand (former Fig. 9b) and a combination of moored and shipboard observations on the other hand (former Fig. 8b). Exemplarily, in about the upper 300m, shipboard observations suggest substantial salinity fluctuations over the whole decade (compare new Fig. 5 in the manuscript) with a minimum in the beginning and the end of the period as well as a maximum in between. The period of moored observations only captures the branch of the salinity decrease. Moreover, we revisited again the salinity time series at 100m for the last mooring period for the 5°N mooring. Indeed, the corresponding sensor likely had a bad conductivity cell after about 1/5 of the mooring period. This data was removed.

In contrast, we have to disagree with the reviewer's statement that also the section of oxygen change is too noisy for interpretation. Even though parts of the estimated changes are insignificant, we found valuable regimes with significant (95% level) oxygen change. These regimes become even more trustworthy due to the large and homogeneous pattern of oxygen decrease and increase (this is already stated in the manuscript in ll. 482-612).

A direct comparison of the oxygen change pattern with the estimated salinity change pattern from shipboard observations might be taken with care. In order to come up with a more robust estimate of the decadal salinity change and thus with a more robust comparison of the oxygen changes, we directly estimated the decadal salinity change from float observations (similar period as for ship section data, i.e. 2006 – 2015). AR-Fig. 3 shows the decadal oxygen and salinity change from shipboard observations (as before) as well as the decadal salinity change from float observations along 23°W.



AR-Fig. 3: (a) Decadal oxygen tendency and (b) decadal salinity trend tendency from shipboard observations between 4°N and 14°N (similar to former Fig. 9 in the manuscript). (c) Decadal salinity tendency from float observations along 23°W between 4°N and 14°N. All observations are from the period 2006-2015 (this figure is now Fig. 6 in the manuscript).

380 The decadal salinity change estimated from float observations is more significant than the
corresponding estimate from the very limited number of shipboard observations. However,
both estimates show a positive salinity tendency between about 6°N and 13°N at about
200 - 300 m (isopycnal 26.8). Below 400 m, both estimates show a good coherence of
alternating regimes of salinity increase and decrease along the section. A significant salinity
385 decrease is found between about 7°N and 10°N.

The salinity increase above 350 m generally goes along with a coherent oxygen decrease
north of 6°N. Below 400 m, the salinity decrease between about 7°N and 11°N goes along
with a significant oxygen increase. We think, this consideration better shows the
anticorrelated relation of oxygen and salinity at both depth layers. We may conclude that
390 these changes are caused by only one major process. In contrast, the incoherent structures of
salinity increase and decrease below 400 m might have been caused by several processes
(remote or local changes).

Manuscript changes:

1) In ll. 473-481, we introduced the different time scales of oxygen and salinity variability in
395 more detail.

2) Details on the robustness of the decadal oxygen tendency along 23°W are given in ll. 482-
612 of the manuscript.

3) The decadal salinity change was additionally estimated from float observations and is
shown as an additional subpanel (Fig. 6c). The text was adapted accordingly (ll. 613-618).

400 7) Fig.10: What is the purpose to show the insignificant correlations in Fig.10. There are too
many subpanels. Only show significant ones?

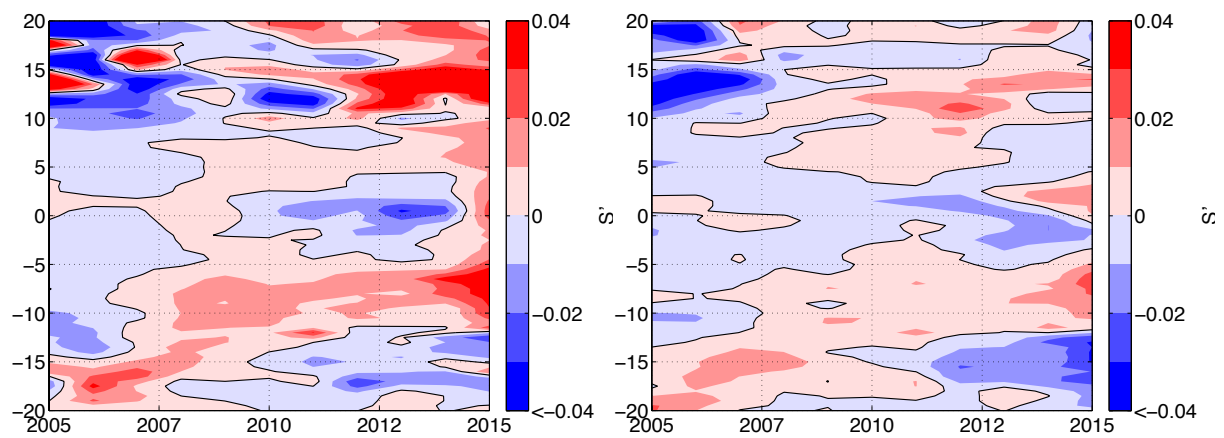
AR/manuscript changes: We agree with the reviewer. We decided to remove the whole
figure. Instead we included a table (Table 3), which shows the average decadal oxygen and
salinity tendency for different latitude boxes (two degrees width) at the Central Water (200-
300m) and Intermediate Water (500-800m) layer, respectively. Oxygen tendency was
405 estimated from shipboard observations. Salinity tendency was estimated from float
observations. We think, that this representation supports the understanding about significant
regimes of decadal changes in oxygen and salinity and the relation of both. The text was
adapted accordingly (ll. 630-633).

410 8) Fig.11a-c and e-f: too noisy to show the propagation signals. Would Hovmöller diagrams,
either along 23W or zonal average, do better job?

AR: Literature shows (e.g. Rabe et al. 2008; Biastoch et al. 2009; Kirchner et al. 2009;
Lübbecke et al. 2015 – references are also given in the manuscript) that water mass pathways
from the subtropical South Atlantic to the tropical and subtropical North Atlantic are due to

the Subtropical Cell and the Meridional Overturning Circulation via the energetic western boundary current system. Hence, Hovmoller diagrams along 23°W are not adequate in representing such propagation signals. Hovmoller diagrams of zonal averages don't show a continuous propagation of salinity anomalies from the southern to the northern hemisphere, either (AR-Fig. 4). Indeed, a reasonable definition of water mass pathways (e.g. definition of a streamfunction) would be necessary in order to follow the propagation of these signals. We speculate that Argo float observations were too sparse (particularly in the narrow and energetic western boundary current system) in order to resolve a continuous pathway of northward propagating salinity anomalies.

Manuscript changes: We have rewritten the according paragraph (ll.982-989) and included the above described expectation and speculation with regard to the Argo float observations.



AR-Fig. 4: Hovmoller diagrams of zonally averaged (40°W-10°W) salinity anomalies from Argo float observations. Left panel: isopycnal surface 26.8. Right panel: isopycnal surface 27.2.

9) Fig.13 vs. Fig.14: The most striking changes of zonal currents are between 12°N and 14°N in the shipboard ADCP data (Fig.14), while the most significant changes in geostrophic currents are between 4°N and 8°N in Fig.13. Why is this difference?

AR: We suspect different reasons for this difference.

First, the zonal (and also meridional) extent as well as the amplitude of the coherent variability pattern of the surface currents is larger between 4°N and 10°N than between 10°N and 14°N. Thus, the EOF analysis of the altimetry observations dominantly reflects the velocity variability between 4°N and 10°N. In contrast, shipboard observations are only given along 23°W and cannot capture the zonal extent of the current field.

Second, the eastward current between 12°N and 14°N (Cape Verde Current) has its core below the surface as shown in the mean velocity section along 23°W (Fig. 2c in the manuscript; see also Brandt et al. 2015 or Pena-Izquierdo et al. 2015 – references are given in the manuscript). The maximum variability of this current is likely at the subsurface as well.

Third, shipboard observations represent only snapshots of the strongly variable current field. Hence, there is likely an aliasing effect in the variability analysis due to the limited number of shipboard observations.

445 However, a detailed variability analysis of the Cape Verde Current goes beyond the scope of this study, but we see this as a worthwhile approach for future studies.

Manuscript changes: We included the three above mentioned speculations in the manuscript (ll. 1091-1099) to state this difference between shipboard and altimetry observations.

Decadal oxygen change in the eastern tropical North Atlantic

Johannes Hahn¹, Peter Brandt¹, Sunke Schmidt¹, Gerd Krahmann¹

¹GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany

Correspondence to: Johannes Hahn (jhahn@geomar.de)

Abstract. Repeat shipboard and multi-year moored observations obtained in the oxygen minimum zone (OMZ) of the eastern tropical North Atlantic (ETNA) were used to study the decadal change in oxygen for the period 2006-2015. Along 23°W between 6°N and 14°N, oxygen decreased with a rate of $-5.9 \pm 3.5 \mu\text{mol kg}^{-1} \text{decade}^{-1}$ within the depth covering the deep oxycline (200-400 m), while below the OMZ core (400-1,000 m) oxygen increased by $4.0 \pm 1.6 \mu\text{mol kg}^{-1} \text{decade}^{-1}$ on average. The inclusion of these decadal oxygen trends in the recently estimated oxygen budget for the ETNA OMZ suggests a weakened ventilation of the upper 400 m, whereas the ventilation strengthened homogeneously below 400 m. The changed ventilation resulted in a shoaling of the ETNA OMZ of $-0.03 \pm 0.02 \text{ kg m}^{-3} \text{decade}^{-1}$ in density space, which was only partly compensated by a deepening of isopycnal surfaces, thus pointing to a shoaling of the OMZ in depth space as well ($-22 \pm 17 \text{ m decade}^{-1}$). Based on the improved oxygen budget, possible causes for the changed ventilation are analyzed and discussed. Largely ruling out other ventilation processes, the zonal advective oxygen supply stands out as the most probable budget term responsible for the decadal oxygen changes.

1 Introduction

Over the past decades, tropical oceans have been subject to a conspicuous deoxygenation (Brandt et al., 2015; Stramma et al., 2008; Stramma et al., 2012) at thermocline to intermediate depths comprising the upper 700 m of the ocean. These well-documented changes manifest themselves in a profound decrease of dissolved oxygen and a volumetric increase of open ocean tropical oxygen minimum zones (OMZs) (Stramma et al., 2010). OMZs are located in the weakly ventilated shadow zones of the ventilated thermocline (Luyten et al., 1983) in the eastern tropical Atlantic and Pacific ocean basins off the equator as well as in the northern Indian Ocean between 100 m and 900 m (Karstensen et al., 2008). Their existence predominantly results from a weak oxygen supply to these sluggish flow regimes accompanied by locally enhanced oxygen consumption in proximity to coastal and open ocean upwelling regions (Helly and Levin, 2004).

Among all OMZs, the open ocean OMZ of the eastern tropical North Atlantic (ETNA), with its core position around 10°N, 20°W and 400 m (Brandt et al., 2015), was observed as the region with the strongest multi-decadal oxygen decrease since the 1960s (Stramma et al., 2008). Within the recent decade, this region exhibited record low oxygen concentrations well below 40 $\mu\text{mol kg}^{-1}$ (Stramma et al., 2009). Beyond that, Brandt et al. (2015) found for the past decade an even stronger oxygen decrease at depth of the deep oxycline (corresponding to the upper OMZ boundary) and a weak oxygen increase below the OMZ core, superimposed on the multi-decadal oxygen decrease. Compared to the Pacific and Indian OMZs, the open ocean ETNA OMZ – not to be mistaken with the shallow OMZ in the Mauritanian upwelling regime (Wallace and Bange, 2004) or episodically developing open ocean dead zones at shallow depth (Karstensen et al., 2015; Schütte et al., 2016) – exhibits a smaller horizontal and vertical extent (300 m – 700 m) and only moderate hypoxic (oxygen concentration < 60-

- Johannes Hahn 9.5.2017 16:06
Gelöscht: At the depth of the deep oxycline (200-400 m),
- Johannes Hahn 25.4.2017 22:31
Gelöscht: 6.2
- Johannes Hahn 25.4.2017 22:31
Gelöscht: 8
- Johannes Hahn 25.4.2017 22:32
Gelöscht: 1
- Johannes Hahn 25.4.2017 22:32
Gelöscht: 7
- Johannes Hahn 22.5.2017 11:55
Gelöscht: showed
- Johannes Hahn 9.5.2017 16:08
Gelöscht: over depth
- Johannes Hahn 9.5.2017 16:08
Gelöscht: is
- Johannes Hahn 9.5.2017 16:11
Gelöscht: Shipboard, float and satellite observations of velocity and hydrography indicate different regional as well as remote changes in the circulation pattern to be responsible for the change in the ventilation of the ETNA. The reduced ventilation in the upper 400 m may have been induced by a southward shift of the wind-driven circulation or by a change of the composition of South Atlantic Central Water. There are hints that below 400 m, latitudinally alternating zonal jets have strengthened, thus contributing to the increased ventilation. Nevertheless, temporal changes in isopycnal eddy supply or diapycnal supply (diapycnal mixing as well as diapycnal advection) cannot be excluded in having contributed to the observed oxygen change.
- Johannes Hahn 22.5.2017 12:11
Gelöscht: levels
- Johannes Hahn 9.5.2017 16:14
Gelöscht: regionally
- Johannes Hahn 9.5.2017 16:15
Gelöscht: regionally

65 120 $\mu\text{mol kg}^{-1}$) conditions. In comparison to the Pacific, the smaller basin width of the tropical Atlantic results in quicker ventilation from the western boundary and overall younger water mass ages (Brandt et al., 2015; Karstensen et al., 2008)). Hence, temporal changes of circulation and ventilation of the ETNA likely have a comparatively fast impact on the local oxygen concentration.

70 Various processes related to anthropogenic as well as natural climate variability might have contributed to the global multi-decadal oxygen decrease. It is generally accepted that decreasing oxygen solubility (thermal effect) in a warming ocean is not the dominant driver (Helm et al., 2011; Schmidtke et al., 2017) of the observed deoxygenation. Other anthropogenically driven mechanisms were identified instead by various model studies investigating changes in biogeochemical processes that impact the oxygen consumption (production effect) (Keeling and Garcia, 2002; Oschlies et al., 2008) as well as changes in ocean circulation, subduction and mixing (dynamic effect) (Bopp et al., 2002; Plattner et al., 2002; Frölicher et al., 2009; Matear and Hirst, 2003; Schmittner et al., 2008; Cabre et al., 2015). Despite a general agreement between different models on an anthropogenically driven and still ongoing global mean oxygen decrease, regional patterns of the modeled oxygen changes often do not agree with the observed trend patterns (Stramma et al. 2012).

80 Natural climate variability has been found to be an essential driver for oxygen variability on interannual to multi-decadal time scales (Duteil et al., 2014a; Frölicher et al., 2009; Cabre et al., 2015; Stendardo and Gruber, 2012; Czeschel et al., 2012). Alternating phases of oxygen decrease and increase might be superimposed on the suggested anthropogenically forced multi-decadal oxygen decrease and might lead to a damping or reinforcing of such a trend on different time scales. Multi-decadal changes in circulation such as an intensification/weakening of the tropical zonal current system, the Subtropical Cells (STC) or the Meridional Overturning Circulation (MOC) (Chang et al., 2008; Rabe et al., 2008; Lübbecke et al., 2015) are related to changes in the ventilation and consequently lead to varying oceanic oxygen concentrations (Brandt et al., 2010; Duteil et al., 2014a). Nonetheless, biogeochemical and physical processes may also compensate each other leading to a damped oxygen variability on interannual to decadal time scales (Duteil et al., 2014a; Cabre et al., 2015).

90 The mean horizontal oxygen distribution is mainly set by the mean current field (Wyrki, 1962). In the tropical Atlantic, the upper ocean large-scale flow field (Schott et al., 2004; Schott et al., 2005; Brandt et al., 2015; Eden and Dengler, 2008) comprises (i) the northern and southern STC, (ii) the western boundary current regime and (iii) the system of equatorial and off-equatorial mean zonal currents (Fig. 1). The STC describes the large-scale shallow overturning circulation, which connects the subtropical subduction regions of both hemispheres to the eastern equatorial upwelling regimes by equatorward thermocline and poleward surface flow (Schott et al., 2004; McCreary and Lu, 1994). As part of the northern STC, the North Equatorial Current (NEC) partly entrains thermocline water from the subtropics into the zonal current system south of the Cape Verde Archipelago either via the western boundary or via interior pathways (Pena-Izquierdo et al., 2015; Schott et al., 2004; Zhang et al., 2003), but most of this water does not reach the equator. The western boundary current system, given by the North Brazil Current (NBC) and North Brazil Undercurrent (NBUC), acts as the major pathway for the interhemispheric northward transport of South Atlantic water. It represents a superposition of the Atlantic MOC (AMOC), the southern STC and the recirculation of the southward interior Sverdrup transport (Schott et al., 2004).

Johannes Hahn 9.5.2017 16:15

Gelöscht: particular

Johannes Hahn 9.5.2017 16:16

Gelöscht: with

Johannes Hahn 9.5.2017 16:17

Gelöscht: regional

Johannes Hahn 22.5.2017 12:14

Gelöscht: variability

Johannes Hahn 22.5.2017 12:15

Gelöscht: world

Johannes Hahn 22.5.2017 12:16

Gelöscht: for long-term changes in the oxygen distribution

Johannes Hahn 22.5.2017 12:20

Gelöscht: with

Johannes Hahn 22.5.2017 12:21

Gelöscht: on

Johannes Hahn 23.5.2017 19:12

Gelöscht: the

Johannes Hahn 23.5.2017 19:12

Gelöscht: es

Johannes Hahn 22.5.2017 12:22

Gelöscht: ing

Johannes Hahn 22.5.2017 12:22

Gelöscht: of the

Johannes Hahn 9.5.2017 16:17

Gelöscht: pattern of the

Johannes Hahn 23.5.2017 10:14

Gelöscht: as well as

Johannes Hahn 9.5.2017 16:18

Gelöscht: of

Johannes Hahn 9.5.2017 16:18

Gelöscht: is driven by

The zonal current system in the tropical North Atlantic drives the water mass exchange between the well-ventilated western boundary and the eastern basin (Stramma and Schott, 1999). Between 5°S and 5°N, strong mean as well as time varying zonal currents exist from the surface to intermediate depth (Schott et al., 2003; Ascani et al., 2010; Johns et al., 2014; Bunge et al., 2008; Eden and Dengler, 2008; Brandt et al., 2010; Ascani et al., 2015); the associated oxygen flux is responsible for the existence of a pronounced equatorial oxygen maximum (Brandt et al., 2008; Brandt et al., 2012) herewith setting the southern boundary of the ETNA OMZ. Between 5°N and the Cape Verde Archipelago, wind-driven mean zonal currents are present down to a depth of about 300 m (the North Equatorial Countercurrent / North Equatorial Undercurrent (NECC/NEUC) centered at 5°N and the northern branch of the NECC (nNECC) centered at 9°N). In accordance with the meridional migration of the Intertropical Convergence Zone (ITCZ) these currents exhibit strong seasonal to interannual variability in their strength and position (Hormann et al., 2012; Garzoli and Katz, 1983; Garzoli and Richardson, 1989; Richardson et al., 1992). Their connection to the western boundary seasonally alternates as well. Next to a more permanent supply of the EUC, water from the NBC retroflexion is injected either into the NECC/NEUC or the nNECC. Below 300 m, latitudinally alternating zonal jets (LAZJ), occasionally referred to as latitudinally stacked zonal jets or North Equatorial Undercurrent jets, dominate the mean current field. They are a pervasive feature in all tropical oceans at intermediate depth and occur as nearly depth-independent zonal current bands with weak mean zonal velocity of a few cm s⁻¹ alternating eastward/westward with a meridional scale of about 2° (Maximenko et al., 2005; Ollitrault and de Verdiere, 2014; Brandt et al., 2010; Qiu et al., 2013). Within the upper 300 m, the signature of the LAZJ is often masked by a strong wind-driven circulation (Rosell-Fieschi et al., 2015). The generation of the LAZJ is not fully understood yet and different forcing mechanisms have been suggested (Kamenkovich et al., 2009; Qiu et al., 2013; Ascani et al., 2010). Nevertheless, eddy permitting ocean circulation models partly simulate these jets leading to an improved simulated oxygen distribution in global biogeochemical circulation models (Duteil et al., 2014b) and indicating that LAZJ play an important role in ventilating the ETNA from the western boundary.

Two different water masses spread into the ETNA between about 100 and 1,000 m depth: North Atlantic Water (NAW) and South Atlantic Water (SAW), which have their origin either in the North or South Atlantic (Kirchner et al., 2009). Within the depth range 150 and 500 m (corresponding to potential density layers between 25.8 and 27.1 kg m⁻³), these water masses correspond to North and South Atlantic Central Water (NACW and SACW). Both NACW and SACW exhibit almost linear θ - S relationships, where NACW is distinctly saltier than SACW. The fraction of SACW in the upper Central Water (UCW) layer between 150 and 300 m is larger than the fraction of SACW in the lower Central Water (LCW) layer between 300 and 500 m. This layering of SACW dominated water in the upper layer above NACW dominated water in the lower layer suggests a stronger ventilation from the South Atlantic in the UCW. The boundary between both regimes, located at about 300 m (corresponding to a potential density of about 26.8 kg m⁻³), is marked by the presence of the deep oxycline and indicates a vertically abrupt change in the circulation and associated ventilation (Pena-Izquierdo et al., 2015).

Below the Central Water (CW) layer, low-saline Antarctic Intermediate Water (AAIW) is found at densities between 27.1 and 27.7 kg m⁻³ (600 – 1500 m) (Stramma et al., 2005; Karstensen et al., 2008; Schmidtke and Johnson, 2012). AAIW spreads to latitudes of about 20°N becoming less oxygenated toward north.

Johannes Hahn 9.5.2017 16:20

Gelöscht: .

