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Diapycnal diffusivity in the core and oxycline of the tropical North Atlantic oxygen minimum zone

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ABSTRACT

Diapycnal diffusivity estimates from two Tracer Release Experiments (TREs) and microstructure measurements in the oxycline and core of the oxygen minimum zone (OMZ) in the Eastern Tropical North Atlantic (ETNA) are compared. For the first time, two TREs within the same area at different depths were realized: the Guinea Upwelling Tracer Release Experiment (GUTRE) initiated in 2008 in the oxycline at approximately 320 m depth, and the Oxygen Supply Tracer Release Experiment (OSTRE) initiated in 2012 in the core of the OMZ at approximately 410 m depth. The mean diapycnal diffusivity D^z was found to be insignificantly smaller in the OMZ core with $(1.06\pm0.24)\times10^{-5}$ m^2 s^{-1} compared to $(1.11\pm0.22)\times10^{-5}$ m^2 s^{-1} 90 m shallower in the oxycline. Unexpectedly, GUTRE tracer was detected during two of the OSTRE surveys which showed that the estimated diapycnal diffusivity from GUTRE over a time period of seven years was within the uncertainty of the previous estimates over a time period of three years. The results are consistent with the D^z estimates from microstructure measurements and demonstrate that D^z does not vary significantly vertically in the OMZ within the depth range of 200–600 m and does not change with time. The presence of a seamount chain in the vicinity of the GUTRE injection region did not cause enhanced D^z compared to the smoother bottom topography of the OSTRE injection region, although the analysis of vertical shear spectra from ship ADCP data showed elevated internal wave energy level in the seamount vicinity. However, the two tracer patches covered increasingly overlapping areas with time and thus spatially integrated increasingly similar fields of local diffusivity, as well as the difference in local stratification counteracted the influence of roughness on D^z. For both experiments no significant vertical displacements of the tracer were observed, thus diapycnal upwelling within the ETNA OMZ is below the uncertainty level of 5 m yr^{-1}.

1. Introduction

Diapycnal diffusivity plays an important role in the ventilation of the Eastern Tropical North Atlantic (ETNA) oxygen minimum zone (OMZ). OMZs are areas of low oxygen concentration due to weak ventilation with oxygen rich water masses (e.g. Karstensen et al., 2008). In the ETNA oxygen concentrations below 40 μmol kg^{-1} were found in the core of the OMZ at approximately 400 m depth (e.g. Stramma et al., 2008). Above the oxygen minimum zone, a pronounced oxycline is located between 300 and 350 m depth. Fig. 1 shows the horizontal and vertical oxygen distribution of the ETNA OMZ. Low oxygen concentrations in the ETNA OMZ have a noticeable influence on the organisms living in this area. Macro-organisms are stressed or die under hypoxic conditions, which is defined as concentrations below about 60 μmol kg^{-1} (Keeling et al., 2010; Stramma et al., 2008, 2012). Studies by Fischer et al. (2013) and Banyte et al. (2012) and the synthesis by Brandt et al. (2015) found that diapycnal mixing contributes up to 20%, and locally up to 30%, to the oxygen supply in the OMZ. This comparatively high contribution to the oxygen supply for the ETNA OMZ is the consequence of the weak horizontal circulation and associated exchange within the so-called shadow zone of the subtropical gyre (Luyten et al., 1983). Moreover, enhanced mixing over rough topography in the seamount area south of the Guinea Dome could play a role (Brandt et al., 2015).

In the study region, diapycnal diffusivity has been estimated from microstructure profiles (MSS), vertical shear of horizontal current velocity measurements by ship ADCP and vertical tracer spreading rates from purposeful Tracer Release Experiments (TREs). Limited by the available ship time MSS profile based estimates of vertical mixing might suffer from temporal and spatial aliasing or other unresolved variability. ADCP shear based diapycnal diffusivity estimates were calibrated by comparison to 400 MSS stations in the ETNA OMZ region and allowed for much better spatial coverage. This data set gave

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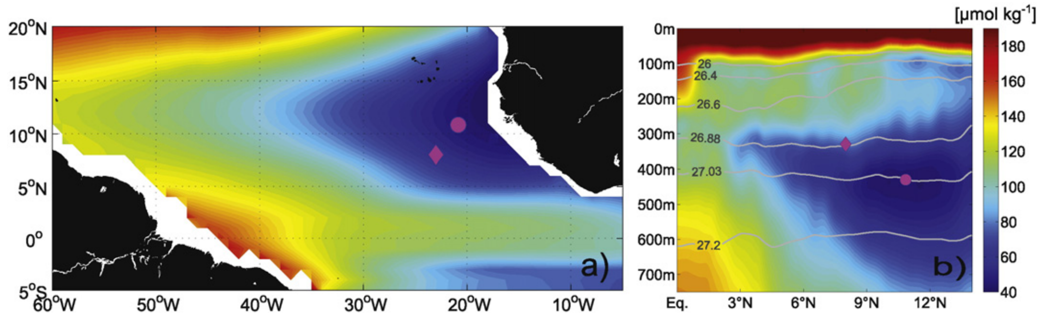

Fig. 1. Oxygen concentration [μmol kg^{-1}] in the tropical Atlantic. The colorbar is valid for a) and b). The magenta diamonds mark the injection site of the GUTRE experiment, the magenta dots mark the injection site of the OSTRE experiment. a) Map of average oxygen concentration [μmol kg^{-1}] at 400 m depth from the MIMOC climatology (Schmidtko et al., 2013). b) Section of oxygen concentration [μmol kg^{-1}] along 23°W from meridional ship sections during 1999–2012 (Brandt et al., 2015). The gray lines and numbers mark different density anomalies in kg m^{-3}.

consistent estimates compared to a TRE based estimate (Fischer et al., 2013; Banyte et al., 2012). Purposeful Tracer Release Experiments provide another approach to accurately estimate the time and space-averaged diapycnal diffusivity. First a tracer is injected on a certain density level. Then repeated measurements of the vertical tracer spread allow the estimation of diffusivity averaged over a time from six months to several years. The vertical spread of the tracer includes all dispersion processes contributing to mixing. The success of a TRE relies on an accurate tracer injection and precise detection of low tracer concentrations over a significant timespan within a large sampling area (see Watson and Ledwell, 2000).

