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Simulated reduction in upwelling of tropical oxygen minimum waters in a warmer climate

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Abstract
Waters of the Atlantic and Pacific tropical oxygen minimum zones (OMZs), located in the poorly ventilated shadow zones of their respective ocean basins, reach the sea surface mostly in the eastern boundary and equatorial upwelling regions, thereby providing nutrients sustaining elevated biological productivity. Associated export of sinking organic matter leads to oxygen consumption at depth, and thereby helps to maintain the tropical OMZs. Biogeochemical feedback processes between nutrient-rich OMZ waters and biological production in the upwelling regions and their net impact on the evolution of the OMZs depend on the strengths of the flow pathways connecting OMZs and the upper ocean, because even though water has to be isolated below the mixed layer for some time in order for OMZs to develop, it has to be brought up to the surface mixed layer eventually in order to exchange properties with the atmosphere.

Here, we investigate the connections between OMZs and the surface mixed layer, and their sensitivity to global warming with a coupled ocean–atmosphere general circulation model by analyzing the fate of simulated floats released in the OMZs. We find that under present-day climate conditions, on decadal time scales a much larger portion of the model's OMZ waters reaches the surface ocean in the Pacific than in the Atlantic Ocean: within 20 years, 75% in the Pacific and 38% in the Atlantic. When atmospheric CO_2 is doubled, the fraction of modeled OMZ waters reaching the upwelling in the same time decreases by about 25% in both oceans. As a consequence, feedback between biogeochemical processes in OMZs and in the surface ocean is likely to be weakened in the future.

Keywords: oxygen minimum zones, ventilation, coupled climate model, coastal upwelling, warmer climate

1. Introduction

Oceanic oxygen minimum zones (OMZs) play an important role in biogeochemical cycles and in the climate system, because under low oxygen conditions chemical and biological processes are fundamentally different from the rest of the oxygenated ocean. Under oxic conditions, nutrient trapping in upwelling regions sustains high productivity. If oxygen levels fall below certain thresholds, aerobic respiration of organic carbon ceases and is replaced by denitrification and anammox processes. This results in a net conversion of fixed inorganic nitrogen into molecular nitrogen and, to a minor extent, nitrous oxide. Molecular nitrogen and nitrous oxide are inaccessible to most organisms, and are eventually lost to the atmosphere through outgassing (Codispoti and Richards 1976). This release of nitrous oxide is of some concern because of the very high greenhouse gas potential of nitrous oxide. The nitrogen loss processes lead to low nitrate-to-phosphate ratios which may influence pelagic ecosystems and biogeochemical fluxes in those regions where OMZ waters reach the well-lit surface layer.

Tropical OMZs in the eastern Atlantic and eastern Pacific oceans are generally considered to be connected to the surface

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ocean via the adjacent eastern boundary upwelling systems of the respective basins. This connection is thought to be very tight, and in simple models of the system it is often assumed that the OMZs supply most or all the water that reaches the surface in the coastal upwelling systems (Canfield 2006). However, for the coastal upwelling off Mauritania, Glessmer *et al* (2009) showed in a modeling study that only as little as 1% of the water reaching the upwelling passed through the OMZ. On the other hand, about 7% of the modeled OMZ waters were upwelled within 6 years.

Even if most of the upwelled water does not originate from the OMZs, OMZ waters still have a discernible influence on the surface water properties in coastal upwelling systems, because they mainly reach the surface ocean within those upwelling regions (Glessmer *et al* 2009). OMZ signatures are visible—both directly in the coastal and equatorial upwelling and further offshore—in tracers such as apparent oxygen utilization, nitrous oxide, and nitrate-to-phosphate ratios. These properties may trigger feedbacks such as nitrogen fixation (Deutsch *et al* 2007) or plankton species composition (Mills and Arrigo 2010).

There are two conflicting ideas of how coastal upwelling systems will develop under global warming. Either the enhanced temperatures over the continents and the associated strengthening of thermal lows and coastal winds can increase upwelling transport (Bakun 1990), or the enhanced density stratification can suppress upwelling. The relative proportions of these counteracting processes are not clear yet. Also, the connection of OMZs to the surface ocean does not only depend on the upwelling strength, since water can be drawn from different depth horizons depending on the density stratification.