Johannes Hahn 9.5.2017 16:20

Gelöscht: They form

Johannes Hahn 9.5.2017 16:21

Gelöscht: and

Johannes Hahn 9.5.2017 16:24

Gelöscht: at surface to intermediate depth

Johannes Hahn 9.5.2017 16:24

Gelöscht: Between

Johannes Hahn 9.5.2017 16:25

Gelöscht: y

Johannes Hahn 9.5.2017 16:25

Gelöscht: are further subdivided in

Johannes Hahn 9.5.2017 16:25

Gelöscht: Atlantic

Johannes Hahn 17.3.2017 09:20

Gelöscht: q-S

Johannes Hahn 9.5.2017 16:26

Gelöscht: A larger

Johannes Hahn 9.5.2017 16:26

Gelöscht: intrudes into

Johannes Hahn 9.5.2017 16:27

Gelöscht: compared to a smaller

Johannes Hahn 9.5.2017 16:31

Gelöscht: with a vertically abrupt change in the circulation at the deep oxycline at

The recently derived observationally based oxygen budget for the ETNA (Hahn et al., 2014; Brandt et al., 2015; Fischer et al., 2013; Karstensen et al., 2008; Brandt et al., 2010) has shed light on the different budget terms, which define (i) oxygen supply, (ii) oxygen consumption and (iii) oxygen tendency. In the upper 350 m, mean zonal currents (NECC/NEUC, nNECC) play the dominant role for the ventilation of the ETNA and thus, for the supply at the upper boundary of the OMZ. In the depth range of the OMZ core at about 400 m, lateral and vertical mixing dominate the oxygen supply toward the OMZ; advection plays only a minor role. Below the OMZ core, lateral and vertical oxygen supplies weaken with depth and lateral advection becomes of similar importance compared to the other supply terms roughly below 600 to 700 m. A recent model study (Pena-Izquierdo et al., 2015) proposed the presence of mean vertical advection with reversed flow direction in the UCW and LCW, which is related to two stacked subtropical cells in this depth range. Vertical advection may play an additional role in supplying the ETNA OMZ, but so far, this process has not been considered in the oxygen budget.

Only few processes have been investigated quantitatively (Brandt et al., 2010) that might be responsible for driving oxygen variability on decadal to multi-decadal time scales in the ETNA. Brandt et al. (2015) qualitatively discussed and proposed the following mechanisms: (i) decadal to multi-decadal AMOC changes; (ii) transport variability of Indian Ocean CW entrained into the South Atlantic (variability in the Agulhas leakage); (iii) changes in the strength of LAZJ; (iv) changes in the strength and location of the wind-driven gyres; (v) variability of ventilation efficiency due to changes in solubility or subduction and (vi) multi-decadal changes in the strength of Atlantic STCs. The aim of this study is to contribute to a more comprehensive understanding of the oxygen changes during the last decade and of the dynamical processes that drive this variability. This encompasses three major goals: (i) description of the regional pattern of the decadal oxygen trend; (ii) determination of associated trends in salinity and circulation; (iii) discussion of implications of the decadal oxygen trend for the oxygen budget of the ETNA. The paper is structured as follows. Section 2 describes the observational and climatological data sets used in this study as well as the methods to analyze them. Further, the oxygen budget and individual budget terms for the ETNA are introduced as they were mainly derived in recent studies. In Sect. 3, the results of the present study are presented. They are comprehensively discussed in Sect. 4. Section 5 gives a short summary and conclusive remarks.

2 Data and methods

This study uses a combined set of hydrographic, oxygen and velocity data, which consists of (i) repeat shipboard and moored observations, (ii) the hydrographic climatology MIMOC, (iii) float observations provided by the Argo program and (iv) satellite derived surface velocities provided by Aviso. Further, data products of the different oxygen budget terms are used, which were derived in recent studies. Acquisition and processing of hydrographic, oxygen and velocity data from repeat shipboard and moored observations are described in Sect. 2.1 and 2.2. The climatological data set MIMOC (Schmidtke et al., 2013) is introduced in Sect. 2.3. Section 2.4 presents the Argo float data set (Roemmich et al., 2009) and Sect. 2.5 introduces the sea surface geostrophic velocity data derived from satellite altimetry. A detailed description of the oxygen budget and the oxygen budget terms is given in Sect. 2.6.

Johannes Hahn 22.5.2017 13:56

Gelöscht: A balance is given between

Johannes Hahn 22.5.2017 13:58

Gelöscht: of

Johannes Hahn 9.5.2017 16:34

Gelöscht: y

Johannes Hahn 22.5.2017 14:02

Gelöscht: might

Johannes Hahn 22.5.2017 14:05

Gelöscht: due to rare observational estimates of vertical velocity

Johannes Hahn 9.5.2017 16:37

Gelöscht: associated with the decadal oxygen trend

Johannes Hahn 15.5.2017 14:07

Gelöscht: data analysis and

Johannes Hahn 15.5.2017 14:07

Gelöscht: individual results

Johannes Hahn 22.5.2017 14:06

Gelöscht: data products

Johannes Hahn 23.5.2017 21:33

Gelöscht: AVISO

Johannes Hahn 9.5.2017 17:10

Gelöscht: F

Johannes Hahn 23.5.2017 19:26

Gelöscht: estimated in recent studies

2.1 Repeat ship sections along 23°W

225 Hydrographic, oxygen and velocity data were obtained during repeated research cruises carried out mainly along 23°W in the ETNA in the period from 2006 to 2015 (1999 to 2015 for velocity; see Table 1 for details). The data set is an update of the 23°W ship section data used in Brandt et al. (2015). In the present study, data records from 4°N to 14°N (ETNA OMZ regime) were taken into account.

230 Hydrographic and oxygen data were acquired during CTD (conductivity-temperature-depth) casts, typically performed on a uniform latitude grid with half degree resolution. Velocity data was acquired with different Acoustic Doppler Current Profilers (ADCPs) systems; vessel-mounted ADCPs (vm-ADCP) recorded velocities continuously throughout the section and pairs of lowered ADCPs (l-ADCP), attached to the CTD rosette, recorded during CTD casts.

235 Based on these data sets, meridional sections of hydrography, oxygen and velocity were linearly interpolated for each ship section onto a homogeneous latitude-depth grid with a resolution of 0.05 ° and 10 m, respectively. Details on the methodology as well as on measurement errors are given in Brandt et al. (2010). For a single research cruise the accuracy of hydrographic and oxygen data was assumed to be generally better than 0.002 °C, 0.002 and 2 µmol kg⁻¹ for temperature, salinity and dissolved oxygen, respectively. The accuracy of 1-h averaged velocity data from vm-ADCPs and single velocity profiles from l-ADCP was better than 2–4 cm s⁻¹ and 5 cm s⁻¹, respectively.

240 Mean sections along 23°W were calculated (Fig. 2a to 2c) from 13 (hydrography/oxygen) and 31 (velocity) individual ship sections, respectively (Table 1). For the depth range 100 - 1,000 m, the averaging of all sections yielded an average standard error of the mean fields (which is considered to result mostly from oceanic variability) of about 1.8 µmol kg⁻¹, 0.06 °C, 0.009 and 1.1 cm s⁻¹ for oxygen, temperature, salinity and zonal velocity, respectively.

245 Moreover, a meridional section of the decadal oxygen and salinity trend was estimated. First, the data from each ship section was interpolated on a density grid (grid spacing 0.01 kg m⁻³) by applying an average depth-density relation in the depth range 0 – 1,000 m. Then, linear regressions were calculated (using a 95% confidence level to determine their significance) at each grid point in latitude-density space. The resulting sections were subsequently projected onto depth grid.

250 In order to relate changes in oxygen to changes in salinity, shipboard observations were used to calculate the correlation between both variables at every grid point of the section. All calculations were evaluated in density space and the results were subsequently projected onto depth grid.

2.2 Moored observations

255 Multi-year moored observations (2009 – 2015) were performed in the ETNA to record hourly to interannual oxygen variability at three different positions: 5°N/23°W, 8°N/23°W and 11°N/21°W (see Table 2 for details about available data). All moorings were equipped with oxygen (AADI Aanderaa optodes of model types 3830 and 4330) and CTD sensors (Sea-Bird SBE37 microcats), which were attached next to each other on the mooring cable to allow an appropriate estimate of the dissolved oxygen on density surfaces. At every mooring site, eight

Johannes Hahn 22.5.2017 14:11

Gelöscht: For an individual ship section along 23°W, h

Johannes Hahn 22.5.2017 14:11

Gelöscht: regular

Johannes Hahn 22.5.2017 14:16

Gelöscht: which were

Johannes Hahn 22.5.2017 14:16

Gelöscht: typically

Johannes Hahn 22.5.2017 14:16

Gelöscht: realizations of

Johannes Hahn 22.5.2017 14:18

Gelöscht: ,

Johannes Hahn 22.5.2017 14:18

Gelöscht: where

Johannes Hahn 22.5.2017 14:18

Gelöscht: a

Johannes Hahn 22.5.2017 14:18

Gelöscht: regular

Johannes Hahn 22.5.2017 14:20

Gelöscht: acquired

Johannes Hahn 22.5.2017 14:21

Gelöscht: calculated

Johannes Hahn 9.5.2017 18:32

[3] verschoben (Einfügung)

Johannes Hahn 22.5.2017 14:27

Gelöscht: The m

Johannes Hahn 9.5.2017 18:34

Gelöscht: state 23°W

Johannes Hahn 22.5.2017 14:30

Gelöscht: of oxygen, hydrography and zonal velocity

Johannes Hahn 22.5.2017 14:39

Gelöscht: between 4°N and 14°N

Johannes Hahn 22.5.2017 14:40

Gelöscht: based on all uniformly gridded 23°W sections as obtained

Johannes Hahn 23.5.2017 19:28

Gelöscht: the repeat shipboard observations

Johannes Hahn 22.5.2017 14:32

Gelöscht: cf. Sect. 2 and

Johannes Hahn 22.5.2017 14:43

Gelöscht: dominan

Johannes Hahn 9.5.2017 18:33

Gelöscht: -

Johannes Hahn 9.5.2017 16:50

Gelöscht: at about

evenly distributed optode/microcat combinations were installed in the depth range between 100 to 800 m delivering multi-year long oxygen time series with a temporal resolution of up to 5 min.

Moorings were serviced and redeployed generally every 18 months. In order to achieve the highest possible long-term sensor accuracy, optodes and microcats were carefully calibrated against oxygen and CTD measurements (from a CTD/O₂ unit) by attaching them to the CTD rosette during regular CTD casts immediately prior to and after the mooring deployment period. Optodes were additionally calibrated in the laboratory on board to expand the range of reference calibration points. Details on the optode calibration methodology are given in Hahn et al. (2014). The root mean square error of temperature and salinity measurements (microcats) as well as dissolved oxygen measurements (optodes) was about 0.003 °C, 0.006 and 3 µmol kg⁻¹, respectively.

Oxygen and salinity time series from the three mooring sites were 10-day low pass filtered and subsequently depth-interpolated between 100 and 800 m. Based on this uniformly gridded data set, oxygen and salinity anomalies were calculated by (i) interpolating the moored and shipboard observations on a regular density grid (grid spacing 0.01 kg m⁻³), (ii) subtracting the respective mean profiles in density space obtained solely from shipboard observations, and (iii) projecting the calculated anomalies back onto depth grid (by applying an average depth-density relation). This calculation removed the effect of isopycnal heave due to internal waves, mesoscale eddies or seasonal variability in the circulation. Depth averages of these oxygen and salinity anomaly time series were calculated for the two depth layers 200 - 400 m and 500 - 800 m.

Linear trends were fitted to the oxygen and salinity anomaly time series from the combined observational data set of moored and shipboard observations for the two respective depth layers. A weighted linear regression scheme was used, where a single ship section was weighted similar to 30 days of moored observations. Intervals on a 95% confidence level were calculated for the estimated trends.

Moored observations were additionally used to calculate a correlation between oxygen and salinity (see also Sect. 2.1 for a similar analysis based on shipboard observations). As we consider only long-term variability, the correlation was computed from the 90-day median of the mooring time series at the three respective latitudes. All calculations were evaluated in density space and the results were subsequently projected onto depth grid.

2.3 MIMOC climatology

The monthly, isopycnal and mixed-layer ocean climatology (MIMOC) (Schmidt et al., 2013) was used as a reference mean state in order to (i) perform a water mass analysis and (ii) quantify the temporal evolution of salinity anomalies in the tropical Atlantic. The climatological fields of potential temperature and salinity were interpolated on respective density layers and mean θ -S characteristics were defined for the two predominant water masses NAW and SAW found in the tropical Atlantic.

2.4 Argo float data set

All Argo data available for the study region was considered (<http://dx.doi.org/10.13155/29825>). Argo float data is collected and made freely available by the international Argo project and the national programs that contribute to it. For the analysis, only delayed mode data with a data quality flag of *probably good* or better was used.

Johannes Hahn 9.5.2017 16:51

Gelöscht: all

Johannes Hahn 22.5.2017 14:55

Gelöscht: available

Johannes Hahn 23.5.2017 19:34

Gelöscht: used

Johannes Hahn 9.5.2017 16:54

Gelöscht: Here, Argo float data flagged by the data centers was removed and d

Johannes Hahn 22.5.2017 14:56

Gelöscht: was used for the profiles as available

Johannes Hahn 9.5.2017 16:55

Gelöscht: .

The Argo profile data was used in this study to quantify the temporal evolution of salinity anomalies in the tropical Atlantic, on two characteristic density surfaces (26.8 kg m^{-3} and 27.2 kg m^{-3}). Anomalies of salinity were calculated with respect to the mean state given by the MIMOC climatology (see Sect. 2.3) for the period 2004-2016. Subsequently, mean salinity anomalies were calculated for different periods as well as a decadal tendency was estimated for the whole period.

2.5 Surface geostrophic velocity from altimeter products

Surface geostrophic velocities derived from satellite altimetry were used in this study to estimate the decadal change of the near-surface circulation and ventilation of the ETNA. The altimeter product was produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (<http://www.aviso.altimetry.fr/duacs/>). Absolute geostrophic velocity data was taken from the delayed time global product *MADT* (Maps of Absolute Dynamic Topography) given in the version *all sat merged*. The data was extracted for the box $4^{\circ}\text{N} - 14^{\circ}\text{N} / 35^{\circ}\text{W} - 20^{\circ}\text{W}$ for the data period January 1993 – September 2015 (processing date: 27-Nov-2015).

The two main variability patterns of the surface circulation in the tropical North Atlantic can be described by the first complex EOF (empirical orthogonal function) mode of the zonal geostrophic velocity anomaly, where the real part of the EOF pattern mimics the meridional migration of the NECC and the imaginary pattern reflects the variability in its strength (Hormann et al., 2012). We applied an EOF analysis to the grid point wise filtered (mean and seasonal cycle removed and subsequently 2-year-low-pass-filtered) time series of Aviso zonal geostrophic velocity for the region given above in order to capture the interannual to decadal variability of the NECC/nNECC throughout the past decades. The first two EOF modes explained 23% and 14% of the total variance of the filtered time series and can be considered similarly to the real and imaginary pattern of the complex EOF as given in Hormann et al. (2012).

2.6 Oxygen budget terms

The oceanic oxygen distribution is governed on the one hand by oxygen supplying processes such as physical transport and photosynthetic oxygen production and on the other hand by oxygen consumption driven by biological respiration and remineralisation of sinking organic matter (Karstensen et al., 2008; Brandt et al., 2015). In the ETNA, supply and consumption have not been in balance for the past decades (oxygen consumption was about 10 - 20 % larger than the supply processes), resulting in the aforementioned multi-decadal oxygen trend (Brandt et al., 2010; Hahn et al., 2014; Karstensen et al., 2008)). Mathematically the oxygen budget is balanced, when we allow for an oxygen tendency in addition to the oxygen supply and consumption terms. However, in order to investigate causes for the change in the oxygen trend from decadal to multi-decadal time scales (Brandt et al., 2015), temporal changes in the oxygen budget terms have to be analyzed. Following Hahn et al. (2014) and Brandt et al. (2015), we formulate the non-steady state depth-dependent oxygen budget for the ETNA over the latitude range $6^{\circ}\text{N} - 14^{\circ}\text{N}$ as:

$$\left[\frac{\partial_t O_2}{[1]} \right]^{(i)} = \underbrace{aOUR}_{[2]} + \underbrace{K_e \partial_{yy} O_2}_{[3]} + \underbrace{K_p \partial_{zz} O_2}_{[4]} + \underbrace{[R_{O_2}]}_{[5]}^{(i)}, \quad (1)$$

where the superscript on both sides of the equation denotes the time variation with respect either to the decadal ($i=1$) or multi-decadal ($i=2$) oxygen trend. This oxygen budget equation (1) describes the components

Johannes Hahn 10.5.2017 11:03

Gelöscht:

Johannes Hahn 9.5.2017 16:55

Gelöscht: n, the remaining good

Johannes Hahn 10.5.2017 11:03

Gelöscht: .

Johannes Hahn 22.5.2017 14:59

Gelöscht: y

Johannes Hahn 22.5.2017 14:59

Gelöscht: data

Johannes Hahn 22.5.2017 14:59

Gelöscht: as

Johannes Hahn 22.5.2017 20:30

Gelöscht: or

Johannes Hahn 22.5.2017 20:30

Gelöscht: or

Johannes Hahn 22.5.2017 20:35

Gelöscht: Supply

Johannes Hahn 22.5.2017 20:36

Gelöscht: are usually

Johannes Hahn 22.5.2017 20:39

Gelöscht: as for the ETNA the oxygen consumption is about 10 - 20 % larger than the supply processes

Johannes Hahn 23.5.2017 19:40

Gelöscht: Hence,

Johannes Hahn 22.5.2017 20:41

Gelöscht: including

Johannes Hahn 22.5.2017 20:42

Gelöscht: the

Johannes Hahn 22.5.2017 20:42

Gelöscht: ally

Johannes Hahn 22.5.2017 20:47

Gelöscht: analyze

Johannes Hahn 22.5.2017 20:46

Gelöscht: temporal changes in the budget terms, which cause

Johannes Hahn 22.5.2017 20:46

Gelöscht: a

Johannes Hahn 22.5.2017 20:47

Gelöscht: a time-varying oxygen budget has

Johannes Hahn 22.5.2017 20:47

Gelöscht: taken into account

Johannes Hahn 23.5.2017 22:07

Gelöscht: (1)

contributing to the changes of the oxygen concentration all of which are given in $\mu\text{mol kg}^{-1} \text{ yr}^{-1}$. Term [1] ($\partial_t O_2$) on the left hand side of the equation marks the observed temporal change of oxygen (oxygen tendency). While the multi-decadal oxygen trend was already considered in Hahn et al. (2014), the estimate of the decadal oxygen trend and its inclusion in the oxygen budget is a central part of this study (details on the calculation are given in Sect. 2.1). Term [2] ($aOUR$) defines the oxygen consumption, which has been determined in Karstensen et al. (2008) following an approach that relates the apparent oxygen utilization (AOU) to water mass ages. Term [3] ($K_e \partial_{yy} O_2$) is the divergence of the meridional oxygen flux driven by eddy diffusion (Hahn et al., 2014). Term [4] ($K_p \partial_{zz} O_2$) is the divergence of the diapycnal oxygen flux due to turbulent mixing (Fischer et al., 2013). Term [5] includes all other oxygen supply mechanisms, which could not be directly estimated from observational data: mean advection, zonal eddy diffusion and submesoscale processes. This term is calculated as the residual oxygen supply based on terms [1] to [4]. Here, we follow the argumentation given in Hahn et al. (2014): by considering the meridional structure of the eddy-driven meridional oxygen supply (term [3] in our Eq. (1)) as well as the horizontal oxygen distribution (see also Fig. 10 therein), they argued for a major contribution of the mean zonal advection in the upper 350 m, while zonal eddy diffusion and mean meridional advection have only minor effect and submesoscale processes are not assumed to affect the oxygen distribution well below the base of the mixed layer (Thomsen et al., 2016). Strictly, estimates of mean advection require the analysis of advective oxygen fluxes through the boundaries of a closed volume. Such measurements are however not available. Nevertheless, in Sect. 4.3 we present a rough estimate of the zonal advective flux across the 23°W section derived from data taken only along that section. Note that vertical advection, which was recently proposed in a model study (Pena-Izquierdo et al., 2015) to be present as part of two stacked subtropical cells, is not considered in the observationally based oxygen budget, but will be discussed in Sect. 4.3 as well.

Given the data set in this study, a complete analysis of the temporal change of the consumption and supply terms, which ultimately are responsible for the change in the oxygen trend, cannot be performed due to data coverage and respective uncertainty reasons. Nevertheless, the decadal and multi-decadal oxygen trends ($[\partial_t O_2]^{(1)}$ and $[\partial_t O_2]^{(2)}$) are applied separately in the oxygen budget. All other directly calculated terms (consumption, meridional eddy supply and diapycnal supply) are kept time-invariant, while the residual oxygen supply is calculated for the respective time periods ($R_{O_2}^{(1)}$ and $R_{O_2}^{(2)}$) based on the two oxygen trends. This ad hoc approach is used to particularly discuss zonal advection as a potential driver for the change in the oxygen trend. However, in Sect. 4.3 we also analyze and discuss the potential of all other ventilation terms in having driven the decadal oxygen trend.

3 Results

In this section, results will be shown from the combined analysis of moored, shipboard and float observations in the tropical Atlantic with a particular focus on the ETNA OMZ in order to investigate and quantify decadal changes of oxygen as well as their correlation with changes in salinity. Changes in the velocity field were estimated based on repeat shipboard observations as well as satellite observations obtained mainly in the ETNA OMZ. Eventually, the oxygen budget of the ETNA was reanalyzed and revised from Hahn et al. (2014) with respect to both decadal and long-term oxygen changes.

