Simulated effects of southern hemispheric wind changes on the Pacific oxygen minimum zone

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A coupled ocean biogeochemistry-circulation model is used to investigate the impact of observed past and anticipated future wind changes in the southern hemisphere on the oxygen minimum zone in the tropical Pacific. We consider the industrial period until the end of the 21^{st} century and distinguish effects due to a strengthening of the westerlies from effects of a southward shift of the westerlies that is accompanied by a poleward expansion of the tropical trade winds. Our model results show that a strengthening of the westerlies counteracts part of the warming-induced decline in the global marine oxygen inventory. A poleward shift of the trade-westerlies boundary, however, triggers a significant decrease of oxygen in the tropical oxygen minimum zone. In a business-as-usual CO_2 emission scenario, the poleward shift of the trade-westerlies boundary and warming-induced increase in stratification contribute equally to the expansion of suboxic waters in the tropical Pacific.

1. Introduction

Oxygen is a sensitive indicator for physical and biological changes in the ocean. Its supply can be affected by changes in surface temperature and circulation. The solubility of oxygen decreases as temperature rises, so that warming alone would result in a decline of the global oxygen inventory with time. A decrease in oxygen levels has been observed during the past decades [e.g. Stramma et al., 2012a], in particular in the tropical oceans including the oxygen minimum zone (OMZ) of the eastern equatorial Pacific (EEP). Changes in solubility can, however, explain only about a quarter of the observed oxygen decline [Bopp et al., 2002]. The reminder has to be explained by changes in physical transport or biological source-sink processes.

Global warming tends to enhance stratification and also affects wind patterns, which both can alter the ventilation of the thermocline, biological production and, eventually, respiration and oxygen consumption. Until now the contributions of the individual processes to the observed oxygen decline are not well understood. In addition, the presence of decadal atmospheric variability, such as the Pacific Decadal Oscillation [Deutsch et al., 2014], makes it further difficult to detect the attribution of long-term trends. Improving our mechanistic understanding of past and present oxygen variations is a major challenge for making reliable projections of how tropical oxygen levels may evolve in the future.

Model simulations allow a straightforward investigation of the individual processes that may lead to changes in marine oxygen fields. Previous simulations that employed climatological winds and only applied a CO_2 dependent increase in temperature and buoyancy forcing, consistently showed a decrease of the global oxygen inventory with time [Oschlies

et al., 2008]. They failed, however, to reproduce the observed patterns of oxygen changes and in particular the observed decrease in the tropical thermocline [Dietze and Loeptien, 2013; Oschlies et al., 2008; Stramma et al., 2012a]. Stramma et al. [2012a] showed that simulated oxygen changes in the tropical thermocline are very sensitive to the choice of the applied wind stress forcing. The potential impact of changes in the tropical trade winds has been investigated recently by Ridder et al. [2014], who found a direct correlation between changes in the strength of the trade winds and the spatial extent of the OMZ. This agrees with Duteil et al. [2014] who suggest that the strength of the wind-driven subtropical-tropical cells is closely correlated with thermocline oxygen levels in the EEP.

While these studies focussed on impacts of local wind changes on oxygen levels in the tropical thermocline, we here investigate the potential role of remote wind forcing: Observation-based atmospheric reanalysis products indicate a strengthening and a poleward shift of the southern westerly winds since the 1970s [Thompson and Solomon, 2002]. This is in line with an observed shift of the southern annular mode (SAM) towards a higher index state [Thompson and Solomon, 2002; Marshall, 2003]. Regarding impacts on the ocean, Saenko et al. [2005] show that an increase and poleward shift of the westerlies result in a more intense meridional overturning circulation (MOC) in the southern hemisphere. This is accompanied by a poleward expansion of the subtropical gyre circulation and a strengthening of the Antarctic Circumpolar Current (ACC). Roemmich et al. [2007] describe an observed intensification of the South Pacific subtropical gyre and suggest a link to changes in the mid-latitude winds in response to a decadal or longer-term increase in the SAM. The intensification of the Southern Ocean wind stress curl between the 1970s

and early 2000s has also been related to the observed strengthening of the southward East Australian Current and of the northward interior transport [Cai, 2006]. Changes in the subtropical gyre circulation may not only affect the western Pacific boundary currents [e.g. Ridgway and Hill, 2009], but also the eastern Pacific boundary currents along with the water mass transport into the OMZ of the EEP.