Models used to investigate OMZs range from coarse-resolution coupled climate models, often including a simple biogeochemical model, to rather sophisticated biogeochemical models in box, one-dimensional or regional high-resolution three-dimensional configurations (Peña *et al* 2010, Zhang *et al* 2010). In either case, many processes that are known to have an influence on oxygen concentration are neglected. Complex high-resolution models can, for computational cost reasons, not be run in global setups needed to adequately represent changes in remote forcings due to global warming. Therefore, there is a gap in our knowledge: on the one hand, local processes—both biogeochemical and physical—are fairly well understood, on the other hand it is unclear how sensitive they are to global change. Here, we employ a coarse-resolution coupled ocean–atmosphere model to investigate the influence that changes in transport processes will have in the development and maintenance of OMZs.

Many authors recommend that OMZs, upwelling systems and the biogeochemistry at play are investigated in a combined fashion (Peña *et al* 2010, Zhang *et al* 2010). Obviously, coarse-resolution climate models do not represent all the physical processes that may have an influence on OMZs. The complex interactions of the upwelling systems with boundary currents, wind forcing, waves and mesoscale eddies cannot be resolved explicitly and have to be parameterized (Zhang *et al* 2010). However, such coarse-resolution climate models are the main tools for current projections into the future and the processes at play within such models need to be understood. While it has been suggested that increasing stratification is probably going to lead to enhanced hypoxia in a warmer world (Rabalais *et al* 2010), a more quantitative assessment in terms of global model simulations would be useful.

In this paper we use a coupled ocean–atmosphere model to investigate the connection of OMZs to the surface ocean changes under CO_2 doubling by comparing a current climate simulation with an ensemble of future climate simulations. This paper is structured as follows. In section 2 the model and methods are presented. Section 3 presents and discusses the results, and conclusions are drawn in section 4.

2. Methods

Three different model setups are compared in this study. First, a 'current climate' simulation, using a coupled ocean–atmosphere general circulation model, the Kiel Climate Model (KCM, Park *et al* 2009). Second, we use the same model except for doubled atmospheric CO_2 concentrations ('2 × CO_2'). And third, a simulation using KCM's ocean component forced by a prescribed atmosphere ('forced ocean') is used to assess the performance of the coupled model in terms of mean and variance of the simulated upwelling transport.

2.1. Climate and ocean simulations

KCM consists of an ocean–sea-ice general circulation model (NEMO, Madec 2008) coupled to an atmospheric general circulation model (ECHAM5, Roeckner *et al* 2003) with the OASIS3 coupler (Valcke 2003). No form of flux correction or anomaly coupling is used in fresh water and heat fluxes and wind stress.

The atmospheric model has a 3.75° × 3.75° (T31) horizontal resolution with 19 levels in the vertical. The horizontal resolution of the ocean model is based on a 2° Mercator mesh and is on average 1.3°, with enhanced meridional resolution of 0.5° close to the equator (ORCA2), and with 31 levels in the vertical where the box thickness ranges from 10 m near the surface to 500 m at depth. Vertical mixing is parameterized using the turbulent kinetic energy scheme of Gaspar *et al* (1990).

Two coupled experiments, previously presented by Park *et al* (2009), are analyzed: a 20th century equivalent control experiment that assumes atmospheric pCO_2 levels of 348 μatm, roughly corresponding to the year 1985, and an ensemble of eight 100 yr global warming simulations. In the latter, atmospheric pCO_2 is increased at 1% yr^{-1} until CO_2 has doubled after about 70 years, and atmospheric pCO_2 is kept stable thereafter for another 30 years. The responses of the meridional overturning circulation and the tropical Pacific to global warming in these simulations are reported in Park and Latif (2008) and Park *et al* (2009). Here we use five-daily averaged circulation outputs of the ocean components of the KCM for the 100 years of control simulation and the last 30 years of eight global warming simulations.

The forced ocean model uses the same resolution as in the KCM, but is forced by interannually varying atmospheric forcing for the period 1958–2004 (CORE, Large and Yeager 2004). A weak damping (300 days for a surface layer thickness of 10 m) is applied to the sea surface temperature and salinity, and full three-dimensional restoring is performed for both temperature and salinity in polar regions with a time scale of 181 days.