Johannes Hahn 23.5.2017 19:43

Gelöscht: 3

Johannes Hahn 23.5.2017 19:43

Gelöscht: 2 and 3.4

Johannes Hahn 22.5.2017 20:57

Gelöscht: eddy-driven meridional oxygen supply representing the divergence of the meridional oxygen flux due to isopycnal eddy diffusion

Johannes Hahn 22.5.2017 20:57

Gelöscht: defines

Johannes Hahn 22.5.2017 20:58

Gelöscht: supply representing the divergence of the diapycnal oxygen flux

Johannes Hahn 22.5.2017 21:32

[5] verschoben (Einfügung)

Johannes Hahn 22.5.2017 21:32

Gelöscht: as well as

Johannes Hahn 22.5.2017 21:32

Gelöscht: and

Johannes Hahn 22.5.2017 21:32

Gelöscht: For the sake of completeness, [5] is nonspecifically considered as a composite of

Johannes Hahn 22.5.2017 21:32

[5] nach oben verschoben: mean advection, zonal eddy diffusion as well as submesoscale processes.

Johannes Hahn 22.5.2017 21:32

Gelöscht: w

Johannes Hahn 23.5.2017 22:07

Gelöscht: (1)

Johannes Hahn 10.5.2017 09:34

Gelöscht: 3

Johannes Hahn 9.5.2017 17:04

Gelöscht: was so far

Johannes Hahn 9.5.2017 17:23

Gelöscht: is

Johannes Hahn 9.5.2017 18:35

Gelöscht: Data analysis and r

Johannes Hahn 9.5.2017 18:36

Gelöscht: , although a direct relation among velocity and oxygen or salinity may not be derived for the respective time scales

3.1 Mean state in the ETNA

Given the mean 23°W section from shipboard observations, the core of the deep OMZ is located at 10°N and at 430 m depth with a minimum oxygen concentration of $41.6 \mu\text{mol kg}^{-1}$ (Fig. 2a). Between 100 and 250 m, pronounced oxygen maxima at 5°N and 8°N-9°N coincide well with the core positions of the near-surface NECC and nNECC (Fig. 2c). Similar patterns could not be observed in the salinity distribution (Fig. 2b). However, the largest meridional salinity gradient was found in the CW layer ($25.8 - 27.1 \text{ kg m}^{-3}$) around 10°N and coincides with the northern edge of the near-surface eastward nNECC mirroring the transition zone from SACW to NACW, i.e. from low salinity close to the equator to high salinity in the northern part of the section.

The transition from SAW to NAW is well reflected in the θ -S diagram (Fig. 2d), which shows θ -S characteristics for particular latitudes based on the mean hydrographic ship section along 23°W (Fig. 2b, temperature not shown). Following Rhein et al. (2005) a simple water mass analysis was evaluated taking into account NAW and SAW, whose characteristics were defined from the MIMOC climatology for their respective source areas [25°N-30°N / 60°W-10°W] and [5°S-0°N / 40°W-0°E] (not shown). This revealed a strong spreading of SAW towards the north in the upper 300 m (UCW layer) with a SAW fraction of 0.9 close to the Cape Verde Archipelago at 13°N. Below 300 m (LCW and IW layer), fractions of SAW and NAW are similar, while NAW has its southernmost extension at about 550 m with a fraction of 0.2 at 6°N.

3.2 Interannual variability and decadal change of oxygen and salinity

In this section, we present the temporal variability of oxygen and salinity obtained from shipboard, moored and float observations of the most recent decade and investigate the correlation between these two variables. Decadal trends were derived at the aforementioned mooring positions as well as for the 23°W section between 4°N and 14°N.

While the mean 23°W oxygen section shows a minimum oxygen concentration of $41.6 \mu\text{mol kg}^{-1}$ (see Sect. 3.1), individual CTD profiles taken in the core of the deep OMZ between 300 and 700 m throughout the past decade regularly reached minimum oxygen concentrations well below $40 \mu\text{mol kg}^{-1}$ (see also Stramma et al. (2009)). An absolute minimum of $36.5 \mu\text{mol kg}^{-1}$ was observed at 12.5°N, 23°W at 410 m during RV *Maria S. Merian* cruise MSM22 in November 2012.

The combined analysis of shipboard and moored observations (for details see Sect. 2.2) revealed a remarkable oxygen change in the ETNA OMZ at latitudes 11°N and 8°N throughout the past decade (Fig. 3a/3b and Fig. 4a/4b). Oxygen strongly decreased in the upper depth layer (200 - 400 m) and increased below (500 - 800 m), with salinity partly showing opposite trends (Fig. 3c/3d and Fig. 4c/4d). Superimposed on this decadal change, additional variability on intraseasonal to interannual time scales was observed. At 5°N, intraseasonal to interannual oxygen variability was the dominant signal (Fig. 5) and a decadal oxygen change could not be observed for this latitude. Note, that besides the energetic salinity variability on intraseasonal to interannual time scales, the combination of shipboard and moored observations also suggests salinity fluctuations on a decadal long time scale in the upper depth layer (200 - 400 m, Fig. 5c).

Based on shipboard observations, the 23°W section of decadal oxygen tendency for the period 2006-2015 (Fig. 6a) revealed coherent large-scale patterns of oxygen decrease and oxygen increase. Even though only a part of

Johannes Hahn 9.5.2017 18:32

[3] nach oben verschoben: The mean state 23°W sections of oxygen, hydrography and zonal velocity were calculated between 4°N and 14°N (Fig. 2a to 2c) based on all uniformly gridded 23°W sections as obtained from the repeat shipboard observations (cf. Sect. 2 and Table 1). For the depth range 100 - 1,000 m, the averaging of all sections yielded an average standard error of the mean fields (which is considered to result dominantly from oceanic variability) of about $1.8 \mu\text{mol kg}^{-1}$, 0.06°C , 0.009 and 1.1 cm s^{-1} for oxygen, temperature, salinity and zonal velocity, respectively.

Johannes Hahn 9.5.2017 18:36

Gelöscht: The mean state 23°W sections of 23°W sections of oxygen, hydrography and zonal velocity were calculated between 4°N and 14°N (Fig. 2a to 2c) based on all uniformly gridded 23°W sections as obtained from the repeat shipboard observations (cf. Sect. 2 and Table 1). For the depth range 100 - 1,000 m, the averaging of all sections yielded an average standard error of the mean fields (which is considered to result dominantly from oceanic variability) of about $1.8 \mu\text{mol kg}^{-1}$, 0.06°C , 0.009 and 1.1 cm s^{-1} for oxygen, temperature, salinity and zonal velocity, respectively. ... [1]

Johannes Hahn 9.5.2017 18:40

Gelöscht: For the ETNA, t

Johannes Hahn 9.5.2017 18:43

Gelöscht:

Johannes Hahn 9.5.2017 18:48

Gelöscht: were derived

Johannes Hahn 9.5.2017 18:49

[4] nach unten verschoben: Characteristics for pure NAW and SAW were defined from the MIMOC climatology for the areas [25°N-30°N / 60°W-10°W] and [5°S-0°N / 40°W-0°E], respectively.

Johannes Hahn 9.5.2017 18:49

[4] verschoben (Einfügung)

Johannes Hahn 9.5.2017 18:49

Gelöscht: C

Johannes Hahn 9.5.2017 18:49

Gelöscht: for pure NAW and SAW ... ere d ... [2]

Johannes Hahn 25.4.2017 18:24

Gelöscht: V...ariability and decadal char ... [3]

Johannes Hahn 9.5.2017 18:50

Gelöscht: The mean states of oxygen and hydrography based on shipboard observations along 23°W were examined in the previous section ... [4]

Johannes Hahn 9.5.2017 19:33

Gelöscht: long-term ...ean 23°W oxygen s ... [5]

Johannes Hahn 27.4.2017 10:48

Gelöscht: ...he combined analysis of shipl ... [6]

Johannes Hahn 10.5.2017 10:00

Gelöscht: T...he 23°W section of the ...ec ... [7]

the local trends is statistically significant, the spatial coherence of the trends suggests robust trend patterns. Note also that significant patterns were larger than twice the smoothing and interpolation scale of the individual ship sections. A strongly decreasing oxygen concentration with up to $-2 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ was found in the latitude range from 6°N to 14°N and at a depth range 200 to 400 m (on average $-5.9 \pm 3.5 \mu\text{mol kg}^{-1} \text{decade}^{-1}$). Between 400 and 1,000 m, oxygen was found to increase with an average magnitude of about $4.0 \pm 1.6 \mu\text{mol kg}^{-1} \text{decade}^{-1}$ between 6°N and 14°N . Locally, a significant oxygen increase was observed below the OMZ core depth at 500 – 700 m in the latitude range 7°N – 13°N as well as at 800 – 1,000 m in the latitude range 4°N – 11°N . Box averages of decadal oxygen tendency for selected latitude and depth ranges together with their 95% confidence estimates are presented in Table 3.

Johannes Hahn 10.5.2017 10:01

Gelöscht: patterns ...rends suggests that th... [8]

Shipboard observations mainly showed no significant decadal salinity tendency for the period 2006–2015 (Fig. 6b). In a similar approach, we additionally calculated the decadal salinity tendency from Argo float observations (with reference to the seasonal cycle of the MIMOC climatology) for the same time period (Fig. 6c). This resulted in a more robust estimate (see Table 3 for corresponding box averages) showing a salinity increase over almost the whole latitude range at the depth range of about 100 to 350 m. Between 400 and 1,000 m, salinity decreased between about 7°N and 11°N as well as increased between about 4°N and 7°N .

Johannes Hahn 22.5.2017 22:07

Gelöscht: The section of the ...ecadal salin... [9]

Variability in physical ventilation processes may drive coherent changes in different tracers, such as salinity or oxygen. Based on shipboard and moored observations, we calculated the correlation between oxygen and salinity (see Sect. 2.1 and 2.2 for details of the calculation) and identified significant regimes along 23°W (Fig. 7). A significant negative correlation was found below the deep oxycline and south of the OMZ core (average slope $\partial O_2 / \partial S = -255 \pm 140 \mu\text{mol kg}^{-1}$) - a regime with a pronounced positive gradient in salinity and negative gradient in oxygen on isopycnal surfaces in northeast direction (cf. Fig. 2 in this study, Kirchner et al. (2009); Pena-Izquierdo et al. (2015)). North of the OMZ core, the correlation is positive, which agrees well with the positive oxygen and salinity gradient in northward direction in this regime. Note that above the deep oxycline (upper 300 m) the correlations obtained from moored and shipboard observations partly disagree with each other, which might be due to generally larger variability and the different time periods covered by both observational data sets.

The box averages (Table 3) for selected latitude and depth ranges show that significant decadal changes both in oxygen and salinity were found in the CW layer at 6°N – 8°N and 10°N – 12°N as well as in the IW layer between 8°N and 12°N . All significant tendencies were inversely related to each other and agreed well with regimes of significant anticorrelation of oxygen and salinity (Fig. 7).

For the two respective depth layers, changes in salinity over the past decade (2004–2016) were further investigated for the whole tropical Atlantic by analyzing Argo float observations for two characteristic density surfaces 26.8 kg m^{-3} and 27.2 kg m^{-3} (see Sect. 2.4 for details). At density layer 26.8 kg m^{-3} , salinity generally increased between 10°S and 10°N (Fig. 8a to 8d). Here, a propagation of positive salinity anomalies was observed from the tropical South Atlantic toward North and the western boundary throughout the past decade (cf. Kolodziejczyk et al. (2014) for shallower depths). Further north, a negative salinity trend was found between about 10°N and 20°N , and a positive trend was found north of 20°N . At density layer 27.2 kg m^{-3} , the northward propagation of positive salinity anomalies from the tropical South Atlantic was less pronounced (Fig. 8e to 8h). A generally positive decadal salinity tendency was found for this density layer between about 10°S and 10°N .

Johannes Hahn 26.4.2017 00:47

Gelöscht: Patterns of the decadal change in salinity along 23°W were found to be negatively correlated with those in oxygen in the density layers of LCW and IW (Fig. 10b and 10c). In particular, the strongest negative correlation occurred in the latitude band 6°N – 8°N weakening northwards and no correlation at all was present north of the OMZ core in the latitude band 12°N – 14°N . This relation qualitatively agrees well with the observed correlation patterns of oxygen and salinity (Fig. 10). [10]

but regionally negative salinity tendencies were found as well, e.g. salinity decreased along 23°W between about 7°N and 11°N (cf. Fig. 6c and 8h).

Changes in the spatial oxygen distribution go along with changes in the OMZ core position. Here, the vertical and meridional position of the OMZ core was estimated for every ship section by taking the center of the 5%-area of lowest oxygen (1% area gave similar results) found between 8°N and 14°N in depth (400 – 460 m) and density space (27.00 – 27.06 kg m⁻³), respectively. Decadal trends with 95% confidence were then calculated for depth, density and latitude of the OMZ core in order to derive the vertical and meridional migration of the OMZ core (Fig. 9). We found a migration of the OMZ core position in density space toward lighter water (-0.03 ± 0.02 kg m⁻³ decade⁻¹), whereas no significant upward migration in depth space could be shown (-10 ± 25 m decade⁻¹) from this estimate. Note that by considering the vertical displacement of density surfaces throughout this decade, a significant upward migration of the OMZ core could be shown in depth space as well (Sect. 4.1). No significant meridional migration of the OMZ core was observed both in depth and density space (about 0.3 ± 2.3 ° decade⁻¹).

The migration of the OMZ core in density space might be due to a decadal change in the depth of the density surfaces (isopycnal heave tendency, Fig. 10). The isopycnal heave tendency was derived from all hydrographic shipboard observations carried out along 23°W between 2006 to 2015. Density surfaces deepened (stratification increased) at latitudes 7°N – 12°N below 100 m (3.2 ± 0.4 m decade⁻¹ at the OMZ core depth) and shoaled north and south of this latitude band (stratification decreased).

3.3 Circulation changes in the ETNA

A change in the large-scale circulation is a possible source for the decadal changes in oxygen and salinity presented in the previous section. Such circulation changes would likely precede changes in the discussed tracers (cf. Brandt et al. (2012)) and several-decade-long observations would be necessary in order to attribute such a relationship. Here, we are far away from quantitatively linking circulation variability to decadal changes in oxygen and salinity. Nevertheless, in the following we present observed changes in the circulation in order to discuss the potential impact on the hydrographic and oxygen distribution in the ETNA.

The isopycnal heave tendency (Fig. 10) showed a change in the stratification around the OMZ, which points to a change in the geostrophic circulation. Repeat shipboard ADCP and hydrographic observations were subsequently used in order to investigate the decadal change in the zonal velocity. Zonal velocity sections derived from a geostrophic approach as well as from shipboard ADCP observations were very similar both reasonably representing the wind-driven near-surface currents (NECC and nNECC) as well as the LAZJ at depth. In the following, only shipboard ADCP observations are shown.

Zonal velocity from shipboard ADCP observations was estimated along 23°W as an average for the periods 1999-2008 and 2009-2015 (Fig. 11a and 11b) to determine the decadal change. A one-tailed t-test (directional hypothesis) was applied to evaluate the significance (95% confidence) of the difference of the means for the two periods (Fig. 11c to 11e). Zonal velocity didn't change for most parts of the section (80% - 90%), but two latitudinal regimes were identified with significant difference between both periods. First, eastward and westward currents were observed at latitudes 12°N-13°N and 13°N-14°N over the whole depth range in the latter period, which was reverse in the first period. Second, the eastward jet, centered at about 9°N, widened at depths

Johannes Hahn 26.4.2017 01:03

Gelöscht: variability

Johannes Hahn 26.4.2017 01:02

Gelöscht: shown

Johannes Hahn 23.5.2017 06:46

Gelöscht: of

Johannes Hahn 26.4.2017 01:10

Gelöscht: decadal change in the depth of the density surfaces (

Johannes Hahn 26.4.2017 01:10

Gelöscht: , Fig. 12

Johannes Hahn 26.4.2017 01:11

Gelöscht: was derived from all hydrographic shipboard observations carried out along 23°W between 2006 to 2015. Density surfaces deepened at latitudes 7°N – 12°N below 100 m (3.3 ± 3.6 m decade⁻¹ at the OMZ core depth) and shoaled north and south of it

Johannes Hahn 26.4.2017 01:12

Gelöscht: This change goes along with an increased stratification within the OMZ and a decreased stratification north and south of it.

Johannes Hahn 25.4.2017 14:57

Gelöscht: Fig. 13

Johannes Hahn 25.4.2017 14:57

Gelöscht: 3

Johannes Hahn 25.4.2017 14:57

Gelöscht: 3

Johannes Hahn 25.4.2017 14:57

Gelöscht: 3

Johannes Hahn 23.5.2017 06:50

Gelöscht: the circulation south of the Cape Verde Islands reversed, where, in contrast to the first period, in the latter period and over the whole depth range

Johannes Hahn 23.5.2017 06:53

Gelöscht: respectively

below about 300 m from the first to the latter period, going along with a narrowing of the westward jet north of it.

In order to investigate the variability of the NECC/nNECC, we applied an EOF analysis to the Aviso altimetry based surface geostrophic velocity observations given for the region [35°W – 20°W, 4°N – 10°N] (for details see Sect. 2.5). Considering the results in relation to the mean zonal geostrophic velocity, the first EOF describes maximum (out-of-phase) variability of the zonal geostrophic velocity north and south of the NECC core latitude at about 6°N (capturing a meridional migration of the NECC, Fig. 12a), whereas the second EOF describes maximum variability at about the core latitude of the NECC (capturing an intensification or weakening of the NECC, Fig. 12b). The principal component (PC) corresponding to the first EOF mode (first and second PC shown in Fig. 12c) declined throughout the past decade, which points to a southward migration of the NECC. The PC corresponding to the second EOF mode revealed only shorter-term (interannual) variability in the strength of the NECC. Reconstructing the zonal geostrophic velocity anomaly out of the first two EOFs and the corresponding PCs with subsequent averaging in the boxes [35°W – 20°W, 4°N – 6°N] and [35°W – 20°W, 6°N – 10°N] (Fig. 12d) showed that eastward velocity increased in the latitude band 4°N – 6°N and decreased in the latitude band 6°N – 10°N throughout the past decade.

3.4 Decadal and long-term changes in the oxygen budget of the ETNA OMZ

The multi-decadal oxygen trend (1972 – 2008) was discussed in the oxygen budget of the ETNA OMZ in Hahn et al. (2014) (see also Sect. 2.6). Here, the depth profile of the decadal oxygen trend observed for the period 2006-2015 (average between 6°N and 14°N of the 23°W section; cf. Fig. 6a) was additionally included in order to discuss temporal changes in the oxygen budget (Fig. 13). The decadal oxygen trend showed an oxygen decrease / increase in the depth range 150 – 400 m / 400 – 800 m, whereas during the period 1972 – 2008 an oxygen decrease was found over the whole depth range (here: shown for 130 – 800 m). Other terms in the oxygen budget, namely oxygen consumption, meridional eddy supply and diapycnal supply were calculated as described in Brandt et al. (2015) as well as in corresponding studies of Karstensen et al. (2008), Fischer et al. (2013) and Hahn et al. (2014).

The vertical profiles of the decadal (2006 - 2015) and multi-decadal (1972 - 2008) oxygen trend were independently treated in the oxygen budget (Fig. 13). Other terms such as consumption, meridional eddy supply and diapycnal supply were kept time-invariant. The change in the oxygen trend between the two periods was projected onto the residual oxygen supply (cf. Eq. (1)), which is mainly attributed to the zonal advective supply due to zonal jets ventilating the eastern basin from the oxygenated western boundary (Brandt et al., 2015). At first glance, this projection seems like a rather strict assumption, though the temporal variability in the oxygen budget shall be discussed exemplarily using the residual supply without loss of generality. However, in Sect. 4.3, we will discuss in detail the potential of all other ventilation terms in explaining the decadal oxygen change pattern. As will be shown, the zonal advective oxygen supply is the most probable budget term responsible for the observed oxygen changes.

According to the two oxygen trend profiles, two different residual supply profiles resulted for the periods 1972 - 2008 and 2006 - 2015, respectively. Both residuals show a strong zonal advective supply in the upper 350 m including a steep drop-off and subsequently a rather homogeneous supply between 400 and 800 m. In

Johannes Hahn 23.5.2017 07:04

Gelösch: wind-driven near-surface currents

Johannes Hahn 10.5.2017 11:47

Gelösch: used

Johannes Hahn 23.5.2017 07:02

Gelösch: provided by AVISO

Johannes Hahn 10.5.2017 11:46

Gelösch: The two main variability patterns of the surface circulation in the tropical North Atlantic can be described by the first complex EOF (empirical orthogonal function) mode of the zonal geostrophic velocity anomaly, where the real part of the EOF pattern mimics the meridional migration of the NECC and the imaginary pattern reflects the variability in its strength (Hormann et al., 2012). We applied an EOF analysis to the grid point wise filtered (mean and seasonal cycle removed and subsequently 2-year-low-pass-filtered) time series of AVISO zonal geostrophic velocity for the region 35°W-20°W and 4°N-14°N in order to capture the interannual to decadal variability of the NECC/nNECC throughout the past decades (Fig. 14). The first two EOF modes (Fig. 14a and 14b) explained 23% and 14% of the total variance of the filtered time series and can be considered similarly to the real and imaginary pattern of the com. ... (11)

Johannes Hahn 10.5.2017 11:49

Gelösch: (additionally shown in Fig. 14a ... (12)

Johannes Hahn 25.4.2017 14:56

Gelösch: Fig. 14

Johannes Hahn 25.4.2017 14:56

Gelösch: Fig. 14

Johannes Hahn 10.5.2017 11:51

Gelösch: s

Johannes Hahn 10.5.2017 12:02

Gelösch: past decade

Johannes Hahn 10.5.2017 12:03

Gelösch: (Fig. 15)

Johannes Hahn 10.5.2017 12:03

Gelösch: depth profile of the

Johannes Hahn 10.5.2017 11:54

Gelösch: was calculated as an average bc ... (13)

Johannes Hahn 10.5.2017 11:57

Gelösch: . D

Johannes Hahn 10.5.2017 11:59

Gelösch: ,

Johannes Hahn 10.5.2017 12:04

Gelösch: observed

Johannes Hahn 10.5.2017 11:59

Gelösch: , whereas for the past decade (2 ... (14)

Johannes Hahn 10.5.2017 11:57

Gelösch: an oxygen decrease / increase w ... (15)

Johannes Hahn 23.5.2017 07:06

Gelösch: , respectively,

Johannes Hahn 23.5.2017 07:06

Gelösch: applied

Johannes Hahn 25.4.2017 14:53

Gelösch: Fig. 15

Johannes Hahn 26.4.2017 19:30

Gelösch: (1)

comparison to the earlier period 1972 - 2008, the residual supply in the depth range below 400 m homogeneously doubled in magnitude for the recent decade (2006 - 2015). The strong zonal advective supply in the upper 350 m only changed marginally and shifted to a slightly shallower depth in the past decade (2006 - 2015) being barely significant with regard to the large confidence intervals.

