SFB 754: Climate-Biogeochemistry Interactions in the Tropical Ocean

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Project summary

The Collaborative Research Centre (Sonderforschungsbereich, SFB) 754 has been funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) since January 2008. After passing a thorough evaluation by an international review board, the second research period started in January 2012. The SFB 754 addresses climate induced ocean deoxygenation, with a focus on tropical oxygen minimum zones (OMZ) in the Atlantic and Pacific, and implications for the global marine biogeochemical system.

The overall scientific goal of the SFB 754 is to understand the coupling of tropical climate variability and circulation with the ocean's oxygen and nutrient budgets, to quantitatively evaluate the functioning of oxygen-sensitive microbial processes and their impact on biogeochemical cycles, and to assess potential consequences for the ocean's future. The overall goal can be broken down into three main scientific questions:

1. How does subsurface dissolved oxygen in the tropical ocean respond to variability in ocean circulation and ventilation?
2. What are the sensitivities and feedbacks linking low or variable oxygen levels, organic matter dynamics, and key nutrient source and sink mechanisms? In the benthos? In the water column?
3. What are the magnitudes and time scales of past, present and likely future variations in oceanic oxygen and nutrient levels? On the regional scale? On the global scale?

In addressing these basic science issues, the SFB 754 will be able to answer questions of key relevance for assessing impacts of climate change on the future ocean and its ecosystem; e.g., what is the likelihood that future climate change will lead to significant shifts in the ventilation, oxygen balance and hence nutrient cycling of tropical oceans, and ultimately, the entire ocean? More specifically: will the present-day oxygen minimum zones grow further in intensity and extent? How sensitive are oceanic nutrient inventories to changes in oxygen minimum zones? Could the tropical Atlantic low oxygen zone develop to become like today's very low oxygen zones in the Indian and Pacific Oceans with their significantly different biogeochemistry and ecosystems? Could positive feedbacks in a future warmer and high CO_2 world eventually result in interior ocean anoxia as has happened in the past?

The project consists of more than 80 researchers from the Christian-Albrechts University of Kiel, the Helmholtz Centre for Ocean Research Kiel (GEOMAR) and the Max-Planck Institute for Marine Microbiology (Bremen), working closely together in eight projects in the thematic area "Circulation and Oxygen" and eight projects in the thematic area "Redox-dependent Biogeochemistry" with tightly integrated modelling and field-work activities. In this article we will focus on the CLIVAR related work in subprojects of the thematic area "Circulation and Oxygen" in the tropical Atlantic (see Fig. 1).

Background

Oxygen-poor waters, called oxygen minimum zones (OMZs), occupy large volumes of the intermediate-depth eastern tropical oceans in the depth range between 100 and 900 m. They are a consequence of the combined effect of weak ocean ventilation, which supplies oxygen, and strong respiration, which consumes oxygen. Accordingly, the geographic location of OMZs in the open ocean is to a first order determined by the proximity to upwelling areas with associated high biological productivity and restricted to regions of generally sluggish horizontal transport, namely the "shadow zones of the ventilated thermocline" (Luyten et al., 1983) along the eastern boundaries.

The Northern Tropical Atlantic hosts two oxygen minima at about 70 m and 400 m depth, respectively. The shallow minimum is most pronounced near the coast between Senegal and the Cape Verde Islands and linked to subsurface remineralisation associated with high biological productivity and a shallow mixed layer (Karstensen et al., 2008). Offshore the deeper oxygen minimum exhibited record low minimum concentrations slightly less than 40 μmol l^{-1} during recent SFB 754 cruises (Stramma et al., 2009). In contrast to the Pacific the Northern Tropical Atlantic regime displays a nitrite maximum near the base of the euphotic zone, but lacks the second maximum within the OMZ. This is indicative that neither N_2O is consumed, nor denitrification is happening, consistent with measurements of the isotopic signature of nitrate in this region.