The KCM simulates the present climate relatively well, in particular the simulated tropical variability in terms of semi-annual and annual cycle and El Niño/Southern Oscillation variability agree well with observations (Park *et al* 2009). However, the KCM has systematic biases in representing the tropical and subtropical oceans, similar to other typical climate models. These biases include a cold sea surface temperature (SST) bias in the tropical Pacific and a warm SST bias in the eastern tropical Pacific/Atlantic and coastal upwelling regions. This error is common in most of the state-of-the-art climate models (e.g. IPCC 2007) but may hinder the correct representation of the circulation particularly in the tropics. This bias is currently being addressed (Wahl *et al* 2011).

2.2. Trajectory calculations

In a trajectory study of the model's ocean circulation field, the flow field is assumed to consist of floats, each associated with the same volume of water. The trajectory of a float is calculated from the instantaneous three-dimensional Eulerian velocity field of the model, $\vec{v}$, by numerical integration over the differential equation $\frac{\mathrm{d}\vec{x}}{\mathrm{d}t} = \vec{v}$, with the float position $\vec{x}$ (Döös 1995). For all calculations, velocities defined on the model grid are interpolated linearly in space and time onto the float position.

To calculate those trajectories, a modified version of the packet ARIANE[2] (Blanke and Raynaud 1997) was used. ARIANE is a FORTRAN code which computes 3D streamlines from a given velocity field, i.e. the output of an Ocean General Circulation Model. It is used as an offline diagnostic tool. In this study, five-daily averages of the model fields are used for the ARIANE simulations.

Simulated floats only feel the velocity resolved by the model and neglect explicit and implicit diffusion, which, however, affects tracers, e.g. temperature, salinity, oxygen or nutrients. According to a simple scaling analysis, the time scale t after which diffusive processes are starting to dominate can be estimated as $t = \frac{L^2}{K}$, with L being the typical length scale of the system and K being the average diffusivity in the area. Here, the time scale on which vertical mixing starts to dominate the transport of tracers from the OMZ to the mixed layer is deduced. Floats are only tracked until they reach the mixed layer, hence while they are in a low-diffusivity environment. A typical vertical length scale of this process is 100 m from the upper boundary of the OMZ to the surface mixed layer, and vertical diffusivities are typically well below 10^{-5} m^2 s^{-1}. This leads to a time scale of 32 years. Time scales longer than that or regions with enhanced diffusivities have to be investigated by other methods that do not neglect diffusion, like for example tracer release experiments. However on the decadal time scales investigated here, float and tracer release experiments lead to similar results (Glessmer 2010).

[2] http://stockage.univ-brest.fr/~grima/Ariane/.

2.3. Definition of the 'OMZs'

A number of different definitions have been used to locate and quantify the extent of OMZs, and different terms have been used to describe waters with low oxygen concentrations (Canfield and Thamdrup 2009, Rabalais *et al* 2010). Translating an oceanic definition of OMZs to a model is also not straightforward. Modeled oxygen fields are sensitive to the details of the physical and biochemical model components used and differ among models in both extent of and intensity of OMZs (Najjar *et al* 2007, Meissner *et al* 2005). Hence, the modeled OMZs are not necessarily located in the exact same regions as in the real ocean, and additionally often have too low oxygen concentrations.

In this study, OMZs are defined using the annual mean oxygen fields of the World Ocean Atlas 2005 (WOA05, Garcia *et al* 2006) interpolated onto the model grid. The critical assumption we cannot test until we have a reliable biogeochemical model that could be coupled to the circulation model is that the WOA05 oxygen fields are consistent with the model's velocity fields.

Numerical floats were deployed over the depth range from 197 to 240 m. This depth range was chosen in order to represent the average upper edge of the tropical North Atlantic OMZ. In the Pacific Ocean, the OMZ reaches much closer to the surface. However, runs with floats deployed at shallower depths (50–60 m and 169–197 m) showed that at those depths all waters reach the mixed layer within a few years to decades after deployment. So OMZ depths have to be chosen well below the mixed layer at all seasons.