4 Discussion

A comprehensive observational data set consisting of moored, shipboard, float and altimetry observations from the past two decades in the ETNA has been used to study the variability of hydrography, oxygen and circulation with a focus on changes in the last decade and their implication for the oxygen budget. Decadal changes in oxygen and salinity are discussed in Sect. 4.1. The role of circulation changes is addressed in Sect. 4.2. In Sect. 4.3, the individual supply terms of the oxygen budget are examined and discussed with respect to their potential in having caused the decadal oxygen change.

4.1 Decadal oxygen and salinity changes in the ETNA

For the period 2006 – 2015, shipboard and moored observations in the ETNA along 23°W revealed a decadal change of oxygen between 6°N and 14°N with a strong decrease (Fig. 6a) at depth of the deep oxycline between 200 and 400 m ($-5.9 \pm 3.5 \mu\text{mol kg}^{-1} \text{decade}^{-1}$) and a large-scale increase below ($4.0 \pm 1.6 \mu\text{mol kg}^{-1} \text{decade}^{-1}$). This vertically oriented dipole pattern is centered approximately at depth of the OMZ core and is consistent with the observed upward migration of the OMZ core in density and depth space throughout the past decade (Fig. 9). Strictly, shipboard observations revealed a significant shoaling of the OMZ core only in density space. However, the average vertical migration in density space ($-0.03 \pm 0.02 \text{ kg m}^{-3} \text{decade}^{-1}$) was too large to be compensated by the isopycnal heave (Fig. 10; $3.2 \pm 0.4 \text{ m decade}^{-1}$) when considering the observed mean background vertical density gradient of about $1.2 \times 10^{-3} \text{ kg m}^{-3} \text{ per m}$ (not shown). By taking into account these estimates, we additionally expect that an upward migration of the OMZ core has happened in depth space as well by about $-22 \pm 17 \text{ m decade}^{-1}$.

While the decadal oxygen change is characterized by a vertical dipole pattern, the multi-decadal oxygen trend (period 1972 – 2013), analyzed for the tropical and subtropical Atlantic along 23°W by Brandt et al. (2015), shows a large-scale moderate oxygen decrease for the whole ETNA OMZ regime. Maximum rates of about $-5 \mu\text{mol kg}^{-1} \text{decade}^{-1}$ therein were substantially smaller than maximum rates of oxygen decrease ($-20 \mu\text{mol kg}^{-1} \text{decade}^{-1}$) found in this study for the recent decade (Fig. 6a). At the OMZ core depth and below, observed opposite oxygen trends on decadal and multi-decadal time scales suggest that different mechanisms may act in parallel and drive these oxygen changes. Note that the local maximum of the multi-decadal oxygen decrease (Brandt et al., 2015) is at around 20°N and 450 m ($-7 \mu\text{mol kg}^{-1} \text{decade}^{-1}$) indicating a northward shift of the ETNA OMZ likely associated with a similar shift in the circulation pattern. In contrast, the observed upward migration of the ETNA OMZ in the recent decade might be understood as the consequence of a decreased ventilation in the upper 400 m and an increased ventilation below.

Oxygen variability was strongly related to salinity variability in the ETNA at the depth of the deep oxycline and below (Fig. 7). Both variables were found to be significantly negatively correlated south of the OMZ core, while a weak positive correlation was found north of it. This reflects the supply of the OMZ with fresher SAW from

Johannes Hahn 23.5.2017 09:02

Gelöscht: the decadal

Johannes Hahn 23.5.2017 09:03

Gelöscht: as well as its respective

Johannes Hahn 23.5.2017 09:03

Gelöscht: Shipboard observations give a detailed view on the regional pattern of the decadal change, whereas moored and float observations additionally capture variability on interannual and shorter time scales.

Johannes Hahn 10.5.2017 12:06

Gelöscht: Variability of o

Johannes Hahn 26.4.2017 10:48

Gelöscht: S

Johannes Hahn 15.5.2017 14:01

Gelöscht: between 4°N and 14°N

Johannes Hahn 26.4.2017 01:17

Gelöscht: 3 to 5, 8a and

Johannes Hahn 10.5.2017 09:30

Gelöscht: 9

Johannes Hahn 25.4.2017 22:32

Gelöscht: 6

Johannes Hahn 25.4.2017 22:32

Gelöscht: 2

Johannes Hahn 25.4.2017 22:32

Gelöscht: 8

Johannes Hahn 25.4.2017 22:32

Gelöscht: 1

Johannes Hahn 25.4.2017 22:32

Gelöscht: 7

Johannes Hahn 10.4.2017 15:12

Gelöscht: Fig. 6

Johannes Hahn 25.4.2017 14:58

Gelöscht: Fig. 12

Johannes Hahn 26.4.2017 10:31

Gelöscht: 3

Johannes Hahn 26.4.2017 10:31

Gelöscht: 3

Johannes Hahn 26.4.2017 10:31

Gelöscht: 6

Johannes Hahn 10.5.2017 12:17

Gelöscht: This inconsistency is compensated by assuming an additional upward migration of the OMZ core in depth space, which we estimated to be $-22 \pm 17 \text{ m decade}^{-1}$.

Johannes Hahn 10.4.2017 15:11

Gelöscht: Fig. 9

Johannes Hahn 10.4.2017 15:13

Gelöscht: Fig. 7

Johannes Hahn 23.5.2017 09:19

Gelöscht: position

the southern hemisphere as well as saltier NAW from the northern hemisphere via different ventilation pathways (Brandt et al., 2015; Pena-Izquierdo et al., 2015; Kirchner et al., 2009). Nevertheless, we cannot exclusively link decadal changes in hydrography to decadal changes in the water mass composition in order to explain changes in oxygen, as source waters may change their θ - S characteristics as well. Instead, a straightforward approach is the analysis of salinity variability to detect both a change in the ventilation as well as a change in the source water masses.

Johannes Hahn 23.5.2017 09:19
Gelöscht: its

The significant decadal change in oxygen along 23°W was inversely related to a significant decadal change in salinity in the CW and IW layer (below 200 m) south of the OMZ core position (Fig. 6 and Table 3). In the deep oxycline, the strong oxygen decrease was accompanied by a salinity increase, whereas below 400 m the large-scale oxygen increase was accompanied partly by a salinity decrease, but salinity increase was observed as well. Indeed, Argo float observations from the tropical and subtropical Atlantic (Fig. 8) revealed a large-scale salinity increase between 10°S to 10°N at depth of the deep oxycline (around density surface 26.8 kg m⁻³). In contrast, in the IW layer (here shown for density surface 27.2 kg m⁻³) the salinity increase was weaker and less homogeneous regionally alternating with salinity decrease as exemplarily shown for the 23°W section.

Johannes Hahn 26.4.2017 11:41
Gelöscht: D...ecadal change in oxygen al ... [16]

Argo float observations further suggest that this salinity increase in the tropical Atlantic might be due to a northward migration of positive salinity anomalies advected from the southern to the northern hemisphere along the western boundary. This is in agreement with the generally expected shallow northward propagation of SAW due to the presence of the STC and the AMOC (Lübbecke et al., 2015; Kirchner et al., 2009; Rabe et al., 2008; Biastoch et al., 2009). However, a continuous pathway of propagating positive salinity anomalies along the western boundary into the ETNA could barely be observed. We speculate that the analyzed data set of Argo float observations was too sparse (particularly in the narrow and energetic western boundary current regime) to identify a continuous propagation of these signals.

Johannes Hahn 26.4.2017 12:57
[2] nach unten verschoben: Different mechanisms can be responsible for the decadal change in salinity.

Johannes Hahn 27.4.2017 15:31
Gelöscht: The ...rgo float observations fu ... [17]

Different mechanisms may have caused the positive salinity anomalies in the South Atlantic: (i) a change in the Agulhas leakage (Kolodziejczyk et al., 2014; Hummels et al., 2015; Biastoch et al., 2009; Lübbecke et al., 2015) or (ii) a change in the subduction rate in the subtropical South Atlantic (Liu and Huang, 2012). Both scenarios might have gone along with a change in the water mass age and thus with a change in the ventilation time of the ETNA. However, (iii) global warming could be another cause for the observed change in the salinity distribution (vertical displacement of isopycnal surfaces in the tropical Atlantic or horizontal displacement of isopycnal surfaces in the subduction regimes in the subtropics).

Johannes Hahn 26.4.2017 12:57
[2] verschoben (Einfügung)

Johannes Hahn 26.4.2017 14:47
Gelöscht: can be responsible for the decadal change in salinity...ay have caused [18]

4.2 Role of circulation changes

The generally inversely related decadal changes in oxygen and salinity (Fig. 6 and Table 3) in the ETNA along 23°W suggest a change in the circulation pattern of the tropical Atlantic (200 – 400 m: weakened ventilation; below 400 m: intensified ventilation). This is in line with the shoaling of the ETNA OMZ (Fig. 9; see also Sect. 4.1), with the deepening of isopycnal surfaces in the OMZ regime between 7°N and 11°N as well as with the shoaling of isopycnal surfaces north and south of this latitude band (Fig. 10).

Johannes Hahn 10.5.2017 12:34

Gelöscht: Changes in the ...f circulation ... [19]

Johannes Hahn 26.4.2017 13:18

Gelöscht: negatively ...nversely correlate ... [20]

Changes in circulation and ventilation in the ETNA may be driven either by local or remote processes. Remote processes were already qualitatively discussed in Sect. 4.1 along with salinity changes in the tropical and subtropical Atlantic. Exemplarily, an increasing Agulhas leakage would result in positive salinity anomalies in

1070 the subtropical South Atlantic (Biaostoch et al., 2009; Kolodziejczyk et al., 2014), which is assumed to go along with negative oxygen anomalies and larger water ages of Indian Ocean CW and IW. Further, changes in the subduction rate in the subtropical South or North Atlantic or a horizontal displacement of isopycnal surfaces in these subduction regimes would change the ventilation as well. A quantitative analysis of these remote processes with respect to ventilation changes in the ETNA is challenging and goes beyond the scope of this study. In the following, we concentrate on local processes in the Tropical Atlantic, which might have particularly driven circulation changes in the ETNA.

1075 In the deep oxycline (200 – 400 m), advection of SAW from the western boundary is an important factor for the ventilation of the ETNA (see Fig. 2 and Fig. 8 in this study, and Hahn et al. (2014); Brandt et al. (2015); Pena-Izquierdo et al. (2015); Lübbecke et al. (2015)). Thus, it is likely that interannual to decadal variability in the position and strength of the largely wind-driven currents in the top few hundred meters might have caused the changes in oxygen and salinity. Repeated 23°W sections didn't show a large-scale change in the strength of the zonal velocity (Fig. 11). However, the analysis of altimetry based surface zonal geostrophic velocity revealed a strengthening of the eastward velocity between 4°N and 6°N (NECC) and a weakening between 6°N and 10°N (nNECC) from 2006 to 2015 (Fig. 12d), which is associated with a southward shift of the wind-driven gyres of the tropical North Atlantic. These circulation changes result in a weakened ventilation of the ETNA from the western boundary in the latitude range of the OMCZ, which is in agreement with the observed decadal change patterns of oxygen and salinity in this depth range.

1080 A distinct change in the current field was found directly south of the Cape Verde Islands (Fig. 11). The band of eastward velocity shifted toward south (from 14°N to 12°N-13°N) and a band of weak westward velocity was observed instead around 13°N-14°N during the more recent period. This can be associated with a southward shift of the Cape Verde Current (CVC, Pena-Izquierdo et al. (2015)), which is thought to predominantly advect NAW. However, it remains uncertain, whether a southward shift of the CVC has contributed to a change in the ratio of NAW and SAW, and to a (de)oxygenation in the upper 400 m of the water column. Note that in contrast to shipboard observations, the southward shift of the CVC was not similarly found in the dominant EOF pattern of altimetry based surface zonal geostrophic velocity (Fig. 12). We suspect several reasons for this difference. First, the zonal (and also meridional) extent as well as the amplitude of the coherent variability pattern of the surface zonal geostrophic velocity is larger between 4°N and 10°N than between 10°N and 14°N. Second, the CVC has its core below the surface as shown in the mean velocity section along 23°W (Fig. 2c; see also Pena-Izquierdo et al. (2015)). The maximum variability of this current is likely at the subsurface as well. Third, shipboard observations represent only snapshots of the strongly variable current field possibly resulting in an aliasing of short-term variability.

1100 In addition to the decadal change, moored observations have also revealed pronounced oxygen and salinity variability on interannual time scales. Associated interannual to decadal variability of the wind-driven circulation in the tropical Atlantic is predominantly driven by ocean-atmosphere interactions related to Atlantic climate modes, namely the Atlantic Zonal Mode (AZM) and Atlantic Meridional Mode (AMM) (Chang et al., 2006; Joyce et al., 2004; Marshall et al., 2001; Zhu et al., 2012). Servain (1991) introduced the AZM as the equatorial sea surface temperature (SST) anomaly and defined the AMM as the anomalous inter-hemispheric SST gradient with negative AMM corresponding to a negative/positive SST anomaly in the Northern/Southern Hemisphere. A

Johannes Hahn 10.5.2017 09:32

Gelöscht: 11

Johannes Hahn 23.5.2017 20:53

Gelöscht: on isopycnal surfaces

Johannes Hahn 25.4.2017 14:57

Gelöscht: Fig. 13

Johannes Hahn 25.4.2017 14:56

Gelöscht: Fig. 14

Johannes Hahn 10.5.2017 12:43

Gelöscht: is

Johannes Hahn 10.5.2017 12:43

Gelöscht: zonal velocity band

Johannes Hahn 10.5.2017 12:45

Gelöscht: that are typically forced by the large-scale wind-stress curl

Johannes Hahn 25.4.2017 14:57

Gelöscht: Fig. 13

Johannes Hahn 10.5.2017 12:49

Gelöscht: -ocean

negative AZM or a positive AMM was found to be associated with a northward shift and a strengthening of the NECC (Hormann et al., 2012). Although both climate modes are not correlated with each other, the authors report one of the strongest negative/positive AZM/AMM in the year 2005 and a phase of intense positive/negative AZM/AMM in the years 2008-2010 (particularly see Foltz et al. (2012) for the strong negative AMM in 2009). These phases are related to an anomalous strengthening as well as northward shift (in the earlier period) and a weakening as well as southward shift (in the latter period) of the NECC, respectively. Similar analyses in our study showed a still persistent anomalous southern position of the NECC in recent years (Fig. 12) – superimposed by interannual variability in NECC strength and position - resulting in almost a full decade of weakened ventilation of the upper 300 m in the ETNA.

Johannes Hahn 25.4.2017 14:56

Gelöscht: Fig. 14

The AMM has recently been shown to be interrelated to the Guinea Dome variability (Doi et al., 2010), where a negative AMM in boreal spring is connected to a southward shift of the ITCZ as well as a weaker Guinea Dome. The aforementioned multi-annual negative AMM phase might be associated with a comprehensive weakening of the near-surface circulation on interannual to decadal time scales, which contributed to a weakened ventilation and subsequently to the average negative oxygen trend in the deep oxycline in the recent decade.

Below 400 m, the large-scale oxygen increase along 23°W pointed to an intensification of the ventilation of the ETNA throughout the past decade. A likely reason is a strengthening of the LAZJ during the past decade compared to the decade before, subsequently causing the oxygen increase. Time coverage of velocity data was generally too sparse and too short to conduct a profound analysis of the interannual to decadal velocity variability (neither for Argo (Rosell-Fieschi et al., 2015) nor ship section data [*this study*]). However, we found a slight broadening and intensification of the eastward jet at about 9°N and a southward shift of the CVC from 13.5°N to 12.5°N (Fig. 11) for the recent one and a half decades. This change in the velocity field is reasonably reflected in the decadal change pattern of oxygen and salinity. The eastward jet at 9°N advected more SAW (fresh, oxygenated) from the western boundary. In addition, the southward shifted CVC may have led to an advection of more oxygenated water at 13°N. If we assume a time invariant oxygen consumption, higher oxygenated water supplied by eastward jets agrees well with the only little oxygen gain found in the recirculated water of adjacent westward current bands at 7°N and 11°N. This result is not contradictory to the deoxygenation at 200 to 400 m depth: LAZJ are low baroclinic mode currents (e.g. Qiu et al., 2013), which are superimposed on the strong wind-driven current field of the upper 350 m (Rosell-Fieschi et al., 2015). The comparatively small temporal variability of the LAZJ is assumed to have only weak impact on the oxygen and water mass variability in the upper ocean.

Johannes Hahn 25.4.2017 14:57

Gelöscht: Fig. 13

Johannes Hahn 23.5.2017 09:46

Gelöscht: loss up to little gain of

Johannes Hahn 10.5.2017 12:50

Gelöscht: almost no

Johannes Hahn 10.5.2017 12:50

Gelöscht: close to the surface

Hahn et al. (2014) showed that lateral mixing is a dominant driver in supplying the OMZ below 400 m through its meridional boundaries. Tropical instability waves, acting at the southern boundary at about 5°N, have varied in strength throughout the past decade potentially leading to a temporal change in the ventilation. They were anomalously weak in the years 2006-2008 and strengthened afterward in the years 2009-2010 (Perez et al., 2012). This may explain the pronounced interannual variability at 5°N in comparison to 8°N and 11°N (Fig. 3 to 5); a possible effect of decadal changes in the strength of the lateral mixing on the oxygen variability cannot be addressed with the available data. However, an increase of the meridional eddy diffusivity would have also affected the upper 400 m. We suspect that an increasing meridional eddy diffusion on interannual to decadal time scales would have projected the band structure of the eddy-driven meridional oxygen supply (latitudinally

alternating loss and gain of oxygen; cf. [Fig. 11](#) in Hahn et al. (2014)) into the decadal change pattern of oxygen. Thus, an exclusive intensification of the lateral eddy diffusion does not reasonably fit with the observed variability patterns.

Johannes Hahn 25.4.2017 14:57

Gelöscht: Fig. 13

4.3 Oxygen budget for decadal and multi-decadal oxygen changes

1165 A time varying oxygen budget of the ETNA (6°N-14°N) was evaluated by including both the decadal and multi-decadal oxygen trend ([Fig. 13](#)) in order to discuss potential changes in the ventilation terms (lateral mixing, diapycnal mixing, advection). The following discussion shall strengthen the argumentation on decadal changes in the ventilation given in the last section.

Johannes Hahn 25.4.2017 14:53

Gelöscht: Fig. 15

1170 Brandt et al. (2010) argued that a weakening of the zonal jets over the past decades might have contributed to the average multi-decadal deoxygenation in the ETNA OMZ. In fact, the authors found a multi-decadal oxygen decrease over the whole depth range between 100 and 1,000 m likely being the result of a weakening of the wind-driven surface intensified zonal currents (NECC, nNECC) as well as the low baroclinic mode LAZJ. Multi-decadal changes in the STC or the MOC might have led to long-term changes in the oceanic oxygen concentration as well (Duteil et al., 2014a), but no relation to oxygen was shown so far for the ETNA.

1175 In the recent decade, oxygen decreased above the OMZ core (shallower than 400 m) and increased below. Diapycnal supply and meridional eddy supply were assumed to be time invariant in the oxygen budget and time dependence was included in the residual oxygen supply (cf. Eq. (1)) mainly associated with zonal advection. First, the slight shoaling of the residual supply in the upper 350 m indicated a weakening and shoaling of the near-surface circulation resulting in a weakened ventilation of the ETNA. Second, the vertically homogeneous increase of the residual supply below 400 m suggested a homogeneous strengthening of the circulation over depth. Obviously, this homogeneous change in the residual supply fits best with the structure of the residual supply profile itself, whereas temporal variability in the diapycnal or meridional eddy supply would likely have led to a non-homogeneous change in the oxygen supply. We shall additionally note that almost at the depth of strongest negative multi-decadal oxygen trend the decadal oxygen trend is zero switching from negative (above) 1180 to positive (below). This depth also coincides with the minimum of the residual oxygen supply separating a region with strong near surface supply from the region with weaker, depth-independent supply below. The different vertical structures of the decadal and multi-decadal trends, together with the residual supply profile, further suggest different ventilation mechanisms at work for the different time scales.