Within the ETNA OMZ, the diapycnal diffusivity from microstructure and ADCP measurements was estimated to be $(1.0 \pm 0.2) \times 10^{-5}$ m^2 s^{-1} within the depth range of 150 to 500 m (Fischer et al., 2013). Diffusivity determined from TREs within the oxycline of the ETNA OMZ region was first estimated during the Guinea Upwelling Tracer Release Experiment (GUTRE) 2008–2010 (Banyte et al., 2012). The diapycnal diffusivity in the oxycline was found to be $(1.19 \pm 0.18) \times 10^{-5}$ m^2 s^{-1} (Banyte et al., 2012). The results of the two methods were consistent within the uncertainty range.

A second tracer experiment, the Oxygen Supply Tracer Release Experiment (OSTRE), was set up primarily to investigate lateral exchange within the ETNA OMZ and thus to better quantify the horizontal supply paths for oxygen into the OMZ. However, it also provided an opportunity to measure the vertical diffusivity at an additional depth layer. Two TREs within the same area at different depth levels have never been done before. In this paper we are using the OSTRE results to estimate diapycnal diffusivity coefficients for the OMZ core (Fig. 1). To our surprise, we were also able to follow the GUTRE signal at the oxycline over a total of seven years. We compare the diapycnal diffusivity coefficients within the core of the OMZ and within the oxycline, and also with the diapycnal diffusivity results obtained from microstructure and vertical shear measurements.

Section 2 describes the experimental setup and sampling strategies of GUTRE and OSTRE. Section 3 describes the data analysis methods. Section 4 presents the results of OSTRE (core) in direct comparison with the GUTRE (oxycline) results. Finally, Section 5 discusses the main results and the comparison of GUTRE and OSTRE with other measurements and the role of roughness due to topography.

2. Experimental setup

2.1. Tracer injection

Diffusivity within the OMZ region of the ETNA was first estimated from TREs during the Guinea Upwelling Tracer Release Experiment (GUTRE). In April 2008 92 kg (470 mol) of the tracer CF_3SF_5 were injected at 8°N, 23°W into the oxycline of the ETNA OMZ on the 26.88 kg m^{-3} potential density surface at approximately 320 m depth (Fig. 1), where the highest vertical oxygen gradients are found (Banyte et al., 2012). The injection was accomplished in 5 separate tows within a 20 × 20 km area with the Ocean Tracer Injection System (OTIS) (Visbeck and Schulz-Bull, 2008). The injection was controlled by a winch system, automatically responding to deviations from the targeted injection density measured by a CTD on OTIS.

The OSTRE tracer release took place at 10°30′N, 21°W where the lowest oxygen concentrations were found (Fig. 1). In December 2012 88.5 kg (451 mol) of CF_3SF_5 were injected into the core of the OMZ at the potential density level of 27.03 kg m^{-3} which is located at approximately 410 m depth. The injection was accomplished in four separate tows with a duration of 5–7 h each. 87% of the tracer was injected within ± 1.5 m of the targeted injection density level, and virtually all of the tracer within ± 3 m (Fig. 2). During the injection, the tracer was distributed in the vertical due to deviation from the target density plus turbulent mixing behind the injection sled (Visbeck and Tanhua, 2012). An estimate of this initial tracer spreading was given by Ledwell et al. (1998) to be about 5.5 m using a similar OTIS. Thus, we chose the initial second moment of the tracer spread for both experiments to be 5.5 m which corresponds to 0.0093 kg m^{-3} in density space for GUTRE and 0.0072 kg m^{-3} for OSTRE.

2.2. Tracer surveys

Details of the GUTRE and OSTRE surveys, including the notation, can be found in Table 1. Note that we changed the notation of the GUTRE surveys compared to Banyte et al. (2012). The GUTRE patch was surveyed 7 (GUTRE-II), 20 (GUTRE-III) and 30 (GUTRE-IV) months after injection (see Fig. 3b, d, f). Tracer was found in 50% of the measured profiles during GUTRE-II and in 85% of the measured profiles during GUTRE-III. During GUTRE-IV tracer was found in all casts. Tracer was

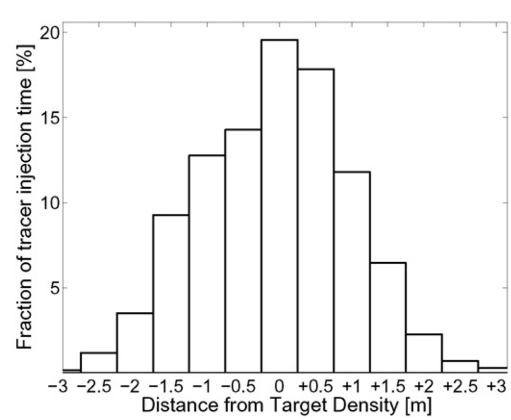

Fig. 2. Vertical precision of tracer injection during OSTRE, shown as the distribution of distance between the tracer injection depth and the depth of the targeted density.