In this study we go beyond wind-induced impacts on ocean physics and evaluate the impact of southern hemispheric wind changes on marine oxygen distributions. In particular, we distinguish the effect of wind changes within the zonal band of the westerlies from wind changes in the entire southern hemisphere that also include a poleward expansion of the tropical trade winds. We hypothesize that changes in the strength of the westerlies mainly affect the MOC and consequently the water mass formation rates of southern hemispheric intermediate waters and mode waters. Changes in the meridional extension of the trade winds, on the other hand, are expected to affect the subtropical gyre circulation and, in turn, the ventilation of the subtropical thermocline and the associated oxygen supply to the OMZ.

The paper is organized as follows: Section 2 describes the numerical model and the experiments performed. In section 3, we discuss the model results and section 4 provides a summary and conclusions.

2. Model

We use the University of Victoria (UVic) Earth System Climate model [Weaver et al., 2001] version 2.9. The model includes a global three-dimensional primitive-equation ocean model [Pacanowski, 1995], a single-level atmospheric energy-moisture balance model

[based on Fanning and Weaver, 1996], a dynamic-thermodynamic sea ice model, a marine ecosystem model [Keller et al., 2012] and a terrestrial vegetation and carbon cycle model. All model components use a horizontal resolution of 1.8° latitude $\times$ 3.6° longitude. The vertical grid of the oceanic component has 19 z-levels with a surface thickness of 50 m increasing to 500 m at depth.

The ocean model includes isopycnal mixing and the Gent and McWilliams [1990] parameterization of eddy-induced tracer transport. It is coupled to the atmospheric energy-moisture balance model and to the dynamic-thermodynamic sea ice model. The spin-up time is 11,000 years until equilibrium is reached under preindustrial atmospheric CO_2. A detailed description of the model configuration is given in Keller et al. [2012].

In all experiments we employ a background isopycnal diffusion coefficient of $1200\,m^2s^{-1}$ and additionally use the parameterization of the unresolved equatorial current system as described in Getzlaff and Dietze [2013] where the zonal (anisotropic) isopycnal diffusion coefficient is increased by $50\,000\,m^2s^{-1}$ in the equatorial region between 5°S and 5°N. This parameterisation improves the global representation of temperature, salinity and oxygen by reducing spurious tracer gradients in the equatorial Pacific. This yields a more realistic representation of tropical oxygen distributions, including the patterns of low oxygen environments. The standard model configuration is forced by monthly climatological NCAR/NCEP wind stress fields.

In all experiments, we apply anthropogenic CO_2 emissions according to the RCP 8.5 business-as-usual scenario. For diagnostic purposes, an ideal age tracer and three water mass tracers were implemented that trace the pathways of Subantarctic mode water

(SAMW), Antarctic intermediate water (AAIW) and Antarctic bottom water (AABW) in our model. The three artificial tracers are continuously set to values of 1 in the surface layer between 41.4°S and 52.2°S, 52.2°S and 66.6°S, and south of 66.6°S, respectively. Outside their respective release sites the tracers are reset to zero in the surface layer. The meridional bounds are based on pragmatic reasoning and are chosen to ensure that the respective water mass formation regions are comprised throughout the transient simulations.

In the reference simulation, REF, monthly climatological NCAR/NCEP wind forcing is applied. In the first sensitivity study, WIND, we add a 300-year record of monthly meridional and zonal wind stress anomalies in the southern hemisphere to the monthly climatology. The wind stress anomalies (see Figure 1 a) are the same as used by Spence et al. [2010] and described in greater detail in Fyfe et al. [2007]. These monthly means are derived from 10 different global climate models from the World Climate Research (WCRP) Coupled Model Intercomparison Project (phase 3; CMIP3) and corrected by a small equatorward bias [Fyfe and Saenko, 2006]. Changes in the wind fields include an intensification of the maximum zonal wind stress by about 25% and a southward shift by about 3.5° until 2100 [see Spence et al., 2010], as well as a southward shift of the boundary between southern westerlies and trades in the tropics.

In order to differentiate between effects resulting from wind stress changes within the meridional extent of the Southern Ocean westerlies and effects that modulate the tropical trade winds, we include a second sensitivity experiment, posWIND, where only the positive zonal (directed eastward) wind stress anomalies are added to the climatological

forcing. The resulting changes of the wind stress curl in experiment posWIND occur only in the polar and subpolar region south of 40° S (Figure 1 b, red line).