Johannes Hahn 26.4.2017 19:30

Gelöscht: (1)

1190 It might be argued that a depth-independent oxygen trend below 400 m could have been induced by a temporal change of several processes superimposing each other in the oxygen budget. Lateral eddy diffusion has already been ruled out as the main driver for this decadal trend ([Sect 4.2](#)). Decadal variability in the diapycnal supply, which is parameterized as a diffusive process given as $-\frac{\partial}{\partial z}\Phi = \frac{\partial}{\partial z}(\rho K_{\rho} \frac{\partial}{\partial z} O_2)$ (with diapycnal oxygen flux Φ , density ρ , diapycnal diffusivity K_{ρ} and vertical oxygen gradient $\frac{\partial}{\partial z} O_2$, Fischer et al. (2013)), has not explicitly been investigated so far. The question is, how much of a change in K_{ρ} is required to explain the observed trend. 1195 The trend was typically found in the range $\pm 1 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$, which is the same order of magnitude as the diapycnal oxygen supply itself. Hence, K_{ρ} needed to have varied by a factor 2 to explain this trend. Recent observational (2008 – 2015) studies quantified K_{ρ} for the ETNA and found only slight differences between $1.0 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ to $1.19 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ (with 95% confidence limits $0.8 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ and $1.4 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$) in the depth

range of 150 to 600 m (Banyte et al., 2012; Fischer et al., 2013; Köllner et al., 2016). Such a marginal variability in the strength of the diapycnal mixing cannot solely account for the observed oxygen trend – neither for the deoxygenation in the deep oxycline nor for the oxygenation in the OMZ core. Note also that constant diffusivities would always act to damp a weakening or strengthening of an oxygen minimum.

Strictly, a straightforward estimate of the advective oxygen supply can be derived only by accounting all advective fluxes across the boundary of a closed volume. This cannot be achieved for the ETNA OMZ with the data set given at hand. Nevertheless, in order to strengthen our discussion about the physical drivers of the observed decadal oxygen tendency, we provide an estimate of the zonal advective oxygen supply to the ETNA OMZ by evaluating only data taken along the 23°W section as presented in the following. First, we define a box (23°W-15°W and 6°N-14°N) and assume that the dominant advective ventilation of this box is zonally across the 23°W section. Fluxes across the northern, southern and eastern boundary of the box are neglected. Note that the eastern boundary of this box is roughly given by the western margin of the African continent. Further, we weight the eastward and westward advective oxygen flux to account for a possible mass imbalance across 23°W. The oxygen flux across 23°W associated with zonal advection can then be written as follows:

$$F(z) = 2(T_2 F_1 - T_1 F_2) / (T_2 - T_1), \quad (2)$$

with

$$T_n = \int_{z-\Delta z/2}^{z+\Delta z/2} \int_{y_1}^{y_2} H((-1)^n u) u \, dy dz', \quad (3)$$

$$F_n = \int_{z-\Delta z/2}^{z+\Delta z/2} \int_{y_1}^{y_2} H((-1)^n u) O_2 u \, dy dz', \quad (4)$$

T_n and F_n are the mass transport and oxygen flux across 23°W, with $n = 1, 2$, where $n = 1$ represents westward (negative) and $n = 2$ eastward (positive) transports and fluxes, respectively. y is latitude, z is depth, u is zonal velocity and O_2 is oxygen. $H((-1)^n u)$ is the Heaviside function, which is 1 for $(-1)^n u \geq 0$ and 0 for $(-1)^n u < 0$. The vertical resolution, Δz , was chosen to be 10 m, and y_1 and y_2 are the southern and northern boundaries located at 6°N and 14°N, respectively. If the mass flux across this section is balanced at a given depth range, $z \pm \Delta z/2$, i.e. $T_2 = -T_1$, Eq. (2) reduces to $F(z) = F_1 + F_2$. The relative mass imbalance can be defined as $(T_2 + T_1) / (T_2 - T_1)$. The depth-averaged value of this imbalance with 95% confidence (double standard error) for the depth range 200 to 700 m was 0.06 ± 0.18 (average over all ship sections) corresponding to a weak eastward mean flow with the imbalance generally smaller than 10%. Close to the surface (above 200 m), the mass imbalance was larger (10 – 40%) with westward flow dominating. This flow must be balanced by the flow through the other box boundaries making the estimate of zonal advective oxygen supply across 23°W above 200 m less relevant.

Eventually, a vertical profile of the zonal advective oxygen supply was calculated for every ship section from the zonal oxygen flux given in Eq. (2) divided by the volume of the predefined box. Further, a vertical profile of the mean zonal advective oxygen supply as well as of its decadal change was calculated based on the 13 available ship sections along 23°W (Fig. 14). The vertical structure of both estimates is qualitatively in agreement with the residual supply and the decadal oxygen tendency, respectively, in the oxygen budget (Fig. 13), i.e.: (i) strong

Johannes Hahn 23.5.2017 09:49

Gelöscht: exclusively

Johannes Hahn 23.5.2017 09:49

Gelöscht: at all

supply above 300 m and reduced supply below and (ii) oxygen loss between 200 m and 400 m and oxygen gain below. Particularly, the qualitatively reasonable vertical structure of the zonal advective oxygen supply tendency emphasizes that changes in the zonal advection may have substantially contributed to the decadal oxygen tendency in the ETNA.

So far, the impact of vertical advection on the oxygen concentration in the ETNA was not discussed at all, as observationally based estimates of vertical velocity are rare. Even though a robust analysis is impossible, we roughly estimated the advective vertical oxygen supply by referring to a model study of Pena-Izquierdo et al. (2015), who came up with a vertical structure of the mean vertical velocity in the ETNA. From the obtained vertical velocity that is in general agreement with an observationally based estimate from Banyte et al. (2012), we constructed a vertical velocity profile with upward velocities in the UCW layer ($-3 \times 10^{-7} \text{ m s}^{-1}$ at 100 m or 26.3 kg m^{-3}) and downward velocities in the LCW ($1.5 \times 10^{-7} \text{ m s}^{-1}$ at 535 m or 27.15 kg m^{-3}), and a zero crossing at the interface of both layers (at 270 m or 26.8 kg m^{-3}). We then estimated the advective vertical oxygen supply by taking the divergence of the advective vertical oxygen flux ($-w \partial O_2 / \partial z$) and found alternating depth ranges of oxygen gain (roughly 100 – 180 m and 270 – 430 m) and oxygen loss (roughly 180 – 270 m and below 430 m) with magnitudes of up to $0.3 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$ (not shown). Even though, this term seems to be up to 5 to 10 times smaller than other oxygen supply terms, its vertical structure at depth of the OMZ is qualitatively similar to the vertical structure of the observed decadal oxygen change (Fig. 6a and Fig. 13). This indicates that a decadal change of the advective vertical oxygen supply could have additionally contributed to the decadal oxygen change.

5. Summary and conclusion

Based on moored, repeat shipboard, Argo float and altimetry observations carried out mainly in the region of the ETNA OMZ, this study quantified decadal changes of hydrography and oxygen during the past decade (2006-2015) and aimed to relate these changes to changes in circulation and ventilation. A time dependent oxygen budget of the ETNA was evaluated and decadal to long-term changes of oxygen supply pathways were discussed. The major results are the following:

- (1) In the past decade, the ETNA was subject to an accelerated oxygen decrease around the deep oxycline (200 - 400 m) and a large-scale depth-independent oxygen increase below 400 m (Fig. 6a), which is associated with a weakened and strengthened ventilation, respectively (Fig. 15). This decadal oxygen change pattern is superimposed on the multi-decadal deoxygenation pattern observed in recent studies for the ETNA (Stramma et al., 2008; Brandt et al., 2015). While the decadal change in the oxygen distribution was shown to be mainly associated with an upward migration of the OMZ core in density and depth space, the multi-decadal oxygen decrease, that is found above and below the deep oxycline, is associated with a northward shift of the OMZ.
- (2) The decadal oxygen change was predominantly inversely related to the decadal salinity change in the CW and IW layers ($>200 \text{ m}$) south of the OMZ core (cf. Fig. 6a, 6c and 7d). In particular, a large-scale salinity increase was observed for the tropical Atlantic (10°S - 10°N) at the depth of the deep oxycline potentially going along with a propagation of a positive salinity anomaly from the southern hemisphere across the equator toward the ETNA.

Johannes Hahn 10.5.2017 17:21

Gelöscht: from

Johannes Hahn 10.5.2017 17:23

Gelöscht: rough

Johannes Hahn 10.5.2017 17:22

Gelöscht: Given their results, which are of the same order of magnitude as

Johannes Hahn 10.4.2017 15:11

Gelöscht: Fig. 9

Johannes Hahn 10.5.2017 09:35

Gelöscht: 4

Johannes Hahn 23.5.2017 21:16

Gelöscht: a

Johannes Hahn 23.5.2017 10:03

Gelöscht: explicitly

Johannes Hahn 15.5.2017 14:39

Gelöscht: , which were related

Johannes Hahn 15.5.2017 14:39

Gelöscht: decadal

Johannes Hahn 15.5.2017 14:40

Gelöscht: the

Johannes Hahn 23.5.2017 21:18

Gelöscht: was

Johannes Hahn 26.4.2017 14:40

Gelöscht: negatively

Johannes Hahn 26.4.2017 14:40

Gelöscht: correlated

Johannes Hahn 26.4.2017 14:40

Gelöscht: with

Johannes Hahn 26.4.2017 13:16

Gelöscht: L

Johannes Hahn 26.4.2017 13:16

Gelöscht: 3

- 1295 (3) The decadal oxygen decrease and salinity increase around the deep oxycline (200 – 400 m) of the ETNA were associated with local and remote circulation changes. A weakening and southward shift of the wind-driven current field between 5°N and 10°N (NECC, nNECC) - which are likely related to changes in the large-scale wind-stress curl - or a southward shift of the Cape Verde Current between 12°N and 14°N might have directly led to a weakened ventilation of the ETNA. Changes in the Agulhas leakage (Kolodziejczyk et al., 2014; Hummels et al., 2015; Biastoch et al., 2009; Lübbecke et al., 2015) or the subduction rate in the subtropical South Atlantic (Liu and Huang, 2012) might have changed the characteristics of SAW reaching the ETNA OMZ.
- 1300 (4) Below the deep oxycline (>400 m), a likely reason for the intensified ventilation is a strengthening of the LAZJ during the last decade that followed a period of weakened LAZJ during the decades before (Brandt et al., 2010). LAZJ are considered to be a major branch of the subsurface circulation in the ETNA.
- 1305 (5) The observed decadal oxygen change likely cannot be explained by changes in consumption, lateral and diapycnal diffusion, as they are not able to provide the required amplitude and/or vertical structure. Although associated with large uncertainties, changes in the oxygen supply by zonal advection across the 23°W section has the highest potential to explain the observed decadal oxygen changes in the ETNA OMZ (Fig. 13 and 14).

This study addressed the hydrographic and oxygen variability on intraseasonal to multi-decadal time scales in the ETNA with a focus on decadal changes. Nevertheless, a comprehensive quantitative analysis of the different physical drivers causing the superimposed variability patterns in oxygen or hydrography, as well as the variability in the oxygen supply pathways, is still lacking. Changes in oxygen and hydrography might be phase-lagged to changes in the circulation and longer periods of observational data are necessary in order to capture such relations.

1315 Coupled climate-biogeochemistry models can reproduce the observed long-term mean global deoxygenation, but they are generally not yet capable of properly simulating regional scale changes in oxygen, oxygen supply processes or consumption (Cabre et al., 2015; Stramma et al., 2012; Duteil et al., 2014b), which makes a model supported interpretation of our observational results challenging. However, ocean circulation and reanalysis models may be used to study circulation variability, which is generally related to climate modes like the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), the AMOC or the AZM and AMM (Doi et al., 2010; Hormann et al., 2012; Chang et al., 2006; Marshall et al., 2001; Zhu et al., 2012). Characteristic time scales of climate modes may be associated with circulation and ventilation variability and consequently with hydrographic and oxygen variability on similar time scales (Frölicher et al., 2009; Czeschel et al., 2012; Duteil et al., 2014a). Hence, these modes might be promising proxies for the description of decadal to multi-decadal oxygen and hydrographic variability.

1325 Data availability

The MIMOC climatology is available at <http://www.pmel.noaa.gov/mimoc/>. Argo float data were collected and made freely available by the international Argo project and the national programs that contribute to it (<http://doi.org/10.17882/42182>). The Argo data used here was downloaded in March 2016. Aviso altimetry

Johannes Hahn 15.5.2017 14:57

Gelöscht: in

Johannes Hahn 10.5.2017 17:27

Gelöscht: in the circulation

Johannes Hahn 15.5.2017 15:05

Gelöscht: They

Johannes Hahn 23.5.2017 10:04

Gelöscht: as

Johannes Hahn 23.5.2017 10:04

Gelöscht: mean

Johannes Hahn 10.5.2017 17:29

Gelöscht: emporal changes of the different oxygen supply terms, given in the oxygen budget, likely have different impact on the temporal variability of the oxygen distribution. Given t

Johannes Hahn 10.5.2017 17:32

Gelöscht: zonal advection was associated with a strong decadal change, whereas reasonable changes in

Johannes Hahn 23.5.2017 10:05

Gelöscht: might not have been able setting the

Johannes Hahn 23.5.2017 10:05

Gelöscht: the

Johannes Hahn 10.5.2017 17:37

Gelöscht: of the oxygen tendency observed for the recent decade

Johannes Hahn 10.5.2017 18:08

Gelöscht: reproducing the mean shape of the OMZs

Johannes Hahn 10.5.2017 18:15

Gelöscht: as well as the observed oxygen variability. The lack of a realistically simulated equatorial mean and variable zonal current system is thought to be one reason for this misrepresentation. showed that an increased model resolution improves the pattern of the equatorial current system in the tropical Atlantic and correspondingly the oxygen distribution. Furthermore, they point out that small changes in the strength of the zonal current system have different effects on oxygen supply and consumption and consequently can affect the oxygen variability. Thus, the simulation of decadal and multi-decadal oxygen variability might be an even more challenging issue. In an analysis of global multi-decadal oxygen changes, (Stramma et al., 2012) showed that the observed mean global deoxygenation was captured by a biogeochemical Earth system model. However, the observed and simulated oxygen change pattern were negatively correlated suggesting that regional scale changes in oxygen supply and consumption and responsible processes are so far not reproduced by the model simulations.

Johannes Hahn 10.5.2017 18:31

Gelöscht: C

Johannes Hahn 10.5.2017 18:31

Gelöscht: can be

Johannes Hahn 10.5.2017 18:33

Gelöscht: these

Johannes Hahn 10.5.2017 18:31

Gelöscht: project into

Johannes Hahn 10.5.2017 18:31

Gelöscht: may be associated

1375 products of surface geostrophic velocity were downloaded from <http://aviso.altimetry.fr/index.php?id=1271> in
July 2016 (processing date: 27-Nov-2015). [Shipboard and mooring data is accessible at](#)
<https://doi.pangaea.de/10.1594/PANGAEA.869568>.

Competing interests. The authors declare that they have no conflict of interest.

1380 *Acknowledgements.* This study was funded by the Deutsche Forschungsgemeinschaft as part of the Sonderforschungsbereich
754 “Climate-Biogeochemistry Interactions in the Tropical Ocean“ through several research cruises with RV *L’Atalante*, RV
1385 *Maria S. Merian*, RV *Meteor*, RV *Polarstern*, [by the project FOR1740](#) and by the Deutsche Bundesministerium für Bildung
und Forschung (BMBF) as part of projects NORDATLANTIK (03F0605B, 03F0443B) and RACE (03F0651B). We thank
the captains and crew as well as our technical group for their support with the fieldwork. We thank J. Lübbecke, M. Dengler
and T. Fischer for helpful discussions and R. Kopte for post-processing of the recent ship section data. Further, we thank the
international Argo program and the national programs that contribute to it, which collected the data and made it freely
available. The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes
(<http://www.aviso.altimetry.fr/duacs/>). [We thank two anonymous reviewers for improving the manuscript.](#)

References

- 1390 Ascani, F., Firing, E., Dutrieux, P., McCreary, J. P., and Ishida, A.: Deep Equatorial Ocean Circulation Induced
by a Forced-Dissipated Yanai Beam, *J. Phys. Oceanogr.*, 40, 1118-1142, 10.1175/2010jpo4356.1, 2010.
- Ascani, F., Firing, E., McCreary, J. P., Brandt, P., and Greatbatch, R. J.: The Deep Equatorial Ocean Circulation
in Wind-Forced Numerical Solutions, *J. Phys. Oceanogr.*, 45, 1709-1734, 10.1175/jpo-d-14-0171.1, 2015.
- 1395 Banyte, D., Tanhua, T., Visbeck, M., Wallace, D. W. R., Karstensen, J., Krahmann, G., Schneider, A., Stramma,
L., and Dengler, M.: Diapycnal diffusivity at the upper boundary of the tropical North Atlantic oxygen minimum
zone, *J. Geophys. Res.-Oceans*, 117, 10.1029/2011jc007762, 2012.
- Biastoch, A., Böning, C. W., Schwarzkopf, F. U., and Lutjeharms, J. R. E.: Increase in Agulhas leakage due to
poleward shift of Southern Hemisphere westerlies, *Nature*, 462, 495-U188, 10.1038/nature08519, 2009.
- 1400 Bopp, L., Le Quere, C., Heimann, M., Manning, A. C., and Monfray, P.: Climate-induced oceanic oxygen
fluxes: Implications for the contemporary carbon budget, *Glob. Biogeochem. Cycle*, 16, 10.1029/2001gb001445,
2002.
- Brandt, P., Hormann, V., Boulès, B., Fischer, J., Schott, F. A., Stramma, L., and Dengler, M.: Oxygen tongues
and zonal currents in the equatorial Atlantic, *J. Geophys. Res.-Oceans*, 113, 10.1029/2007jc004435, 2008.
- Brandt, P., Hormann, V., Körtzinger, A., Visbeck, M., Krahmann, G., Stramma, L., Lumpkin, R., and Schmid,
C.: Changes in the Ventilation of the Oxygen Minimum Zone of the Tropical North Atlantic, *J. Phys. Oceanogr.*,
1405 40, 1784-1801, 10.1175/2010jpo4301.1, 2010.
- Brandt, P., Greatbatch, R. J., Claus, M., Didwischus, S. H., Hormann, V., Funk, A., Hahn, J., Krahmann, G.,
Fischer, J., and Körtzinger, A.: Ventilation of the equatorial Atlantic by the equatorial deep jets, *J. Geophys.*
Res.-Oceans, 117, 10.1029/2012jc008118, 2012.
- 1410 Brandt, P., Bange, H. W., Banyte, D., Dengler, M., Didwischus, S. H., Fischer, T., Greatbatch, R. J., Hahn, J.,
Kanzow, T., Karstensen, J., Körtzinger, A., Krahmann, G., Schmidt, S., Stramma, L., Tanhua, T., and
Visbeck, M.: On the role of circulation and mixing in the ventilation of oxygen minimum zones with a focus on
the eastern tropical North Atlantic, *Biogeosciences*, 12, 489-512, 10.5194/bg-12-489-2015, 2015.
- 1415 Bunge, L., Provost, C., Hua, B. L., and Kartavtseff, A.: Variability at intermediate depths at the equator in the
Atlantic ocean in 2000-06: Annual cycle, equatorial deep jets, and intraseasonal meridional velocity fluctuations,
J. Phys. Oceanogr., 38, 1794-1806, 10.1175/2008jpo3781.1, 2008.