Project results of the first phase (2008-2011)

At the start of SFB 754, a detailed analysis of dissolved oxygen records from a few selected areas with sufficient data coverage in the tropical ocean revealed negative trends for the last 50 years in all ocean basins (Stramma et al., 2008), indicating a measurable expansion of the oxygen minimum zone in the Atlantic both horizontally and vertically. The strongest linear trend for the 300 to 700 m depth layer was found for an area in the eastern tropical North Atlantic (Fig. 2) with a loss of 0.34 +/- 0.13 μmol kg^{-1} per year since 1960. A more spatially expansive analysis conducted by comparing data between 1960 and 1974 with those from 1990 to 2008 supports the local analysis in that it identified oxygen decreases in most tropical regions with an average rate of 2-3 μmol kg^{-1} per decade (Stramma et al., 2010). Furthermore, at 200 dbar, the area with oxygen < 70 μmol kg^{-1}, where some large macro-organisms are unable to abide, has increased by 4.5 million km^2 between these two time periods. For the North Atlantic OMZ, data collected on the SFB cruises in the Atlantic revealed the lowest North Atlantic oxygen concentrations ever measured (Stramma et al., 2009), as well as a decrease in the scatter in the local oxygen-salinity relation, suggesting reduced ventilation by mesoscale eddies and zonal jets (Brandt et al., 2010). However, several open ocean regions also have experienced an increase in dissolved oxygen in the thermocline.

Although numerical models used and developed further during Phase I of the SFB have been able to reproduce many features of the marine oxygen distribution with some degree of realism (Oschlies et al., 2008), the simulated oxygen change over the last decades still shows little resemblance with the change inferred from observations. Likely reasons for these discrepancies are deficiencies in both the simulated circulation patterns and the biogeochemical processes. A common notion has been that high levels of numerically induced diapycnal mixing may explain the general failure of coarse-resolution models to adequately reproduce the OMZs (Keeling et al., 2010). However, Duteil and Oschlies (2011) showed that even coarse-resolution models could be run with realistic levels of diapycnal mixing and that this had relatively little impact on the still limited ability of the models to reproduce observed oxygen changes.

The contribution of physical and/or biogeochemical processes responsible for the observed oxygen decline remains largely unknown. Possible explanations for how changes in ocean physics may cause a decrease in the oceanic oxygen content include (i) changes in solubility, which has been found to explain about a quarter of the observed and simulated oxygen decline (Matear and Hirst, 2003), and (ii) changes in ocean circulation and ventilation (Bopp et al., 2002). Using an advection-diffusion tracer model, Brandt et al. (2010) showed that observed changes in the strength of the latitudinally altering zonal jets from 1972-85 to the more recent period 1999–2008 could contribute to the on-going deoxygenation of the eastern tropical North Atlantic OMZ. Results of the high-resolution modelling studies of the SFB 754 indicate that changes in tropical wind regime and the interhemispheric Atlantic meridional overturning circulation may affect the relative contribution of northern and southern source waters to the ventilation of the tropical North Atlantic OMZ. Since the history and oxygen content of northern and southern source waters differ considerably, this may have immediate impacts on the extent of the OMZ.

Possible biological and biogeochemical mechanisms that may cause a decrease in oceanic oxygen content were also investigated by the SFB. Extrapolating the findings of mesocosm studies of changes in carbon-to-nitrogen drawdown in response to changes in atmospheric pCO_2 (Riebesell et al., 2007), a global model study postulated a substantial increase in heterotrophic respiration due to excess organic carbon formed at elevated CO_2 levels (Oschlies et al., 2008). For a business-as-usual CO_2 emission scenario, the model predicted a 50% increase in the volume of suboxic waters by the end of the 21st century, whereas standard Redfield models suggest essentially unchanged suboxic water volumes at realistic levels of diapycnal mixing (Duteil and Oschlies, 2011).