3. Results

In response to anthropogenically induced global warming, the globally integrated marine oxygen inventory of 256.6 Pmol simulated by experiment REF decreases by 4.8% until year 2100 (Figure 2a). This overall deoxygenation is damped by 15% in WIND and by 30% in posWIND, such that average oceanic oxygen concentrations at the end of the simulation remain higher in WIND and posWIND than in experiment REF. This can be explained by the wind-driven increase of the MOC in experiments WIND and posWIND and associated increase in the formation rate of oxygen-rich mode and intermediate water masses [Liu and Wu, 2012; Downes et al., 2011] and deep water masses, which all represent important pathways for the ventilation of the global ocean with oxygen.

The strengthening of the MOC is brought about by positive wind stress curl anomalies applied in both WIND and posWIND simulations between 40° and 60° S (see Figure 1b). This is illustrated in Figure 2b-d by a deepening of the 20 Sv isoline of the zonally integrated overturning stream function from ∼1500m in REF to ∼2500m in WIND and posWIND. Note that the upwelling branch of the MOC is essentially identical in WIND and posWIND because, in our model, the Southern Ocean upwelling is determined by the strength and position of the westerlies.

Relative to the reference simulation, the formation rates of SAMW, AAIW and AABW increase by about 40%, 50% and 30%, respectively, in the WIND experiment. For the posWIND experiment, the formation rates increase by 20%, 50% and 70%, respectively.

The formation rates of the AAIW are directly linked to changes in the strength of the westerlies, which are the same in WIND and posWIND. The shift of the boundary between westerlies and trades (difference between WIND and posWIND) results in a stronger wind stress curl anomaly between 40°S and 53°S in experiment WIND, which in turn yields a larger increase in SAMW formation than in posWIND.

The response of AABW formation to the shift of the trades–westerlies boundary in WIND is substantial (40% less than compared to posWIND). In both wind scenarios the upwelling, which feeds both the AABW formation in the south and the mode and intermediate water formation further north, is very similar. The northward transport of surface waters from the polar front to the SAMW formation sites is, however, increased by the wind shift of the trade-westerlies boundary in WIND compared to posWIND. The combination of similar upwelling and increased surface water mass transport to the north results in less southward supply to the AABW formation sites and thus in reduced increase of AABW formation in WIND than in posWIND. The changes in the water mass tracers (Figure 2b-c) illustrate that an increase in deep water formation is more important for the global oxygen inventory than an increase in mode water formation.

Figure 3a shows the linear oxygen trend for the time period 1960–2010 at 300 m depth for simulation REF. Contrary to the observed decrease in oxygen, but consistent with earlier UVic model simulations [Stramma et al., 2012a], simulation REF yields slightly increasing oxygen concentrations over large areas of the tropical thermocline including the OMZ. Because simulation REF applies climatological wind fields, the changes in the

oxygen fields are solely driven by buoyancy changes that derive from anthropogenic-CO_2 induced temperature and salinity changes.

When, in addition to CO_2 emissions, changes in southern hemispheric wind fields are applied in experiment WIND, the simulated increase in tropical oxygen concentrations over the 1960–2010 time period becomes significantly smaller (Figure 3b). Applying only the intensification of the southern westerlies in experiment posWIND (Figure 3c), the oxygen trend is close to that of experiment REF. We conclude that the changes in tropical ocean oxygen trends in experiment WIND are, at least for the time period 1960 to 2010, predominantly caused by the southward shift of the boundary between trades and westerlies rather than by the intensification of the Southern Ocean westerlies.

The reduction in tropical thermocline oxygen levels in simulation WIND relative to REF seems, at first sight, contradictory to the previously shown wind-induced increase of the global oxygen inventory. However, the models' ideal age tracers reveal that it is the strengthening and southward shift of the subtropical gyre circulation that leads to a decrease of the northward transport of newly-ventilated oxygen-rich waters of subantarctic origin along the eastern coast of the South Pacific into the OMZ: Figure 3d shows the ideal age (colored contour) and the circulation (vectors) at 300m depth for REF, with the black contour line denoting the equatorward boundary of the subtropical gyre circulation. A southward shift of this boundary in response to the southern hemispheric wind anomalies applied in WIND leads to a strengthening and a southward shift of the subtropical gyre circulation and an increase in simulated ideal age north of this boundary (Figure 3e). The increase in simulated ideal age north of 20°N amounts to up to 29 years in 2100

(Figure 3d-f). When the applied wind anomalies are restricted to the southern westerlies in experiment posWIND, changes in the subtropical gyre circulation and in ideal age are much reduced compared to those of the WIND simulation (Figure 3f).