Johannes Hahn 23.5.2017 21:35

Gelöscht: DOI registration for s

Johannes Hahn 23.5.2017 21:35

Gelöscht: still in progress and

- 1420 Cabre, A., Marinov, I., Bernardello, R., and Bianchi, D.: Oxygen minimum zones in the tropical Pacific across CMIP5 models: mean state differences and climate change trends, *Biogeosciences*, 12, 5429-5454, 10.5194/bg-12-5429-2015, 2015.
- Chang, P., Yamagata, T., Schopf, P., Behera, S. K., Carton, J., Kessler, W. S., Meyers, G., Qu, T., Schott, F., Shetye, S., and Xie, S. P.: Climate fluctuations of tropical coupled systems - The role of ocean dynamics, *J. Clim.*, 19, 5122-5174, 10.1175/jcli3903.1, 2006.
- 1425 Chang, P., Zhang, R., Hazeleger, W., Wen, C., Wan, X. Q., Ji, L., Haarsma, R. J., Breugem, W. P., and Seidel, H.: Oceanic link between abrupt changes in the North Atlantic Ocean and the African monsoon, *Nat. Geosci.*, 1, 444-448, 10.1038/ngeo218, 2008.
- Czeschel, R., Stramma, L., and Johnson, G. C.: Oxygen decreases and variability in the eastern equatorial Pacific, *J. Geophys. Res.-Oceans*, 117, 10.1029/2012jc008043, 2012.
- 1430 Doi, T., Tozuka, T., and Yamagata, T.: The Atlantic Meridional Mode and Its Coupled Variability with the Guinea Dome, *J. Clim.*, 23, 455-475, 10.1175/2009jcli3198.1, 2010.
- Duteil, O., Böning, C. W., and Oschlies, A.: Variability in subtropical-tropical cells drives oxygen levels in the tropical Pacific Ocean, *Geophys. Res. Lett.*, 41, 8926-8934, 10.1002/2014gl061774, 2014a.
- 1435 Duteil, O., Schwarzkopf, F. U., Böning, C. W., and Oschlies, A.: Major role of the equatorial current system in setting oxygen levels in the eastern tropical Atlantic Ocean: A high-resolution model study, *Geophys. Res. Lett.*, 41, 2033-2040, 10.1002/2013gl058888, 2014b.
- Eden, C., and Dengler, M.: Stacked jets in the deep equatorial Atlantic Ocean, *J. Geophys. Res.-Oceans*, 113, 12, 10.1029/2007jc004298, 2008.
- 1440 Fischer, T., Banyte, D., Brandt, P., Dengler, M., Krahmann, G., Tanhua, T., and Visbeck, M.: Diapycnal oxygen supply to the tropical North Atlantic oxygen minimum zone, *Biogeosciences*, 10, 5079-5093, 10.5194/bg-10-5079-2013, 2013.
- Foltz, G. R., McPhaden, M. J., and Lumpkin, R.: A Strong Atlantic Meridional Mode Event in 2009: The Role of Mixed Layer Dynamics, *J. Clim.*, 25, 363-380, 10.1175/jcli-d-11-00150.1, 2012.
- 1445 Frölicher, T. L., Joos, F., Plattner, G. K., Steinacher, M., and Doney, S. C.: Natural variability and anthropogenic trends in oceanic oxygen in a coupled carbon cycle-climate model ensemble, *Glob. Biogeochem. Cycle*, 23, 15, 10.1029/2008gb003316, 2009.
- Garzoli, S. L., and Katz, E. J.: The Forced Annual Reversal of the Atlantic North Equatorial Countercurrent, *J. Phys. Oceanogr.*, 13, 2082-2090, 10.1175/1520-0485(1983)013<2082:tfarot>2.0.co;2, 1983.
- Garzoli, S. L., and Richardson, P. L.: Low-frequency meandering of the Atlantic North Equatorial Countercurrent, *J. Geophys. Res.-Oceans*, 94, 2079-2090, 10.1029/JC094iC02p02079, 1989.
- 1450 Hahn, J., Brandt, P., Greatbatch, R. J., Krahmann, G., and Körtzinger, A.: Oxygen variance and meridional oxygen supply in the Tropical North East Atlantic oxygen minimum zone, *Clim. Dyn.*, 43, 2999-3024, 10.1007/s00382-014-2065-0, 2014.
- Helly, J. J., and Levin, L. A.: Global distribution of naturally occurring marine hypoxia on continental margins, *Deep-Sea Res. Part I-Oceanogr. Res. Pap.*, 51, 1159-1168, 10.1016/j.dsr.2004.03.009, 2004.
- 1455 Helm, K. P., Bindoff, N. L., and Church, J. A.: Observed decreases in oxygen content of the global ocean, *Geophys. Res. Lett.*, 38, 6, 10.1029/2011gl049513, 2011.
- Hormann, V., Lumpkin, R., and Foltz, G. R.: Interannual North Equatorial Countercurrent variability and its relation to tropical Atlantic climate modes, *J. Geophys. Res.-Oceans*, 117, 10.1029/2011jc007697, 2012.

- 1460 Hummels, R., Brandt, P., Dengler, M., Fischer, J., Araujo, M., Veleda, D., and Durgadoo, J. V.: Interannual to decadal changes in the western boundary circulation in the Atlantic at 11 degrees S, *Geophys. Res. Lett.*, 42, 7615-7622, 10.1002/2015gl065254, 2015.
- Johns, W. E., Brandt, P., Boulès, B., Tantet, A., Papapostolou, A., and Houk, A.: Zonal structure and seasonal variability of the Atlantic Equatorial Undercurrent, *Clim. Dyn.*, 43, 3047-3069, 10.1007/s00382-014-2136-2, 2014.
- 1465 Joyce, T. M., Frankignoul, C., Yang, J. Y., and Phillips, H. E.: Ocean response and feedback to the SST dipole in the tropical Atlantic, *J. Phys. Oceanogr.*, 34, 2525-2540, 10.1175/jpo2640.1, 2004.
- Kamenkovich, I., Berloff, P., and Pedlosky, J.: Anisotropic Material Transport by Eddies and Eddy-Driven Currents in a Model of the North Atlantic, *J. Phys. Oceanogr.*, 39, 3162-3175, 10.1175/2009jpo4239.1, 2009.
- 1470 Karstensen, J., Stramma, L., and Visbeck, M.: Oxygen minimum zones in the eastern tropical Atlantic and Pacific oceans, *Prog. Oceanogr.*, 77, 331-350, 10.1016/j.pocean.2007.05.009, 2008.
- Karstensen, J., Fiedler, B., Schütte, F., Brandt, P., Körtzinger, A., Fischer, G., Zantopp, R., Hahn, J., Visbeck, M., and Wallace, D.: Open ocean dead zones in the tropical North Atlantic Ocean, *Biogeosciences*, 12, 2597-2605, 10.5194/bg-12-2597-2015, 2015.
- 1475 Keeling, R. F., and Garcia, H. E.: The change in oceanic O₂ inventory associated with recent global warming, *Proceedings of the National Academy of Sciences*, 99, 7848-7853, 10.1073/pnas.122154899, 2002.
- Kirchner, K., Rhein, M., Hüttl-Kabus, S., and Böning, C. W.: On the spreading of South Atlantic Water into the Northern Hemisphere, *J. Geophys. Res.-Oceans*, 114, 10.1029/2008jc005165, 2009.
- Köllner, M., Visbeck, M., Tanhua, T., and Fischer, T.: Diapycnal diffusivity in the core and oxycline of the tropical North Atlantic oxygen minimum zone, *J. Mar. Syst.*, 160, 54-63, 10.1016/j.jmarsys.2016.03.012, 2016.
- 1480 Kolodziejczyk, N., Reverdin, G., Gaillard, F., and Lazar, A.: Low-frequency thermohaline variability in the Subtropical South Atlantic pycnocline during 2002-2013, *Geophys. Res. Lett.*, 41, 6468-6475, 10.1002/2014gl061160, 2014.
- Liu, L. L., and Huang, R. X.: The Global Subduction/Obduction Rates: Their Interannual and Decadal Variability, *J. Clim.*, 25, 1096-1115, 10.1175/2011jcli4228.1, 2012.
- 1485 Lübbecke, J. F., Durgadoo, J. V., and Biastoch, A.: Contribution of Increased Agulhas Leakage to Tropical Atlantic Warming, *J. Clim.*, 28, 9697-9706, 10.1175/jcli-d-15-0258.1, 2015.
- Luyten, J. R., Pedlosky, J., and Stommel, H.: The Ventilated Thermocline, *J. Phys. Oceanogr.*, 13, 292-309, 10.1175/1520-0485(1983)013<0292:tv>2.0.co;2, 1983.
- 1490 Marshall, J., Kushner, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., Hurrell, J., McCartney, M., Saravanan, R., and Visbeck, M.: North Atlantic climate variability: Phenomena, impacts and mechanisms, *Int. J. Climatol.*, 21, 1863-1898, 10.1002/joc.693, 2001.
- Matear, R. J., and Hirst, A. C.: Long-term changes in dissolved oxygen concentrations in the ocean caused by protracted global warming, *Glob. Biogeochem. Cycle*, 17, 10.1029/2002gb001997, 2003.
- 1495 Maximenko, N. A., Bang, B., and Sasaki, H.: Observational evidence of alternating zonal jets in the world ocean, *Geophys. Res. Lett.*, 32, 4, 10.1029/2005gl022728, 2005.
- McCreary, J. P., and Lu, P.: Interaction between the Subtropical and Equatorial Ocean Circulations: The Subtropical Cell, *J. Phys. Oceanogr.*, 24, 466-497, 1994.
- Ollitrault, M., and de Verdiere, A. C.: The Ocean General Circulation near 1000-m Depth, *J. Phys. Oceanogr.*, 44, 384-409, 10.1175/jpo-d-13-030.1, 2014.

- 1500 Oschlies, A., Schulz, K. G., Riebesell, U., and Schmittner, A.: Simulated 21st century's increase in oceanic suboxia by CO₂-enhanced biotic carbon export, *Glob. Biogeochem. Cycle*, 22, 10.1029/2007gb003147, 2008.

Pena-Izquierdo, J., van Sebille, E., Pelegri, J. L., Sprintall, J., Mason, E., Llanillo, P. J., and Machin, F.: Water mass pathways to the North Atlantic oxygen minimum zone, *J. Geophys. Res.-Oceans*, 120, 3350-3372, 10.1002/2014jc010557, 2015.
- 1505 Perez, R. C., Lumpkin, R., Johns, W. E., Foltz, G. R., and Hormann, V.: Interannual variations of Atlantic tropical instability waves, *J. Geophys. Res.-Oceans*, 117, 10.1029/2011jc007584, 2012.

Plattner, G. K., Joos, F., and Stocker, T. F.: Revision of the global carbon budget due to changing air-sea oxygen fluxes, *Glob. Biogeochem. Cycle*, 16, 12, 10.1029/2001gb001746, 2002.
- 1510 Qiu, B., Chen, S. M., and Sasaki, H.: Generation of the North Equatorial Undercurrent Jets by Triad Baroclinic Rossby Wave Interactions, *J. Phys. Oceanogr.*, 43, 2682-2698, 10.1175/jpo-d-13-099.1, 2013.

Rabe, B., Schott, F. A., and Kohl, A.: Mean circulation and variability of the tropical Atlantic during 1952-2001 in the GECCO assimilation fields, *J. Phys. Oceanogr.*, 38, 177-192, 10.1175/2007jpo3541.1, 2008.

Rhein, M., Kirchner, K., Mertens, C., Steinfeldt, R., Walter, M., and Fleischmann-Wischnath, U.: Transport of South Atlantic water through the passages south of Guadeloupe and across 16 degrees N, 2000-2004, *Deep-Sea Res. Part I-Oceanogr. Res. Pap.*, 52, 2234-2249, 10.1016/j.dsr.2005.08.003, 2005.
- 1515 Richardson, P. L., Arnault, S., Garzoli, S., and Bruce, J. G.: Annual cycle of the Atlantic North Equatorial Countercurrent, *Deep-Sea Research Part a-Oceanographic Research Papers*, 39, 997-1014, 10.1016/0198-0149(92)90036-s, 1992.
- 1520 Roemmich, D., Johnson, G. C., Riser, S., Davis, R., Gilson, J., Owens, W. B., Garzoli, S. L., Schmid, C., and Ignaszewski, M.: The Argo Program Observing the Global Ocean with Profiling Floats, *Oceanography*, 22, 34-43, 10.5670/oceanog.2009.36, 2009.

Rosell-Fieschi, M., Pelegri, J. L., and Gourrion, J.: Zonal jets in the equatorial Atlantic Ocean, *Prog. Oceanogr.*, 130, 1-18, 10.1016/j.pocean.2014.08.008, 2015.
- 1525 Schmidtko, S., and Johnson, G. C.: Multidecadal Warming and Shoaling of Antarctic Intermediate Water, *J. Clim.*, 25, 207-221, 10.1175/jcli-d-11-00021.1, 2012.

Schmidtko, S., Johnson, G. C., and Lyman, J. M.: MIMOC: A global monthly isopycnal upper-ocean climatology with mixed layers, *J. Geophys. Res.-Oceans*, 118, 1658-1672, 10.1002/jgrc.20122, 2013.

Schmidtko, S., Stramma, L., and Visbeck, M.: Decline in global oceanic oxygen content during the past five decades, *Nature*, 542, 335-339, 10.1038/nature21399, 2017.
- 1530 Schmittner, A., Oschlies, A., Matthews, H. D., and Galbraith, E. D.: Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO₂ emission scenario until year 4000 AD, *Glob. Biogeochem. Cycle*, 22, 21, 10.1029/2007gb002953, 2008.
- 1535 Schott, F. A., Dengler, M., Brandt, P., Affler, K., Fischer, J., Boulès, B., Gouriou, Y., Molinari, R. L., and Rhein, M.: The zonal currents and transports at 35 degrees W in the tropical Atlantic, *Geophys. Res. Lett.*, 30, 10.1029/2002gl016849, 2003.

Schott, F. A., McCreary, J. P., and Johnson, G. C.: Shallow Overturning Circulations of the Tropical-Subtropical Oceans, in: *Earth's Climate*, edited by: Wang, C., S.P., X., and J.A., C., American Geophysical Union, Washington, D.C., 261-304, 2004.
- 1540 Schott, F. A., Dengler, M., Zantopp, R., Stramma, L., Fischer, J., and Brandt, P.: The shallow and deep western boundary circulation of the South Atlantic at 5 degrees-11 degrees S, *J. Phys. Oceanogr.*, 35, 2031-2053, 10.1175/jpo2813.1, 2005.

- Schütte, F., Karstensen, J., Krahmann, G., Hauss, H., Fiedler, B., Brandt, P., Visbeck, M., and Körtzinger, A.: Characterization of "dead-zone" eddies in the eastern tropical North Atlantic, *Biogeosciences*, 13, 5865-5881, 10.5194/bg-13-5865-2016, 2016.
- 1545 Servain, J.: Simple climatic indices for the tropical Atlantic Ocean and some applications, *J. Geophys. Res.-Oceans*, 96, 15137-15146, 10.1029/91jc01046, 1991.
- Stendardo, I., and Gruber, N.: Oxygen trends over five decades in the North Atlantic, *J. Geophys. Res.-Oceans*, 117, 18, 10.1029/2012jc007909, 2012.
- 1550 Stramma, L., and Schott, F.: The mean flow field of the tropical Atlantic Ocean, *Deep-Sea Res. Part II-Top. Stud. Oceanogr.*, 46, 279-303, 10.1016/s0967-0645(98)00109-x, 1999.
- Stramma, L., Hüttl, S., and Schafstall, J.: Water masses and currents in the upper tropical northeast Atlantic off northwest Africa, *J. Geophys. Res.-Oceans*, 110, 10.1029/2005jc002939, 2005.
- Stramma, L., Johnson, G. C., Sprintall, J., and Mohrholz, V.: Expanding oxygen-minimum zones in the tropical oceans, *Science*, 320, 655-658, 10.1126/science.1153847, 2008.
- 1555 Stramma, L., Visbeck, M., Brandt, P., Tanhua, T., and Wallace, D.: Deoxygenation in the oxygen minimum zone of the eastern tropical North Atlantic, *Geophys. Res. Lett.*, 36, 10.1029/2009gl039593, 2009.
- Stramma, L., Schmidtko, S., Levin, L. A., and Johnson, G. C.: Ocean oxygen minima expansions and their biological impacts, *Deep-Sea Res. Part I-Oceanogr. Res. Pap.*, 57, 587-595, 10.1016/j.dsr.2010.01.005, 2010.
- 1560 Stramma, L., Oschlies, A., and Schmidtko, S.: Mismatch between observed and modeled trends in dissolved upper-ocean oxygen over the last 50 yr, *Biogeosciences*, 9, 4045-4057, 10.5194/bg-9-4045-2012, 2012.
- Thomsen, S., Kanzow, T., Colas, F., Echevin, V., Krahmann, G., and Engel, A.: Do submesoscale frontal processes ventilate the oxygen minimum zone off Peru?, *Geophys. Res. Lett.*, 43, 8133-8142, 10.1002/2016gl070548, 2016.
- 1565 Wallace, D. W. R., and Bange, H. W.: Introduction to special section: Results of the Meteor 55: Tropical SOLAS expedition, *Geophys. Res. Lett.*, 31, 4, 10.1029/2004gl021014, 2004.
- Wyrski, K.: The oxygen minima in relation to ocean circulation, *Deep-Sea Research*, 9, 11-23, 10.1016/0011-7471(62)90243-7, 1962.
- Zhang, D. X., McPhaden, M. J., and Johns, W. E.: Observational evidence for flow between the subtropical and tropical Atlantic: The Atlantic subtropical cells, *J. Phys. Oceanogr.*, 33, 1783-1797, 10.1175/2408.1, 2003.
- 1570 Zhu, J. S., Huang, B. H., and Wu, Z. H.: The Role of Ocean Dynamics in the Interaction between the Atlantic Meridional and Equatorial Modes, *J. Clim.*, 25, 3583-3598, 10.1175/jcli-d-11-00364.1, 2012.

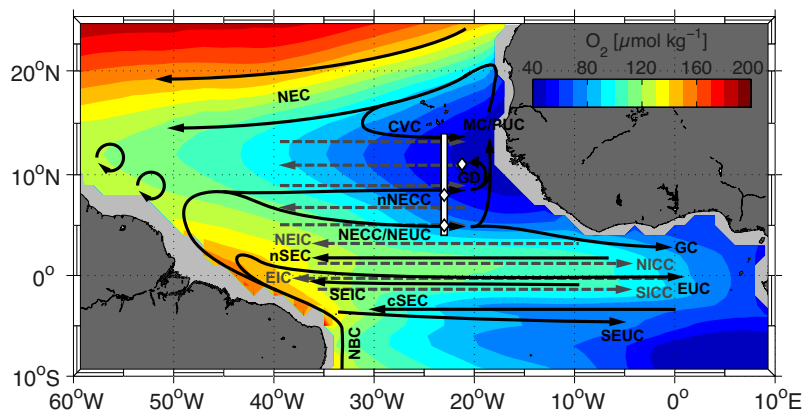


Figure 1. Oxygen concentration in $\mu\text{mol kg}^{-1}$ (shaded colors) in the tropical Atlantic at potential density surface 27.1 kg m^{-3} (close to the deep oxygen minimum) obtained from the MIMOC climatology. Superimposed arrows denote the mean current field (adapted from Brandt et al. (2015); Pena-Izquierdo et al. (2015)). Surface and thermocline (about upper 300 m) currents (black solid arrows) are North Equatorial Current (NEC), Cape Verde Current (CVC), Mauritania Current / Poleward Undercurrent (MC/PUC), Guinea Dome (GD), North Equatorial Countercurrent / North Equatorial Undercurrent (NECC/NEUC), northern branch of the NECC (nNECC), northern and central branch of the South Equatorial Current (nSEC, cSEC), Equatorial Undercurrent (EUC), South Equatorial Intermediate Current (SEIC), South Equatorial Undercurrent (SEUC) and North Brazil Current (NBC). Current branches at intermediate depth (gray dashed arrows) are latitudinally alternating zonal jets (LAZJ) between 5°N and 13°N , North Equatorial Intermediate Current (NEIC), Equatorial Intermediate Current (EIC) as well as Northern and Southern Intermediate Countercurrent (NICC and SICC). The white bar denotes the 23°W section between 4°N and 14°N . White diamonds mark positions of multi-year-long moored observations used in this study.

Johannes Hahn 23.5.2017 21:40

Gelöscht: ,

Johannes Hahn 23.5.2017 10:08

Gelöscht: White

Johannes Hahn 23.5.2017 10:09

Gelöscht: , which was surveyed with repeat shipboard observations during the recent decade

1595

Table 1. Research cruises carried out in the eastern tropical North Atlantic between 4°N and 14°N mainly along the 23°W section between 1999 and 2015. Different columns denote latitude section along mean longitude (lat. / lon.) and maximum profile depth available/used here (depth [m]) for velocity observations performed with vessel-mounted and lowered Acoustic Doppler Current Profilers (vm-ADCP / l-ADCP) as well as for hydrographic and oxygen observations performed with a conductivity-temperature-depth sonde (CTD/O₂). Note that during some research cruises two velocity and/or hydrographic sections were obtained.