In order to better constrain the oxygen supply by diapycnal mixing, a tracer release experiment was conducted in the northeast Atlantic OMZ. The experiment was designed to estimate the diapycnal mixing rate at the upper boundary of the deeper part of the OMZ. In April 2008, 92 kg of SF_5CF_3 was injected at 8°N, 23°W in the Guinea Dome area on the density surface σ_θ=26.88 kg m^{-3} at a depth of about 350 m. The tracer distribution was mapped out during three subsequent SFB cruises; 7, 20 and 30 months after the tracer release. Combining the best estimate diffusivity of (1.2 ± 0.1) ´ 10^{-5} m^{2}s^{-1} (Banyte et al., 2012, under revision) with the observed vertical oxygen profiles, it has been shown that oxygen supply into the OMZ via diapycnal diffusion can explain 25-50% of the total oxygen consumption (Fischer, 2011; Karstensen et al., 2008). Thus, the majority of the oxygen consumed in the North Atlantic OMZ must be supplied by lateral transport mechanisms.

The mean circulation in the central tropical Atlantic – as observed by a large number of recent research cruises including those of the first phase of the SFB 754 as well as of the CLIVAR TACE (Tropical Atlantic Climate Experiment) program – is characterized by narrow east- and westward current bands. Because of a large-scale mean east-west gradient in the dissolved oxygen concentration in the central and intermediate water layers, eastward currents are generally associated with higher oxygen concentrations than westward currents. At the core depth of the tropical eastern North Atlantic OMZ at about 400 m, strongest eastward flow is found within the Northern Intermediate Countercurrent (NICC) at about 2°N. Above 400 m and below the surface mixed layer, the main supply pathways for oxygen-rich waters towards the eastern North Atlantic are the Equatorial Undercurrent (EUC) at the equator between the surface and 200 m, and the weaker eastward flow of the North Equatorial Undercurrent at about 5°N and the northern branch of the North Equatorial Countercurrent that is located at about 9°N.

Along the equator, a broad equatorial oxygen maximum is present in the observational dataset that is largely underestimated by or even absent in state-of-the-art GCMs. In conjunction with lateral eddy mixing it represents an important ventilation pathway toward the eastern tropical North Atlantic OMZ. This equatorial oxygen maximum cannot be explained alone by the mean circulation consisting of a westward flow, i.e., the Equatorial Intermediate Current (EIC) between the eastward NICC and Southern Intermediate Countercurrent (SICC) that are part of the latitudinally alternating zonal jet system. However, narrow oxygen tongues were identified to be superimposed to the mean EIC and could be traced from the western to eastern equatorial Atlantic (Brandt et al. 2008). These oxygen tongues are found to be associated with the presence of equatorial deep jets (EDJ) and are thought to be a ventilation pathway missing even in relatively high-resolution numerical models. The dynamics and periodicity of EDJ were studied using moored, float and satellite observations. These observations revealed a quasi-periodic behaviour of EDJ with period of about 4.5

years and amplitude of 10 to 20 cm/s (Brandt et al. 2011). The interannual variability of EDJ should be linked to a similar variability of the equatorial oxygen distribution, which is indeed suggested by meridional ship sections.

Project plans of the second phase (2012-2015)

The second phase of SFB 754 moves forward from the more exploratory first phase, which provided a very concise overview over the physics and biogeochemistry of OMZs, into targeted process studies that are required to obtain a complete and coherent picture of the relevant transport pathways, microbial processes, and ecological controls on the maintenance and the climate sensitivity of OMZs and their role in global nutrient cycles. The observational program of the second phase of SFB 754 in Thematic Area A "Circulation and Ocean" includes a tracer release experiment, an extension of moored time series stations and repeated ship sections as well as studies focussing on submesocale processes and on the fluxes of solutes released from or up taken by the sediments (Fig. 1).

An "Oxygen Supply Tracer Release Experiment (OSTRE)" will be performed in the centre of the OMZ at the density level of lowest dissolved oxygen concentration to estimate the lateral and vertical oxygen transfer. A simultaneous glider swarm study will be carried out and will focus on the fine scale structures of submesoscale features. Besides the moored and shipboard observations along 23°W, a new aspect will be process modelling that aims to better understand the dynamics of latitudinally altering zonal jets and EDJ, and a quantification of their contribution to the ventilation of the eastern tropical North Atlantic OMZ. Results of the process models are expected to lead to improved parameterizations that will allow a better understanding of the effects of advective ventilation pathways in ocean general circulation models. Relevant processes at the Mauritanian and Peruvian continental slopes and shelves will be studied, using measurements of solutes and microstructure profiling, by a mooring/lander program for measuring benthic fluxes and by glider campaigns aimed at identifying meso- and submesoscale physical processes relevant to the formation and retention of OMZs.