To determine the lateral extent of the Pacific OMZ, oxygen concentrations lower than 10 μmol l^{-1} in the 175–225 m depth range of the WOA05 data set are used as criterion for 'the OMZ' in order to ensure that the whole volume of that water in which denitrification occurs is included. In the case of the Atlantic OMZ with its much higher oxygen concentrations, a concentration of 80 μmol l^{-1} is chosen to mark the lateral boundary of the OMZ. These definitions lead to similar OMZ areas at 200 m depth in the Pacific and the Atlantic Ocean (1.9×10^6 km^2). This definition is shown in figure 1 and lies well within the range of commonly used bounds.

3. Results

Floats can be used to deduce transit times of water masses. When a surface mixed layer criterion is used, the time from the release of a float in a certain region until the mixed layer criterion is met can be interpreted as the travel time. This can be a measure of the time that a subsurface water parcel has to travel from its initial position before it reaches the mixed layer, where exchange of properties with the atmosphere can occur. If applied to OMZ waters, this time scale can serve as a proxy for the minimal time for feedback processes between changes inside the OMZs and the mixed layer to take place. A density criterion of $\Delta\sigma = 0.1$ kg m^{-3} between the surface and waters below is used here to determine the surface mixed layer depth.

The simulated transit times of floats released in the OMZs to the surface mixed layer are shown in figure 2 for both the

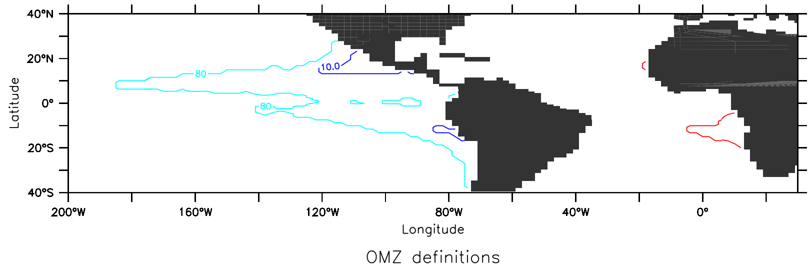

Figure 1. Definition of the 'OMZs' in this study. In the Atlantic, 'the OMZ' is laterally enclosed by the 80 μmol l^{-1} isoline in WOA05 oxygen in 200 m depth interpolated onto the model grid (red contours) and ranges vertically from 197 to 240 m. In the Pacific the depth range is the same, and laterally the OMZ is bounded by the 10 μmol l^{-1} isoline in WOA05 (dark blue contour). The light blue contour shows the 80 μmol l^{-1} (used as bound in the Atlantic) in the Pacific for comparison.

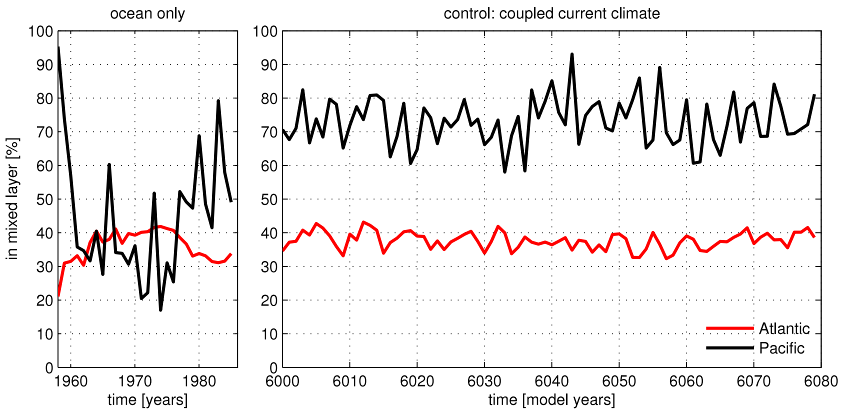

Figure 2. Percentage of floats reaching the mixed layer within 20 years of their release between 197 and 240 m depth in the Atlantic (WOA05 oxygen concentration below 80 μmol l^{-1}) and Pacific (WOA05 oxygen concentration below 10 μmol l^{-1}) OMZs plotted against the year of their release. The left panel shows the results of the forced ocean-only run, the right panel those of the coupled current climate control run. The red curves are for the Atlantic, and the black curves for the Pacific.