To complete our analysis, we now investigate possible downstream effects of changes in the formation rates of SAMW on the tropical oxygen minimum zone. In the steady-state simulations of Palter et al. [2010], 30-60% of the water on the 26.8 isopycnal in the EEP between 30°S and 30°N originate from SAMW (their Figure 6) and suggest that the associated nutrient transport could be sensitive to climate change. In our model experiments, SAMW also circulates northward from the formation area along the 26.8 isopycnal and we find a steady-state average contribution of ∼20% between 30°S and 30°N, slightly lower than Palter et al. [2010]. In the EEP the 26.8 isopycnal is located at a depth of approximately 280-310 m under pre-industrial conditions. Given that the mean water age, derived from the ideal age tracer, in the suboxic waters of the EEP at 300 m depth is 276 years, we suggest that an increase of the Southern Ocean overturning circulation does not have a large impact on the OMZ dynamics on time scales of 50 years (which is currently the time span covered by observations used to estimate oxygen trends). Indeed, after 50 years only 5% of the newly formed SAMW reach the EEP in our experiment. Since there is no significant difference in the depth of the 26.8 isopycnal in the EEP between experiments REF and posWIND we conclude that planetary wave processes forced remotely by a perturbation in the Southern Ocean can, to first order, be neglected in the analysis of southern hemispheric wind impacts on the tropical OMZ.

The sensitivity to southern hemispheric wind anomalies is even larger for simulated suboxic volume changes until the end of the 21st century. Figure 4 shows the suboxic volume of the Pacific Ocean, here defined as water with oxygen concentrations smaller than 10 mmol m^{-3}. In REF, we find an increase of the suboxic volume of $\sim$36% until 2100. Note that the suboxic volume expands already during 1960–2010, when all simulations still show some local oxygen increase in the tropical thermocline (Figure 3a-c). Applying the full southern-hemispheric wind anomalies in WIND results in an increase of the suboxic volume twice as large as in REF (total increase of $\sim$72%), whereas a mere change of the southern westerlies (posWIND) has negligible effect on suboxic volume changes compared to experiment REF. This indicates that observed and expected 21st century changes in the meridional extension of the tropical trade winds are as important for suboxic volume changes as CO_2-induced atmospheric heat flux changes of a business-as-usual emission scenario.

4. Summary and Conclusion

In our study we investigate the impact of changes in the southern hemispheric wind fields on global oxygen as well as on the extension of the tropical OMZ relative to changes forced by CO_2-induced atmospheric buoyancy flux changes only. The changes in the southern hemispheric wind fields, which are in line with an observed shift of the SAM, are a combination of a strengthening and poleward shift of the southern westerlies and a poleward shift of the boundary between southern westerlies and tropical trade winds.

Our results confirm that the Southern Ocean plays an important role for the global ocean oxygen supply. We show that a strengthening of the southern westerlies, that leads

to an increase of the water formation rates of the oxygen-rich deep and intermediate water masses, can counteract part of the warming-induced decline in marine oxygen levels. The wind-driven intensification of the Southern Ocean meridional overturning circulation in both wind experiments leads to an increase in the global oxygen supply (Figure 2a). These results indicate that changes in the formation of deep water are crucial for changes in the global oxygen inventory. While the strength of the westerlies is identical in simulations WIND and posWIND, the southward shift of the boundary between westerlies and trades in WIND results in a larger increase of SAMW production and a smaller increase of deep water formation and associated oceanic oxygen supply.

The southward shift of the boundary between westerlies and trade winds leads to an intensification and a southward shift of the subtropical gyre circulation. Associated with this is a decrease in northward water mass transport along the eastern margin into the shadow zones of the subtropical gyre and thus into the OMZ. Our model simulations reveal that changes in the meridional expansion of the tropical trade winds have a significant impact on the evolution of the suboxic volume in the tropical OMZ during the 21^{st} century: The increase in suboxic volume in experiment WIND (72%) is twice as large as in the buoyancy-only driven experiment REF (36%), whereas a mere change of the southern westerlies, as in posWIND, does not alter the suboxic volume significantly with respect to experiment REF.