The focus of the high-resolution coupled ecosystem-circulation models will be on physical and biogeochemical processes in the evolution of the OMZs. A detailed analysis of the mechanisms by which different atmospheric forcing mechanisms can impact on oxygen supply to the tropical OMZs will be performed with very high-resolution models. A recently funded EUR-OCEANS Flagship project, closely linked to SFB 754, will explore to what extent vertical grid architecture (sigma vs z coordinates) can affect simulated oxygen dynamics close to the shelf. A direct confrontation with observed recent changes in physical and biogeochemical property distributions will provide information as to what extent forced circulation changes can explain observed changes. Biological and biogeochemical mechanisms that have been hypothesised to generate changes in oxygen concentrations (Taucher and Oschlies, 2011) will also be investigated.

Finally, SFB 754 will exploit coupled climate models to extrapolate impacts of climate change on simulated oxygen fields over the next 100 years. Possible effects of CO_2-induced climate change in the farther future will be investigated with coarser resolution Earth system models. The SFB 754 will also exploit paleo information on large changes in oxygen during the Holocene and during the onset of the Cretaceous anoxic events. The large signals suggested by sedimentary records may give valuable information on the underlying mechanisms despite the still considerable uncertainties about the state of the past ocean.

During the second phase of SFB 754, work on the thematic area "Circulation and Oxygen" described above will be carried out in close collaboration with projects of the thematic area "Redox-dependent Biogeochemistry". Thereby, we expect that we can develop a consistent picture of the interplay of the relevant physical, chemical, and biological processes associated with OMZs. The expected outcome will be a mechanistic understanding of controls on, and the impacts of, changing OMZs, and the provision of modelling tools adequate to predict the fate of tropical OMZs and their role in the climate system for various scenarios of environmental change.

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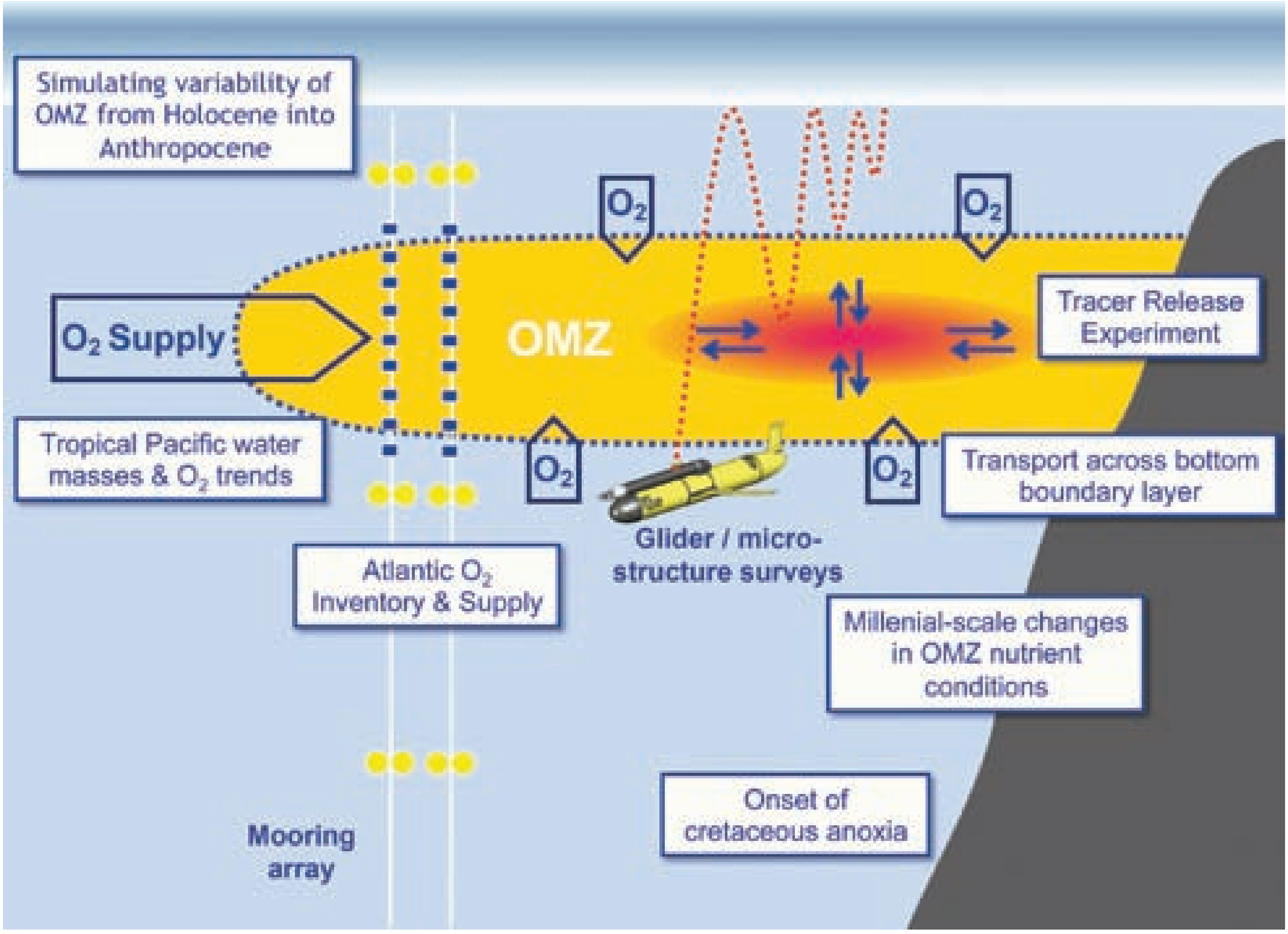