coupled model and the forced-ocean simulations. The average percentages of OMZ waters reaching the surface mixed layer within 20 years are very similar for the coupled 'current climate' and forced-ocean simulations. Because we expect the forced ocean model to have only small deficiencies in the simulation of wind-driven upwelling regions, this indicates a—for our purposes—reasonable representation of OMZs and coastal upwelling regions also in the coupled model. In both forced-ocean and coupled control runs about 38 $\pm$ 3% of the Atlantic OMZ floats reach the surface within 20 years, whereas the percentage is almost twice as high (75 $\pm$ 8%) for the Pacific OMZs. This suggests that under present-day conditions, the connection of the Atlantic OMZ to the surface ocean is weaker than that of the Pacific OMZ, even when only OMZ waters in the depth range of 197–240 m are considered.

Some interannual variability in the strength of the connection between OMZs and surface mixed layer is clearly seen in the simulations. In particular, in the tropical Pacific, the variability is somewhat larger in the ocean-only runs than in the coupled control runs. In addition to the interannual variability, the forced-ocean model shows long-term fluctuations and an initial adjustment after initialization in the early 1960s.

The coupled run has been integrated under constant atmospheric $p\mathrm{CO}_2$ for more than 500 years and is already closer to steady state. It shows a somewhat smaller interannual variability. Interannual variability in the percentage of floats reaching the surface mixed layer within 20 years turns out to be related to the mean density of the water in the deployment region at the time of the deployment. For the southern OMZ in the tropical Pacific, the density is strongly correlated with El Niño cycles: in El Niño years, the density stratification is strong and floats deployed in those years reach the surface ocean much more slowly than those deployed in other years. The model's north Pacific OMZ shows no strong correlations with climate indices, nor do the Atlantic OMZs.

We next investigate the connections between OMZs and the surface ocean in a warmer climate using the last 30 years of a global warming run at 2 $\times$ CO_2. In the absence of reliable information about the future evolution of the OMZs, we release simulated floats in the same volume delineated by present-day oxygen isolines in the depth range, 197–240 m, as used in the present-day simulation. Figure 3 shows the percentage of floats reaching the surface ocean within 20 years of their deployment in the OMZ. In the Atlantic Ocean, the connection on average weakens by 30% in the warmer climate. The standard deviations of each control and warming simulation do not overlap after the first approximately 9 years, indicating a substantial weakening of the connection under global warming. In the Pacific Ocean, the connection weakens by 24% on average, however the standard deviations due to interannual

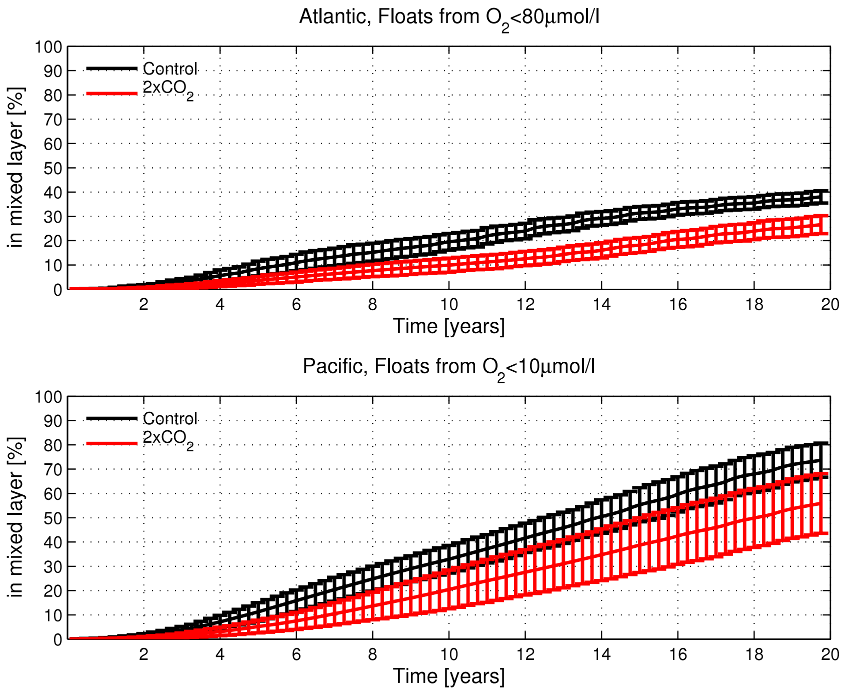

Figure 3. Percentage of floats released in the OMZ defined by WOA05 oxygen concentration at 200 m depth in the Atlantic below 80 μmol l^{-1} (upper panel) and in the Pacific below 10 μmol l^{-1} (lower panel) reaching the surface mixed layer. Current climate control (black) and ensemble mean of CO_2 doubling scenarios (red). The mean $\pm$ standard deviation is shown.

variability are much wider here than in the Atlantic Ocean and they overlap.