Although the total change applied to the model's trade winds is small compared to the climatological wind forcing, the impact on the 21^{st} century OMZ dynamics is as large as the impact of buoyancy driven changes forced by CO_2-induced atmospheric heat flux

changes alone. Our study thus illustrates the importance of realistic wind forcing for adequate modeling of thermocline biogeochemical tracer distributions. Changes in the meridional extension of the trade winds can also be driven by other processes, such as changes in the Pacific Decadel Oscillation, ENSO or by local weather changes, which are not necessarily restricted to the southern hemisphere and will have to be included in future research.

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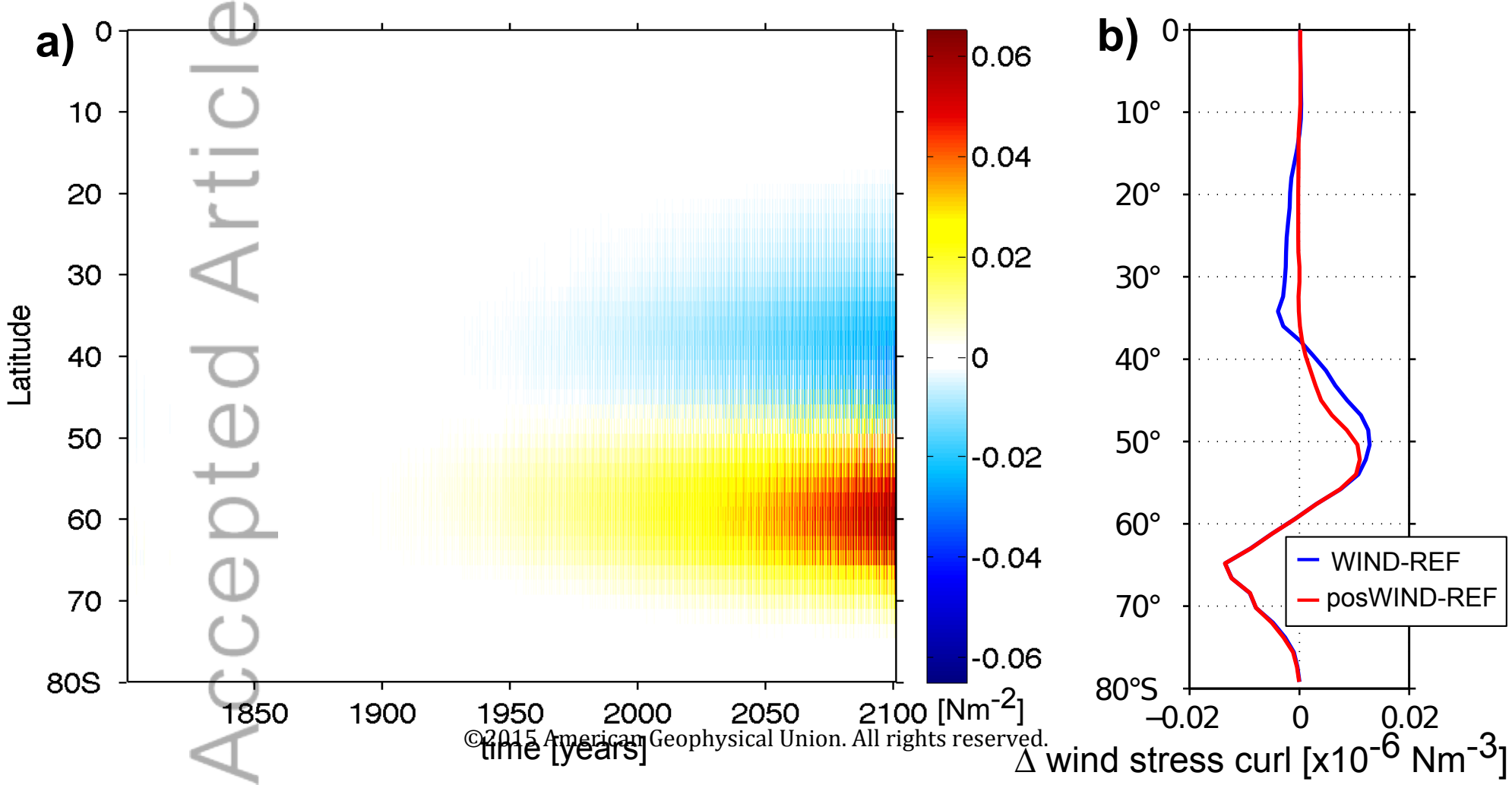
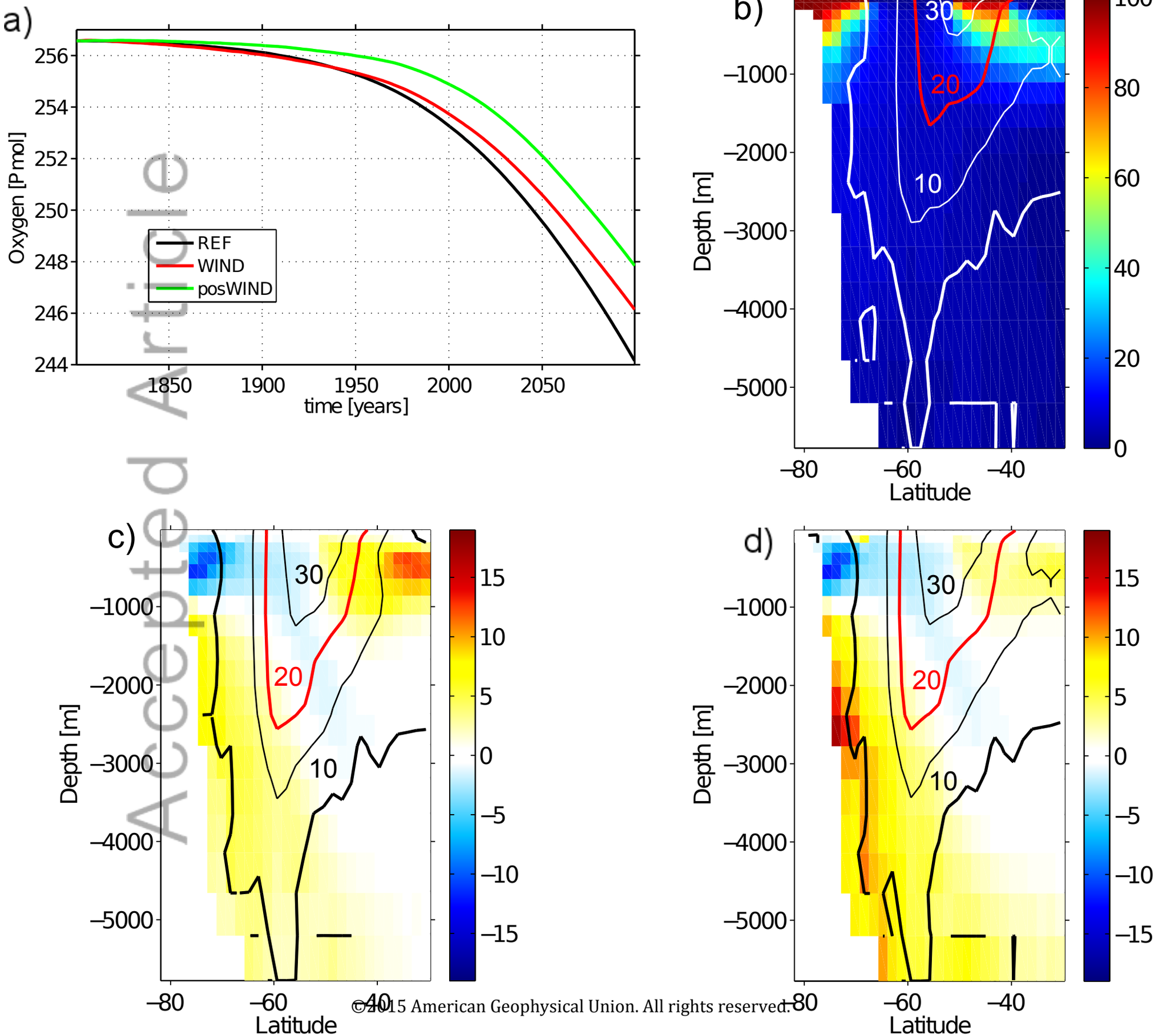
Figure 1. a) Zonal average of monthly zonal wind stress anomalies in Pa applied in the model simulations. b) Zonal average of the annual mean wind stress curl anomaly for experiments WIND (blue) and posWIND (red) in year 2100.