Johannes Hahn 23.5.2017 21:46

Gelöscht: of

| Vessel and cruise (date) | vm-ADCP / l-ADCP | | CTD/O ₂ | |
|--|----------------------|--------------|--------------------------|--------------|
| | lat. / lon. | depth [m] | lat. / lon. | depth [m] |
| Thalassa (Jul-Aug 1999) | 4°N-6°N / 23°W | 1000 | - | - |
| Meteor 55 (Oct 2002) | 4°N-10°N / 24°W | 650 | - | - |
| Ron Brown (Jun-Aug 2003) | 4°N-10°N / ~27°W | 1000 | - | - |
| Polarstern Ant XXII/5 (Jun 2005) | 4°N-14°N / 23°W | 300 | - | - |
| Ron Brown (Jun 2006) | 4°N-13.5°N / 23°W | 750 | 4°N-13.5°N / 23.0°W | 1000 |
| | 4°N-14°N / 23°W | 750 | 4°N-14°N / 23.0°W | 1000 |
| Meteor 68/2 (Jun-Jul 2006) | 4°N-14°N / 23°W | 1000 | 4°N-14°N / 23.2°W-22.0°W | 1000 |
| Ron Brown (May 2007) | 4°N-14°N / 23°W | 750 | 4°N-14°N / 23.1°W-22.6°W | 1000 |
| L'Atalante (Feb-Mar 2008) | 4°N-14°N / 23°W | 400 | 4°N-14°N / 23°W | 1000 |
| | 4°N-14°N / 23°W | 1000 | | |
| Maria S. Merian 08/1 (April-May 2008) | 7.5°N-14°N / 23°W | 600 | - | - |
| | 8°N-14°N / 25°W | 800 | | |
| Polarstern Ant XXIV/4 (Apr-May 2008) | 4°N-14°N / 24°W-22°W | 240 | - | - |
| Maria S. Merian 10/1 (Nov-Dec 2008) | 4°N-14°N / 23°W | 650 | 4°N-14°N / 23°W | 1000 |
| Polarstern Ant XXV/5 (May 2009) | 4°N-14°N / 23°W | 250 | - | - |
| Ron Brown (Jul-Aug 2009) | 4°N-14°N / 23°W | 700 | 4°N-14°N / 23°W | 1000 |
| Meteor 80/1 (Oct-Nov 2009) | 4°N-14°N / 23°W | 1000 | 4°N-14°N / 23°W | 1000 |
| | 4°N-14°N / 23°W | 600 | | |

| | | | | |
|---|-------------------|------|-----------------|------|
| Polarstern Ant XXVI/1 (Nov 2009) | 4°N-14°N / 23°W | 250 | - | - |
| Meteor 81/1 (Feb-Mar 2010) | 4°N-13°N / 22°W | 1000 | - | - |
| Polarstern Ant XXVI/4 (Apr-May 2010) | 4°N-13.5°N / 23°W | 250 | - | - |
| Ron Brown (May 2010) | 4°N-14°N / 23°W | 1000 | - | - |
| Maria S. Merian 18/2 (May-Jun 2011) | 4°N-5°N / 23°W | 1000 | - | - |
| | 4°N-14°N / 23°W | 1000 | | |
| Maria S. Merian 18/3 (Jun-Jul 2011) | 4°N-14°N / 23°W | 600 | 4°N-14°N / 23°W | 1000 |
| Ron Brown (Jul-Aug 2011) | 4°N-14°N / 23°W | 700 | - | - |
| Maria S. Merian 22 (Oct-Nov 2012) | 4°N-8°N / 23°W | 1000 | 4°N-14°N / 23°W | 1000 |
| | 4°N-14°N / 23°W | 1000 | | |
| Meteor 106 (Apr-May 2014) | 4°N-14°N / 23°W | 1000 | 4°N-14°N / 23°W | 1000 |
| Polarstern PS88.2 (Nov 2014) | 4°N-14°N / 23°W | 1000 | 4°N-14°N / 23°W | 1000 |
| Meteor 119 (Sep-Oct 2015) | 4°N-14°N / 23°W | 1000 | 4°N-14°N / 23°W | 1000 |

Johannes Hahn 18.3.2017 21:37

Gelöscht:

1600 **Table 2.** Moored observations carried out in the eastern tropical North Atlantic between 2009 and 2015. Column ‘depth [m]’ denotes the instrument depth at the respective mooring. Columns ‘O₂’ and ‘T, S’ denote the percentage of available oxygen and hydrographic data, respectively, compared to the total time period. A cross (‘x’) marks data coverage of better than 99%.

| mooring position (time period) | depth [m] | O ₂ | T, S |
|------------------------------------|-----------|----------------|------|
| 5°N, 23°W (Nov 2009 - Sep 2015) | 100 | 87% | 81% |
| | 200 | 81% | 97% |
| | 300 | 76% | x |
| | 400 | x | x |
| | 500 | 75% | x |
| | 600 | x | x |
| | 700 | 75% | x |
| | 800 | x | 74% |
| 8°N, 23°W (Nov 2009 - Oct 2012) | 100 | x | x |
| | 200 | x | x |
| | 300 | x | x |
| | 400 | x | x |
| | 500 | x | x |
| | 600 | x | 14% |
| | 700 | x | 71% |
| | 800 | x | x |
| 11°N, 21.2°W (Nov 2012 - Sep 2015) | 100 | x | x |
| | 200 | x | x |
| | 300 | x | x |
| | 400 | x | x |
| | 500 | x | x |
| | 600 | x | x |
| | 700 | 72% | x |
| | 800 | x | x |

Johannes Hahn 15.5.2017 11:52

Gelöscht: x

Johannes Hahn 15.5.2017 11:52

Gelöscht: 52

Johannes Hahn 15.5.2017 11:53

Gelöscht: 96%

Johannes Hahn 15.5.2017 11:54

Gelöscht: 0

Johannes Hahn 15.5.2017 11:53

Gelöscht: 98%

Johannes Hahn 15.5.2017 11:54

Gelöscht: 97%

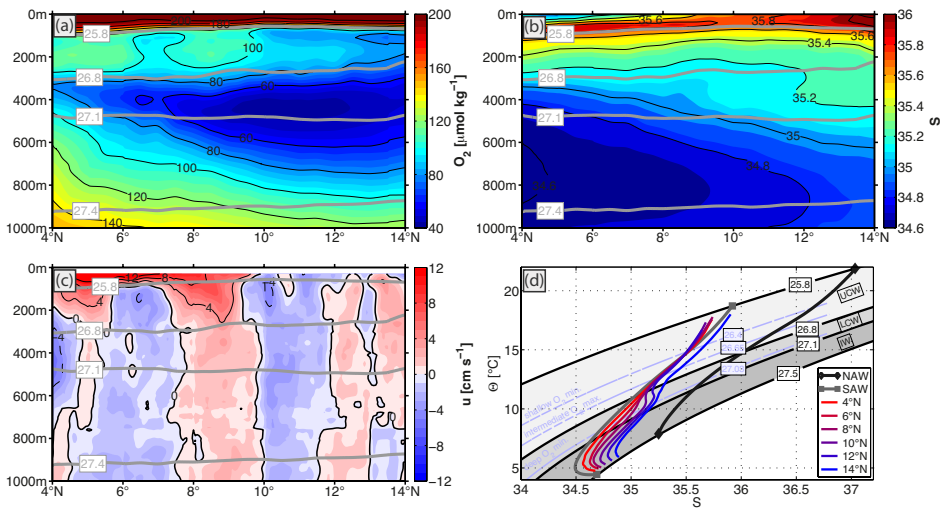


Figure 2. Mean sections of (a) oxygen, (b) salinity and (c) zonal velocity along 23°W between 4°N and 14°N. Black contours denote isolines of the respective mean field. Gray solid contours mark mean surfaces of potential density in kg m^{-3} . Note that no data of mean zonal velocity was derived for the upper 30 m. (d) Mean θ - S characteristics for North Atlantic Water (NAW) and South Atlantic Water (SAW) and for different latitudes along 23°W (details on reference regimes for NAW and SAW are given in the text). Data from about the upper 100 m of the water column was excluded. Black solid lines denote isopycnal surfaces, which define the different water mass regimes for UCW (Upper Central Water), LCW (Lower Central Water) and IW (Intermediate Water). Blue dashed lines denote isopycnal surfaces, which define different oxygen regimes with respect to the mean vertical oxygen profile in the ETNA.

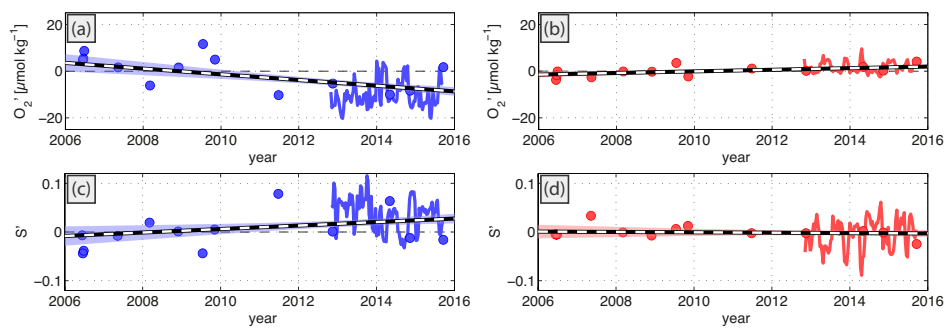
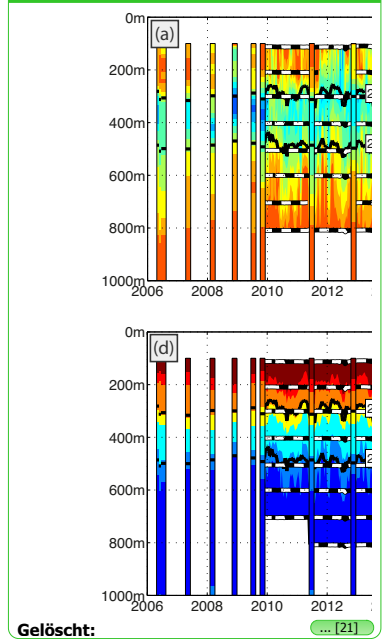


Figure 3. Oxygen ((a) and (b)) and salinity ((c) and (d)) anomaly time series from moored observations (solid line) at 11°N, 21°W and shipboard observations (dots) at 11°N, 23°W. (a) and (c) show averages between 200 and 400 m. (b) and (d) show averages between 500 and 800 m. Black dashed lines show respective trends from combined moored and shipboard observations: (a) $-12.2 \pm 4.9 \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, (b) $3.4 \pm 1.6 \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, (c) $0.036 \pm 0.026 \text{ decade}^{-1}$ and (d) $-0.004 \pm 0.018 \text{ decade}^{-1}$.

Johannes Hahn 25.4.2017 10:02



Gelöscht:

... [21]

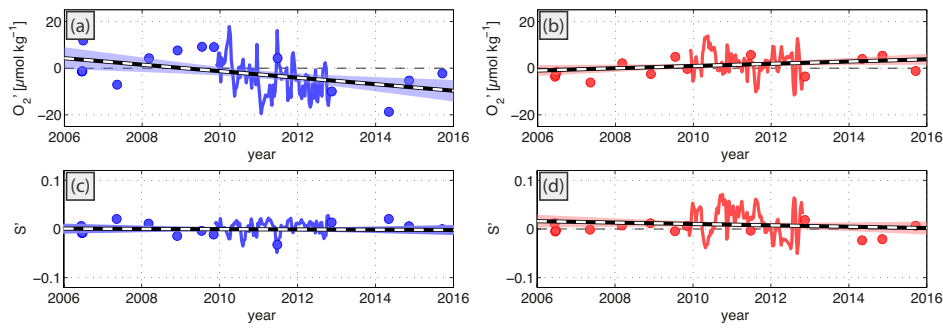


Figure 4. Oxygen ((a) and (b)) and salinity ((c) and (d)) anomaly time series from moored (solid line) and shipboard (dots) observations at 8°N, 23°W. (a) and (c) show averages between 200 and 400 m. (b) and (d) show averages between 500 and 800 m. Black dashed lines show respective trends from combined moored and shipboard observations: (a) $-13.9 \pm 8.7 \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, (b) $4.8 \pm 4.4 \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, (c) $-0.003 \pm 0.020 \text{ decade}^{-1}$ and (d) $-0.014 \pm 0.025 \text{ decade}^{-1}$.

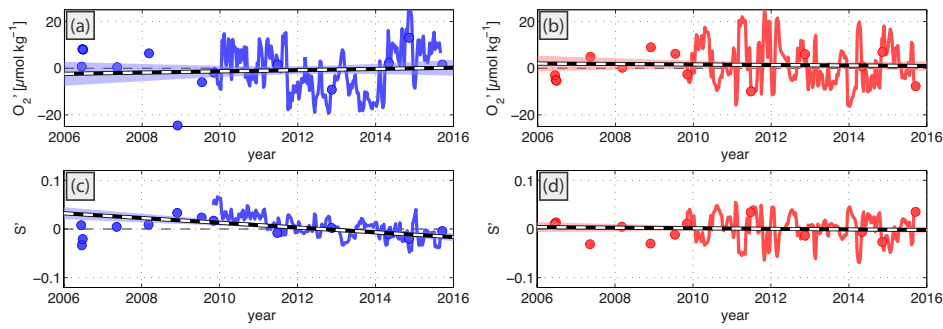


Figure 5. Oxygen ((a) and (b)) and salinity ((c) and (d)) anomaly time series from moored (solid line) and shipboard (dots) observations at 5°N, 23°W. (a) and (c) show averages between 200 and 400 m. (b) and (d) show averages between 500 and 800 m. Black dashed lines show respective trends from combined moored and shipboard observations: (a) $2.6 \pm 7.8 \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, (b) $-1.1 \pm 4.9 \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, (c) $-0.049 \pm 0.019 \text{ decade}^{-1}$ and (d) $-0.006 \pm 0.015 \text{ decade}^{-1}$.

1640

Johannes Hahn 10.5.2017 09:24

Gelöscht: -

... [22]

Johannes Hahn 10.4.2017 14:53

[1] verschoben (Einfügung)

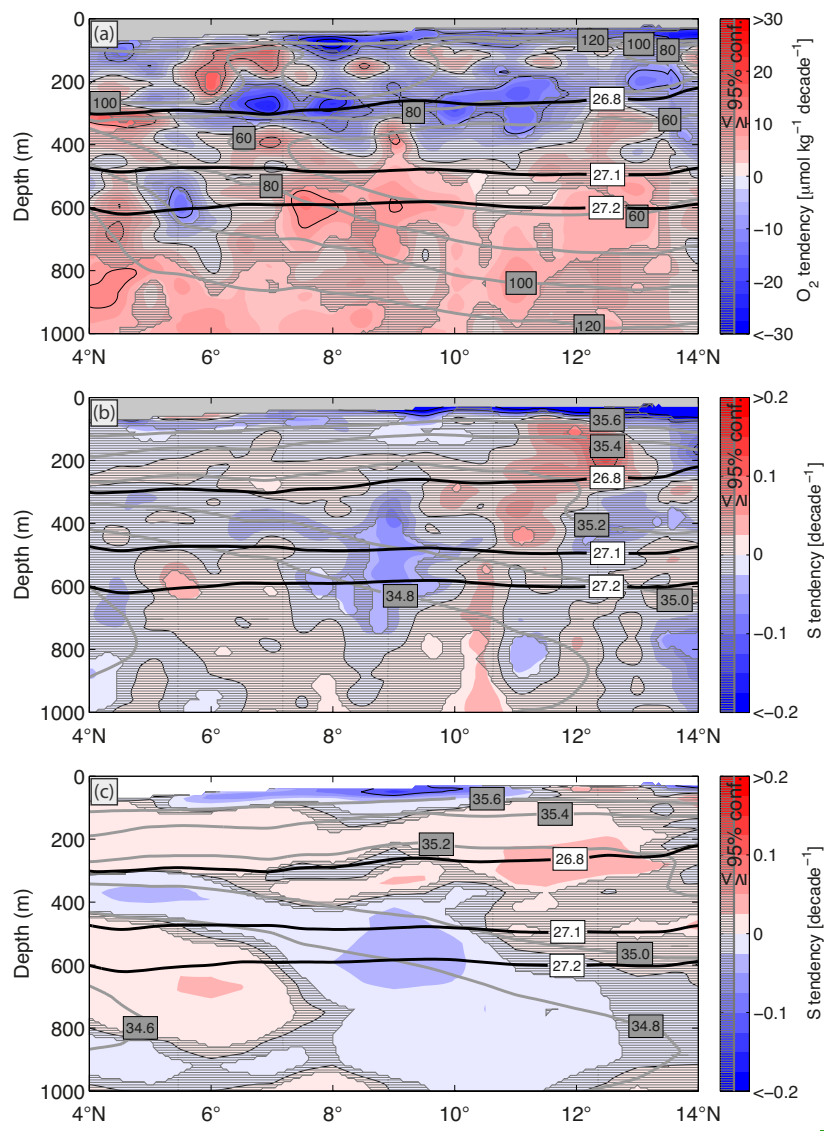


Figure 6. Depth-latitude section of the linear trend (filled contours) of (a) oxygen and (b,c) salinity in the ETNA along 23°W. (a) and (b) were calculated from repeat shipboard observations in the period 2006-2015. (c) was calculated from Argo float observations in the period 2006-2015. All calculations were done on density surfaces with subsequent projection onto depth surfaces. Gray-hatched areas mark non-significant regimes with respect to 95% confidence. Mean fields of oxygen and salinity, respectively, are given as gray contours. Thick black contours define isopycnal surfaces 26.8 kg m⁻³, 27.1 kg m⁻³ and 27.2 kg m⁻³.

Johannes Hahn 10.4.2017 15:11

Gelöscht: 9

Johannes Hahn 20.4.2017 17:03

Gelöscht: The

Johannes Hahn 20.4.2017 17:03

Gelöscht: as

Table 3. Oxygen and salinity tendencies (period 2006 – 2015) with 95% confidence interval estimated for 5 different latitude boxes along 23°W and for the Central Water (200 – 300 m) and Intermediate Water (500 – 800 m) layer, respectively. Oxygen tendency was estimated from shipboard observations (cf. Fig. 6a) and salinity tendency was estimated from float observations (cf. Fig. 6c). Values in gray boxes define regimes with a significant decadal change.

| | | 4°N – 6°N | 6°N – 8°N | 8°N – 10°N | 10°N – 12°N | 12°N – 14°N |
|--|--|-----------|------------|-------------|-------------|-------------|
| Central Water (200 - 300 m) | O₂ tendency [μmol kg ⁻¹ decade ⁻¹] | 2.4 ± 8.8 | -9.9 ± 8.2 | -11.1 ± 8.3 | -11.4 ± 5.9 | -4.1 ± 5.5 |
| | S tendency [10 ⁻² decade ⁻¹] | 1.3 ± 0.3 | 1.0 ± 0.4 | 0.6 ± 0.7 | 2.7 ± 1.1 | 2.4 ± 2.3 |
| Intermediate Water (500 - 800 m) | O₂ tendency [μmol kg ⁻¹ decade ⁻¹] | 1.3 ± 5.3 | 4.0 ± 3.6 | 5.8 ± 3.1 | 4.1 ± 1.9 | 4.5 ± 2.7 |
| | S tendency [10 ⁻² decade ⁻¹] | 1.6 ± 0.5 | 0.4 ± 0.6 | -2.4 ± 0.9 | -1.3 ± 1.1 | -0.2 ± 1.5 |

Johannes Hahn 25.4.2017 15:07

Gelöscht: .

... [23]

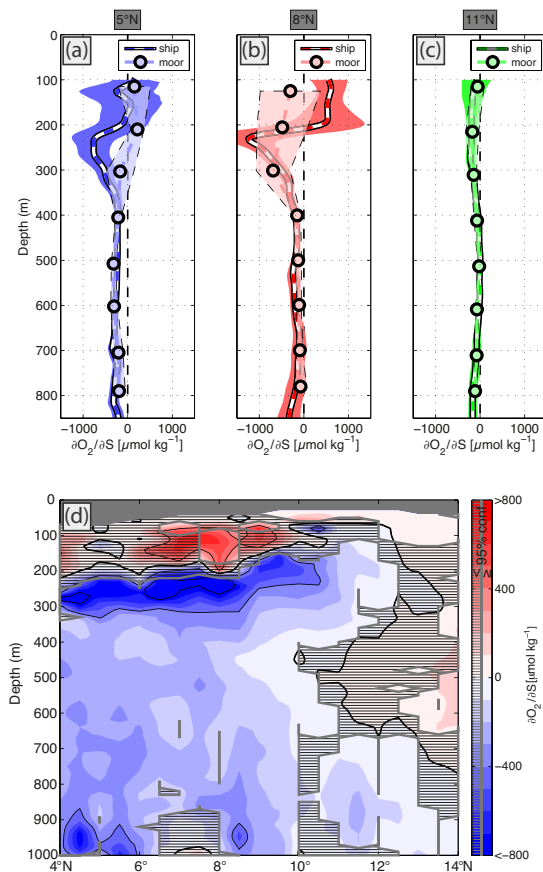


Figure 7. Vertical profiles of the slopes of the linear fits of oxygen against salinity with 95% confidence intervals for moored (white-colored dashed line) and shipboard observations (colored dots) at positions (a) 5°N, 23°W, (b) 8°N, 23°W and (c) 11°N, 21°W. (d) Depth-latitude section (along 23°W) of the slope of the linear fit of oxygen against salinity (filled contours). Gray-hatched areas define non-significant regimes with respect to 95% confidence.

Johannes Hahn 10.4.2017 15:13

Gelöscht: 7

Johannes Hahn 19.4.2017 17:53

Gelöscht: Oxygen vs. salinity at the isopycnal surface 27.1 kg m^{-3} from moored (bright colored dots) and shipboard (dark colored dots) observations at (a) 5°N, 23°W, (b) 8°N, 23°W and (c) 11°N, 21°W. Thick colored dashed lines mark linear fits of oxygen against salinity and percentages in the colored boxes at the bottom mark the explained variance for the respective observational data set. (d) to (f) show v

Johannes Hahn 19.4.2017 17:53

Gelöscht: with same

Johannes Hahn 19.4.2017 17:53

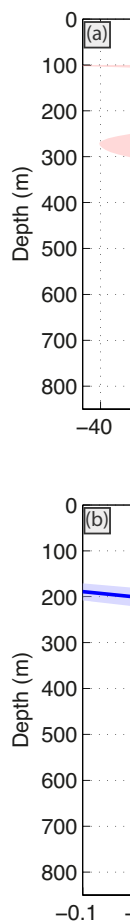
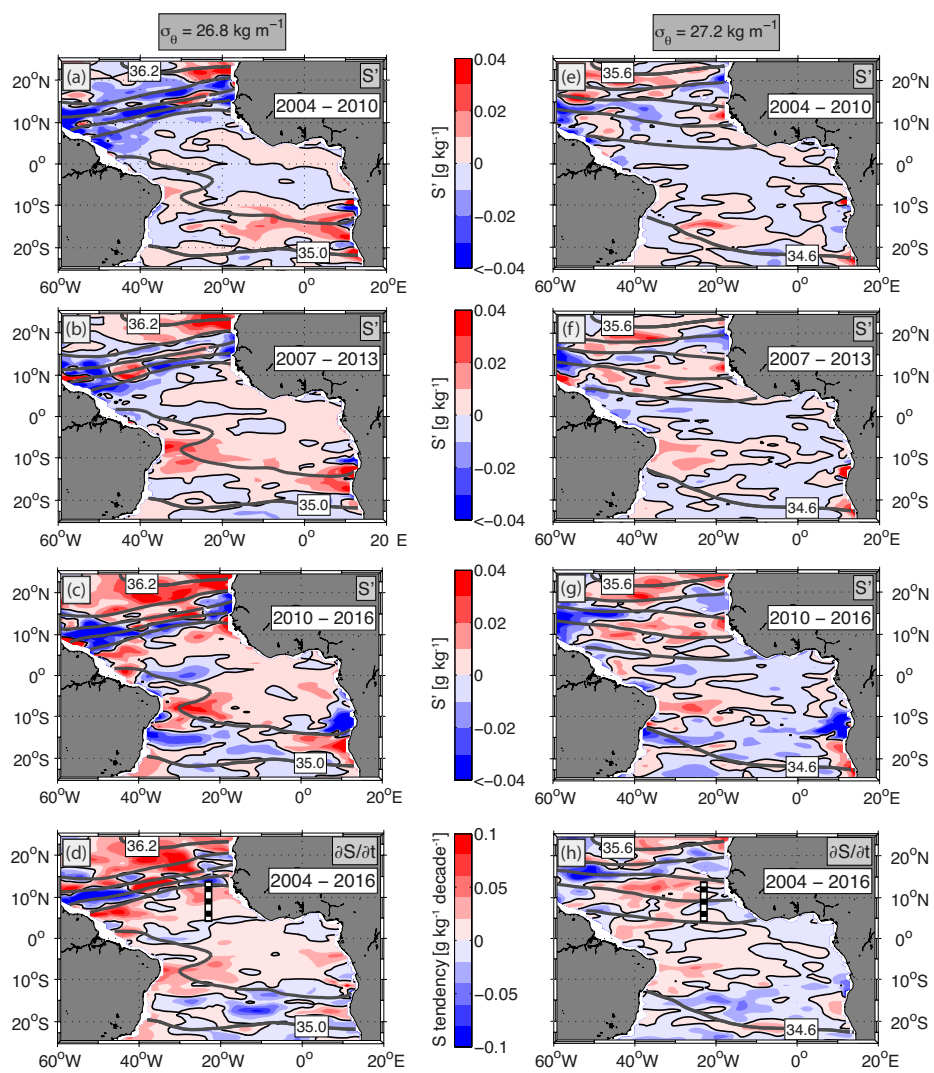
Gelöscht: as in

Johannes Hahn 19.4.2017 17:54

Gelöscht: to

Johannes Hahn 19.4.2017 17:54

Gelöscht: g



[1] nach oben verschoben:
Figure 8. Vertical profiles (against depth and density) of the linear trend of (a) oxygen and (b) salinity calculated from the respective time series as a combination of moored and shipboard observations (Fig. 3 to 5) in the ETNA at 5°N, 23°W (blue), 8°N, 23°W (red) and 11°N, 21°W (green). Respective 95% confidence intervals are given as shaded areas. Note that moored and shipboard observations for the latitude position 11°N were at different longitudes 21°W and 23°W, respectively. See text for details of the calculation.