Fig. 1: Research topics of projects in thematic area "Circulation and Oxygen".

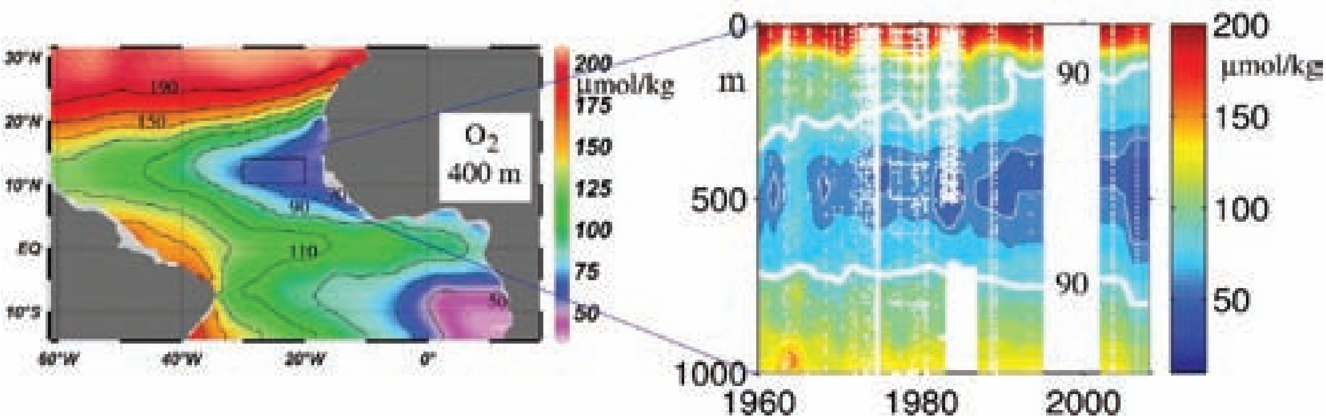

Fig. 2: Climatological mean dissolved oxygen concentration (µmol kg^{-1}) in the tropical Atlantic at 400 m depth (left) and oxygen concentration changes versus time (1960-2008) and depth in the eastern tropical North Atlantic 10° to 14°N, 20° to 30°W (right) (after Stramma et al. 2008).