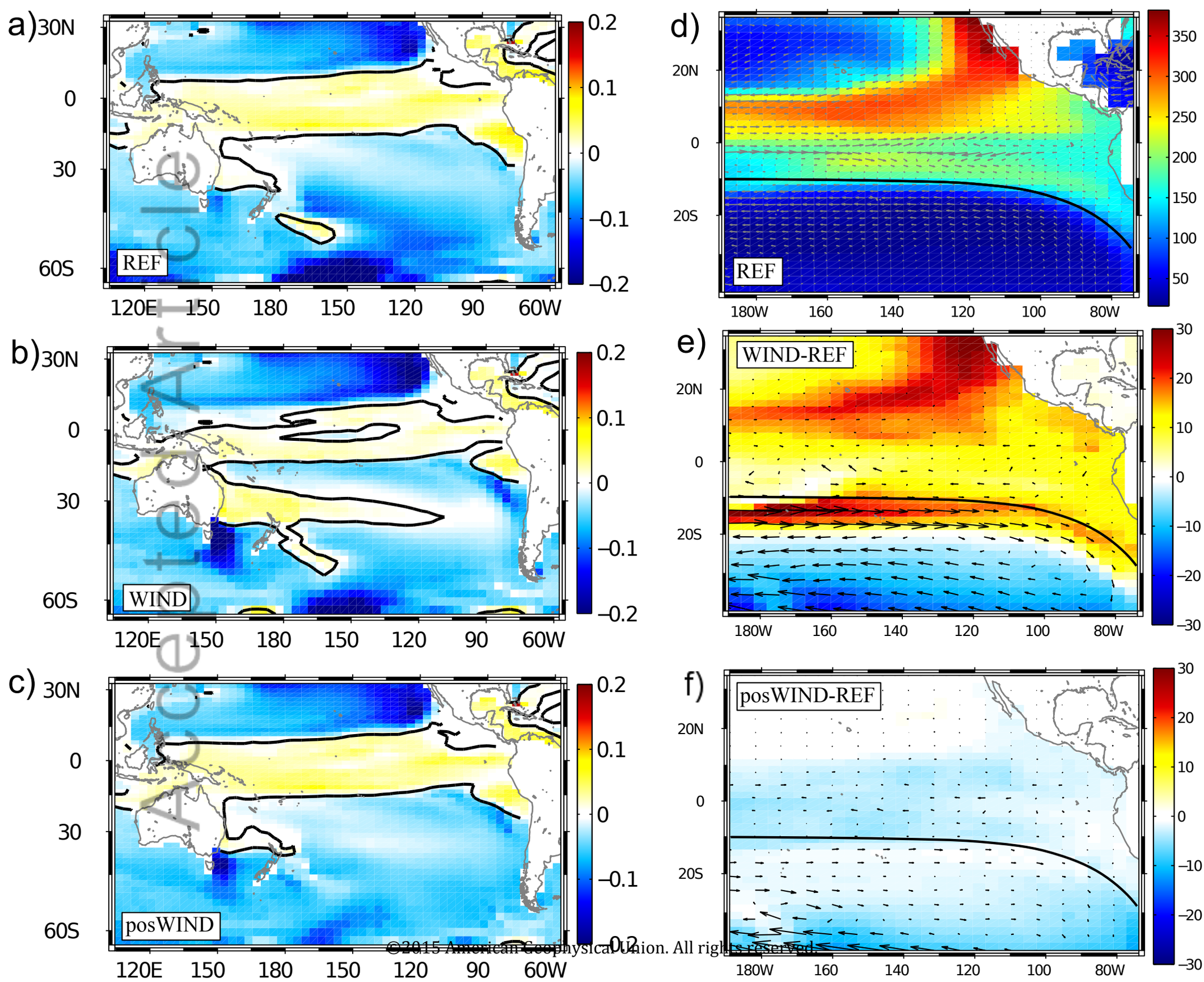
Figure 2. a) Global oxygen inventory in Pmol. The bottom panels show the simulated Eulerian Southern Ocean meridional overturning in Sv in year 2100 (contour): b) REF, c) WIND and d) posWIND. In b) the colored background shows the distribution of the sum of the zonally averaged idealized SAMW and AABW tracers in % in REF for year 2100, c-d) show the differences in % for WIND-REF and posWIND-REF, respectively, for the sum of the zonally averaged idealized SAMW and AABW tracers.