3.1. Atlantic

In the Atlantic, the area of the southern OMZ is approximately ten times larger than that of the northern OMZ. Hence it is not surprising that the southern OMZ contributes more to the waters from the OMZs reaching the surface mixed layer. A typical pathway from the south Atlantic OMZ to the surface ocean is a southward drift along the African coast, possibly recirculating in the area south of the OMZ, then crossing the Atlantic and entering the equatorial current system where recirculation can occur again. Floats from the south Atlantic OMZ mainly reach the surface mixed layer in the equatorial current system or in the recirculation south of the OMZ (figure 4). Floats from the north Atlantic OMZ reach the surface mixed layer in the coastal upwelling along Northwest Africa. Counter-intuitively, OMZ waters do not reach the surface mixed layer predominantly in the typical upwelling regions along the eastern boundaries and the equator. This behavior of the coupled control run is different from that of the forced ocean-only run where OMZ floats almost exclusively reach the surface in the upwelling regions (Glessmer *et al* 2009, Glessmer 2010).

In general, flow and upwelling pattern do not change much under global warming, although upwelling of OMZ waters in the recirculation of the equatorial current system is stronger in the control runs than in the 2 $\times$ CO_2 runs (figure 4). So what makes the connection decrease under global warming? Northern coastal upwelling stays largely the same since the winds do not change substantially between the control and the 2 $\times$ CO_2 runs. The equatorial upwelling decreases related to the reductions of the subtropical cells but is responsible for a very small part of the upwelled OMZ waters anyway. This suggests that increased stratification in a warmer climate may be responsible for a change in the source waters feeding the upwelling. This hypothesis is supported by a backward analysis of float trajectories: floats crossing 50 m depth in the upwelling boxes defined in figure 4 come from shallower depth horizons at 2 $\times$ CO_2 than in the control run. Although the simulated total upwelling transport through 50 m shows little change under global warming, the source regions of the upwelled waters change. This finding is consistent with the average depth of all floats 20 years after release in the OMZ being about 40 m deeper for the 2$\times$$CO_2$ run than for the control run.

3.2. Pacific

In the Pacific Ocean, the area of the northern OMZ is approximately six times larger than that of the southern OMZ. Accordingly, the northern OMZ contributes more to the waters from the OMZs reaching the surface mixed layer. A typical pathway from the northern OMZ to the surface mixed layer is a westward drift across the Pacific, turning back eastward somewhere between 150°W and 150°E, recirculating in the equatorial current system before upwelling in the equatorial current system or at around 12°–20° in the central Pacific Ocean (figure 4). Floats from the southern OMZ take one of three distinct pathways between the OMZ and the surface ocean. They can drift southward along the coast