Johannes Hahn 21.4.2017 17:05
Gelöscht: ... [24]
Johannes Hahn 21.4.2017 17:05
Gelöscht: ... [25]
Johannes Hahn 10.5.2017 09:32
Gelöscht: 11

Figure 8. Salinity anomalies (filled contours) in the tropical Atlantic at the isopycnal surface 26.8 kg m^{-3} from Argo float observations for the period (a) 2004-2010, (b) 2007-2013 and (c) 2010-2016. (d) Salinity trend (filled contours) calculated from all salinity anomalies at isopycnal surface 26.8 kg m^{-3} between 2004 and 2016. Black-white dashed line marks the 23°W section between 4°N and 14°N for reference. Gray contours in panels (a) to (d) define the mean salinity distribution. (e) – (h): Same as (a) – (d), but for isopycnal surface 27.2 kg m^{-3} .

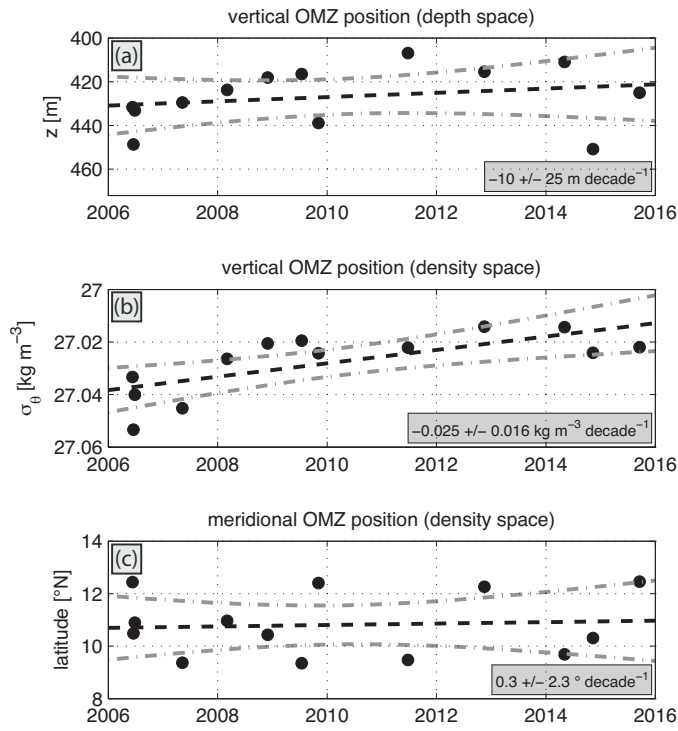
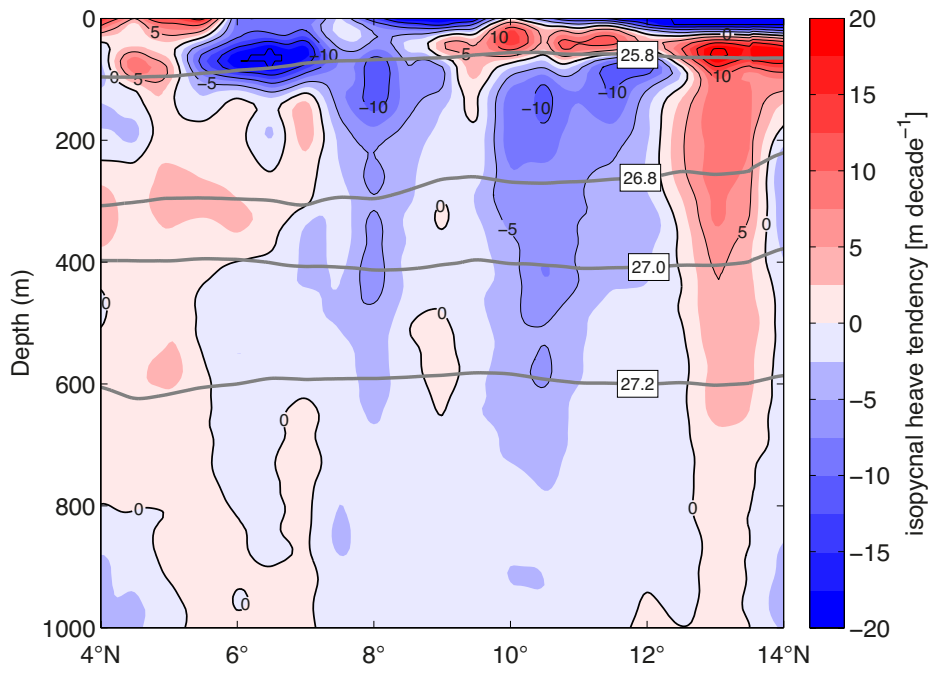


Figure 9. Time series (black dots) of the OMZ core position (defined as the 5% area of lowest oxygen) obtained from individual ship sections along 23°W. (a) and (b) show the vertical position in depth and density space. (c) shows the meridional position in density space (that is similar in depth space). Black dashed line shows the respective linear trend with 95% confidence band (gray dashed-dotted lines).



1715

Figure 10. Depth-latitude section of the isopycnal heave tendency (filled contours) from shipboard observations along 23°W for the period 2006-2015 (positive values denote upward migration of isopycnal surfaces - see text for details of the calculation). Gray contours define average isopycnal surfaces.

Johannes Hahn 25.4.2017 14:58

Gelöscht: 2

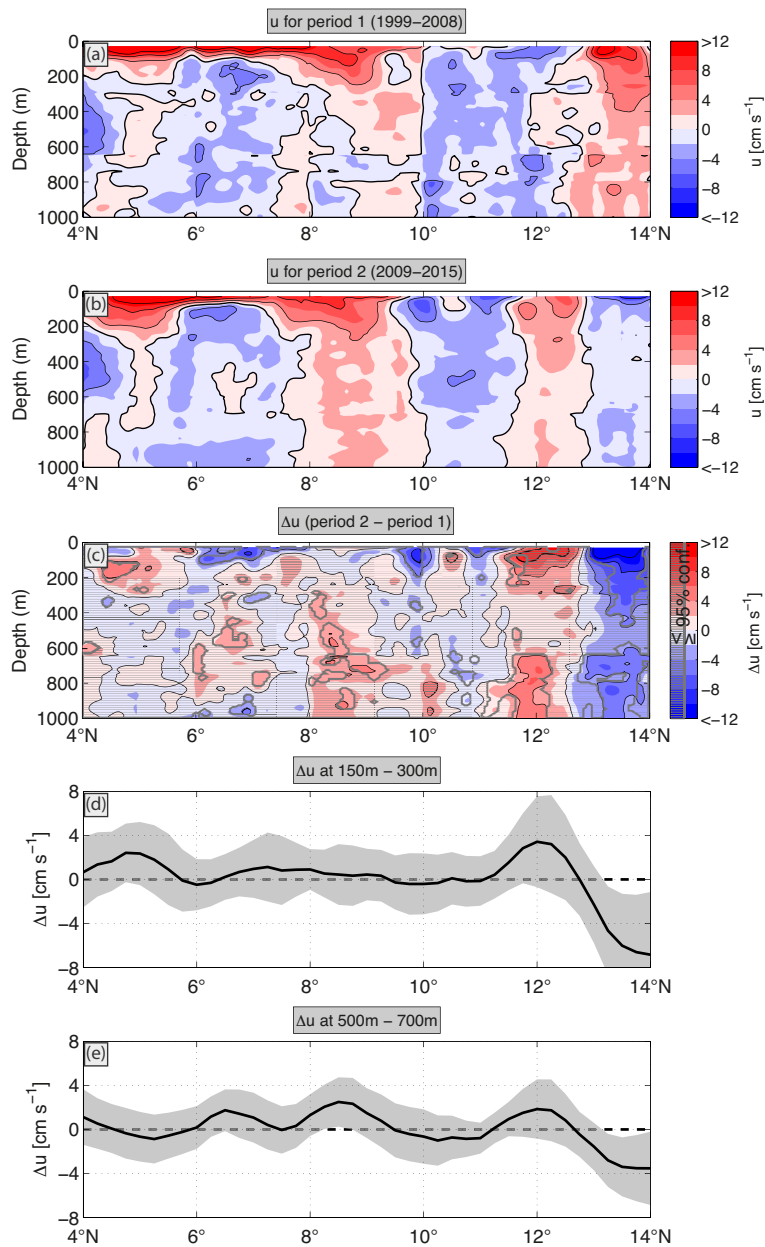


Figure 1 Depth-latitude section of mean zonal velocity from shipboard observations along 23°W for (a) period 1999 - 2008 and (b) period 2009 - 2015. (c) Depth-latitude section of the difference of zonal velocity between the aforementioned two periods '(b) minus (a)'. Gray hatching defines non-significant regimes with respect to 95% confidence. The interval of the black solid velocity contour lines in (a) to (c) is 4 cm s^{-1} . (d) Vertical

Johannes Hahn 25.4.2017 14:56
Gelöscht: 3

average of (c) for the depth range 150 - 300 m (black line). Gray-shaded area marks 95% confidence band. (e)
Same as (d) but for the depth range 500 - 700 m.

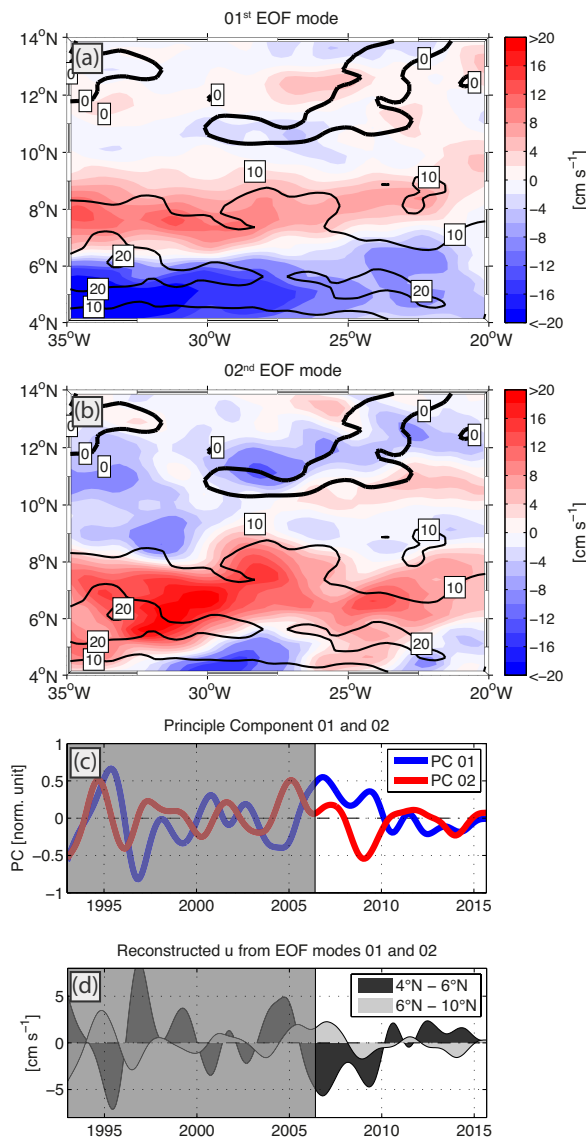


Figure 12 (a) First and (b) second EOF mode of the filtered (mean and seasonal cycle removed and subsequently 2-yr low-pass filtered – see text for details) surface zonal geostrophic velocity from [Aviso](#) (filled contours; positive eastward) for the tropical North Atlantic. Black contours define isolines of mean surface zonal geostrophic velocity from [Aviso](#) in cm s⁻¹ (positive eastward). (c) Principle components 01 and 02 corresponding to the first two EOF modes given in (a) and (b). (d) Time series of eastward velocity (averaged between 35°W and 20°W for the latitude bands 4°N–6°N and 6°N–10°N) reconstructed from the first two EOF modes, given in (a) and (b), and corresponding principle components in (c). White boxes (right parts of panels (c) and (d)) mark

Johannes Hahn 25.4.2017 14:55

Gelöscht: 4

Johannes Hahn 23.5.2017 21:33

Gelöscht: VISO

Johannes Hahn 23.5.2017 21:33

Gelöscht: AVISO

1740 | the time period (2006 – 2015) of shipboard observations used for the estimate of the decadal oxygen and salinity
trend section in [Fig. 6](#) (cf. Table 1). Gray boxes (left parts) mark the time period before.

Johannes Hahn 10.4.2017 15:11

Gelöscht: Fig. 9

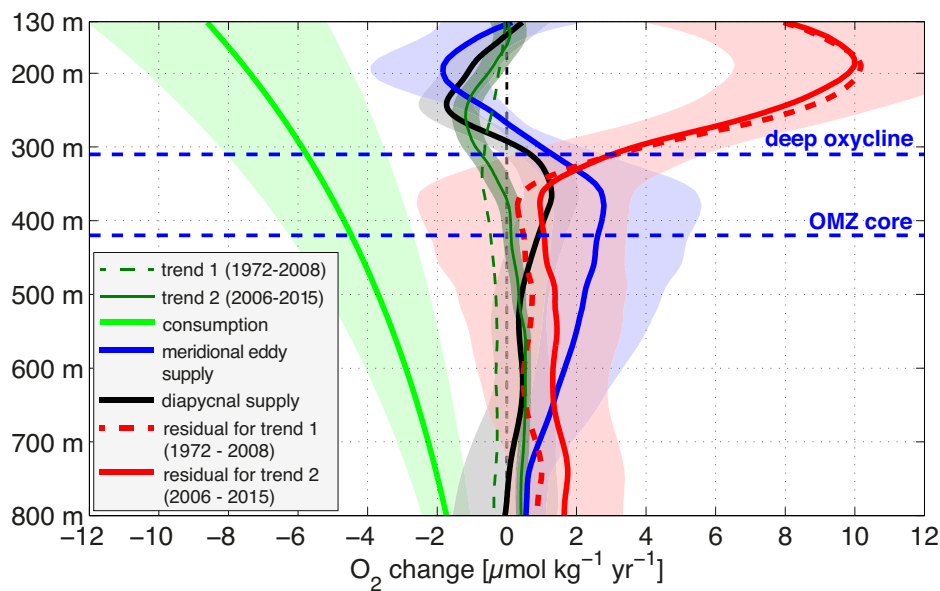


Figure 13. Oxygen budget for the ETNA as an average between 6°N and 14°N (see Eq. (1) and corresponding text in Sect. 2.5, 3.4 and 4.3 for details). The terms consumption, meridional eddy supply and diapycnal supply were kept constant in time, whereas two different oxygen trends for the periods 1972-2008 (multi-decadal trend: dashed green line) and 2006-2015 (decadal trend: solid green line) were implemented in the budget. The corresponding residual supply for both periods (multi-decadal: dashed red line – decadal: solid red line) was calculated by assuming a balance between all respective terms.

Johannes Hahn 25.4.2017 14:53

Gelöscht: 5

Johannes Hahn 25.4.2017 10:36

Gelöscht: (1)

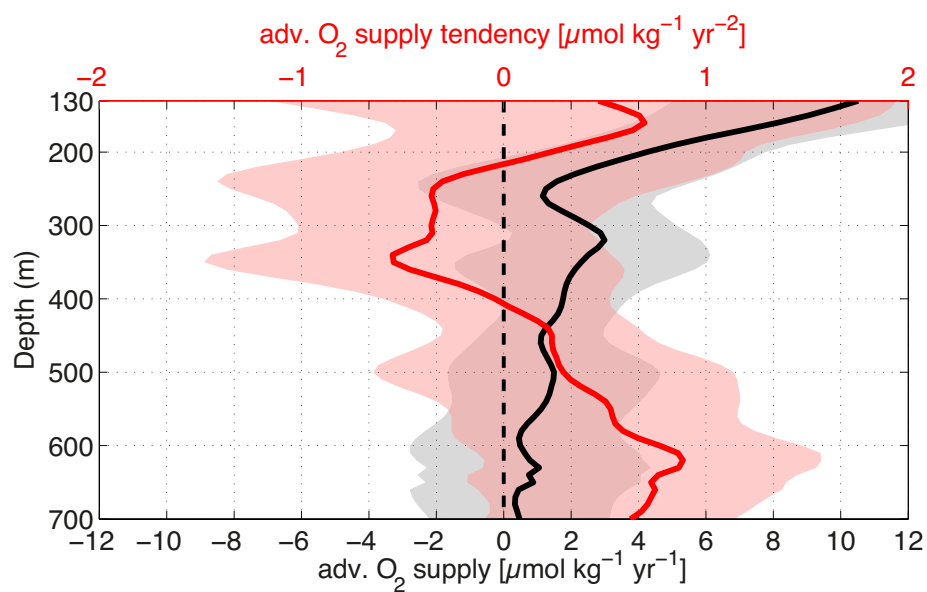


Figure 14. Vertical profiles of the mean zonal advective oxygen supply across 23°W (black) and the respective zonal advective oxygen supply tendency (red) calculated from shipboard observations along 23°W and referred to the box 23°W-15°W and 6°N-14°N. Gray and red shadings define the 95% confidence band of the mean zonal advective oxygen supply and the zonal advective oxygen supply tendency, respectively.

1755

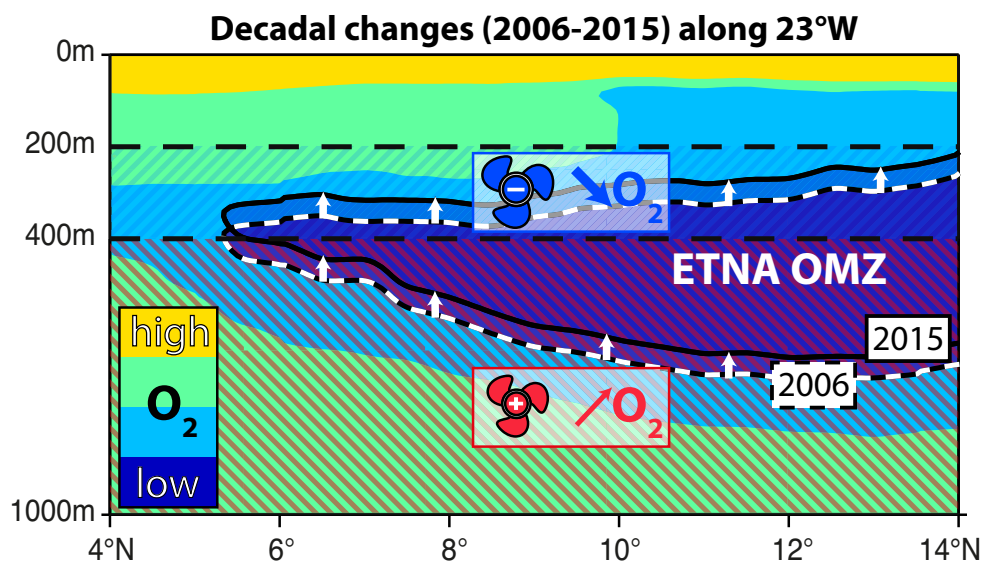


Figure 15. Schematic description of oxygen change associated with ventilation change in the ETNA along 23°W in the period 2006 to 2015. X-axis is latitude, Y-axis is depth, color shading denotes the oxygen distribution (yellow: high oxygen; dark blue: low oxygen). In the depth layer 200-400 m, ventilation has weakened resulting in a strong oxygen decrease (indicated by the blue fan and the blue downward arrow with symbol O_2). In the depth layer 400-1,000 m, moderate oxygen increase was found associated with a preceding strengthening of the ventilation (red fan and red upward arrow with symbol O_2). As a result of the ventilation and oxygen change, the ETNA OMZ has migrated upward (white arrows) - black-white dashed and black contour lines indicate the extent of the OMZ for the year 2006 and 2015, respectively.