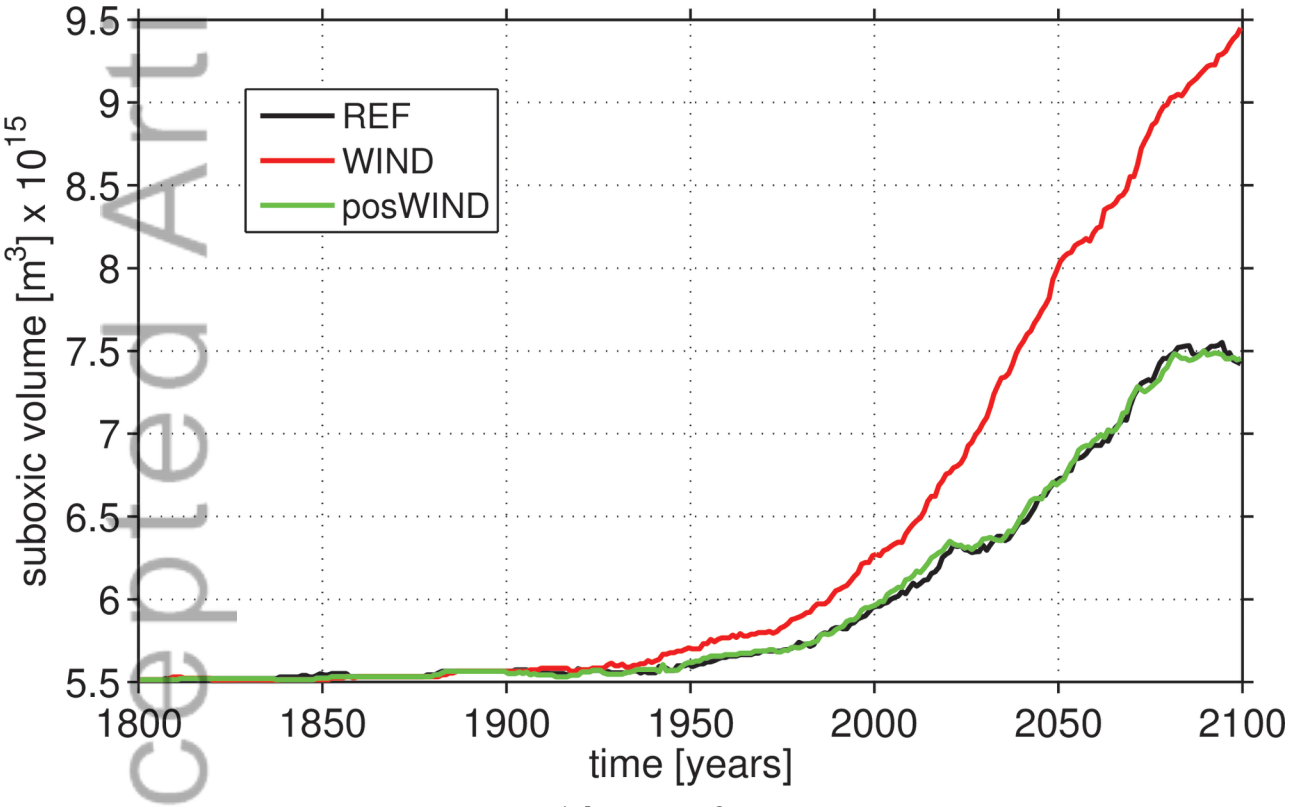
Figure 3. The left-hand panels show the oxygen trend (mmol m^{-3} $year^{-1}$) at 300 m depth for 1960–2010 a) REF, b) WIND and c) posWIND. Negative trends indicate a decrease in oxygen. The right-hand panels show the ideal age in years and velocity vectors at 300 m depth in year 2100 for d) REF, e) difference WIND-REF and f) difference posWIND-REF. Positive values in b) and c) indicate a larger ideal age. The black contour line is the same in all three panels and shows the equatorward boundary of the subtropical gyre in REF, here defined as the location with zero zonal velocity.

Figure 4. Simulated suboxic volume [m^3] of the Pacific Ocean, defined as water hosting O_2 <10 mmol m^{-3}, as a function of time.









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