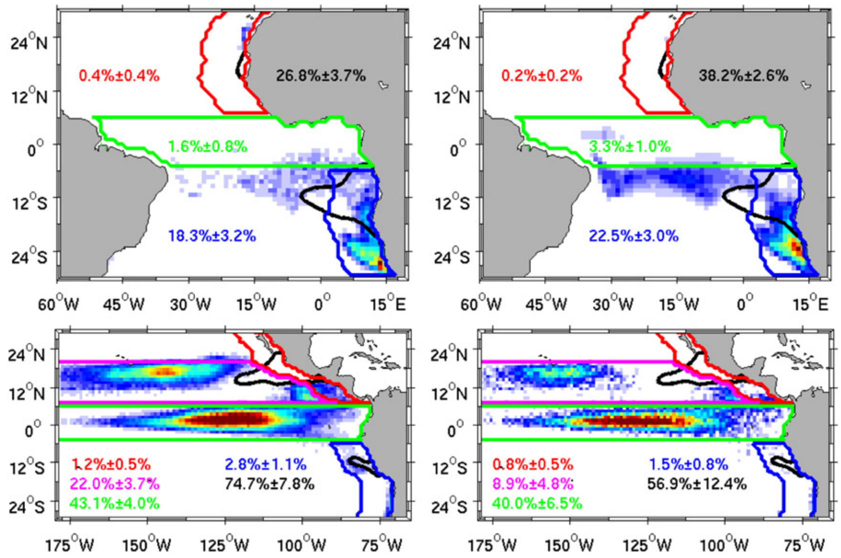

Figure 4. Mean amount of floats/tracer reaching the mixed layer within 20 years after release in the Atlantic (upper panels) or Pacific (lower panels) OMZ, gridded on a 1° × 1° grid and normalized. The colors range from no floats (white) to 0.2% per grid box (dark red). Left panels: coupled current climate control. Right panels: coupled model under 2 × CO_2. The numbers refer to the percentage of floats starting in the OMZs reaching the surface mixed layer in the northern coastal upwelling (red), the equatorial upwelling (green), in the southern coastal upwelling (blue) or anywhere (black). Floats were released between 197 and 240 m depth inside 'the OMZs' shown as black contours, defined by the WOA05 oxygen concentration below 80 μmol l^{-1} in the Atlantic and WOA05 oxygen concentration below 10 μmol l^{-1} in the Pacific.

and recirculate south of the OMZ, analogous to the Atlantic Ocean pathway. A second pathway is westward with a slight northward component. Floats taking this pathway reach the surface mixed layer in the equatorial current system. The third pathway is northwest from the OMZ directly into the equatorial upwelling. Under 2 × CO_2 the importance of the northern surfacing region (magenta box in figure 4) decreases substantially while the upwelling of OMZ waters in other regions decreases only slightly. Upwelling in the coastal and equatorial upwelling regions remains very similar between the control run and the 2 × CO_2 runs, although winds favorable for the northern coastal upwelling increase slightly in strength (not shown).

However, the relation between the curl of the wind stress and the volume transport through 50 m changes. In the northern coastal upwelling, the same wind stress curl results in more transport. Similarly to the southern coastal upwelling in the Atlantic, global warming induced strengthening of the stratification leads to a change in the source waters of the upwelling. The mean depth of floats 20 years after release in the OMZ is 10 m deeper for the 2 × CO_2 run than for the control run.

4. Conclusions

Oxygen minimum zones (OMZs) are locations where oxygen-sensitive processes may influence both the marine nitrogen budget and the formation of climatically relevant gases (e.g. nitrous oxide), with possible consequences on climate, marine ecosystems, biological production and associated marine carbon uptake. We have investigated possible future changes of the connection of OMZ waters to the sea surface in a warmer climate in a coupled climate model. The aim was not to reproduce regional properties as closely as possible, but to understand processes that act within a model system currently used to study climate change. We found the connection to decrease under global warming, in both the Pacific and Atlantic Oceans. This is mainly due to a change in large-scale ocean circulation that is involved in the change of atmospheric circulation due to global warming.

Although the eastern boundary upwelling systems do not show strong changes under global warming, equatorial upwelling systems as a pathway between the OMZs and the surface ocean are effectively sensitive to future changes through changes in the subtropical cell strength.

In the Pacific Ocean, the density difference between the depth at which floats are deployed (197–240 m) and the surface ocean increases. 20 years after deployment, floats released in the 197–240 m depth range of the OMZs are on average 10 m deeper in the 2 × CO_2 runs than in the current climate control runs.

In the Atlantic, shallower source waters feed the wind-driven upwelling and the OMZs in the depths that are investigated in this study become more isolated. Floats released in the 197–240 m depth range of the OMZs are, after 20 years, on average 40 m deeper after 20 years in the 2 × CO_2 runs than in the control runs.

The main limitation of the study reported here is that the model used does not include an interactive biogeochemistry. Thus, our data-based definition of the OMZ waters may not by fully consistent with the model's circulation. Specifically, floats are released in the same regions in the control and 2 × CO_2 runs, assuming no change in the location of the OMZs. The assumptions used in the current study will have to be tested in future work.

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