

Author's answers to Anonymous Referee #1

This is an important manuscript presenting data from repeat sections in the Southern Ocean south of Australia. The data analysis is comprehensive and the results are interesting and seem to be robust; they can be compared with other studies from the Southern Ocean, thus completing the view of this vital ocean region.

Thank you very much for your words.

Actually, I think there are even a few more studies that have recently appeared and addressing similar issues in other areas of the Southern Ocean, which the authors could incorporate in the discussion of the results.

We provide comparisons to many-recent works (12 studies published between 2007 and 2017, 9 of them since 2014). If the referee recommends comparison to specific works beyond these, we are open to consider it.

The authors explain their results through the intensification of winds due to changes in the SAM. Their repeats cover the time period 1995 to 2011. However, they also write, almost at the beginning of the Discussion: "Several studies have reported a trend in the SAM toward its positive phase from the 1960s until the 2000s (Thompson and Solomon, 2002; Marshall, 2002, 2003; Lenton and Matear, 2007; Sallée et al., 2008)." During at least the second half of the time period, the SAM has not been in its positive phase anymore, and thus there will probably not be elevated winds anymore, which will not enhance upwelling. I encourage the authors to identify this and add comments to the manuscript.

The referee is correct. The SAM does not present a constant positive phase from 2000. However, it does exhibit considerable interannual variability, including, for the years 2008 and 2011 (two last occupations of SR03), relatively high SAM index values comparable to those at the end of the positive trend (<https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based>), indicating strong winds over the region. This is shown in Figure A2, which will be added in the supplementary material:

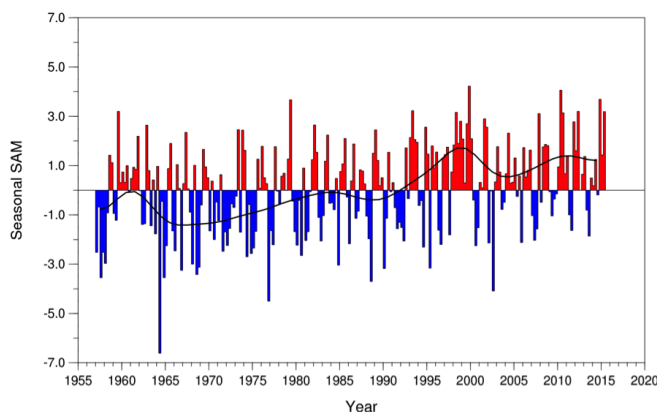


Fig. A2. Seasonal values of the observation-based SAM index. The smooth black curve shows decadal variations. Figure obtained from Marshall, Gareth & National Center for Atmospheric Research Staff (Eds). "The Climate Data Guide: Marshall Southern Annular Mode (SAM) Index (Station-based)." Retrieved from <https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based>.

Lines 27-29 of the Abstract will be corrected to:

“From all our results, we conclude a scenario of increased transport of deep waters into the section and enhanced upwelling at high latitudes for the period between 1995 and 2011 linked to strong westerly winds.”

Line 23 in the Discussion section will be changed to:

“ ... linked to strong westerly winds.”

At the end of the first paragraph of the Discussion section we'll add:

“From the 2000s on, the SAM index no longer presents a positive trend but, although exhibiting considerable interannual variability (Fig. A2 in the supplementary material), the SAM index remains in its positive phase, favouring strong winds over the region.”

Although all cruises used for the analysis were conducted around summer, they were not in the same month. Actually, data may be 3-4 months apart. Certainly, in the deeper water masses, this will not have a big effect on the results. However, for the surface and sub-surface layers the seasonal changes in biologically-mediated properties are large and thus this is likely to have an effect on the computed rates. I think this caveat should be treated in the manuscript. Please comment on this and analyze the possible and expected effects on the results.

The effect of the seasonal variability is implicitly included in the errors of the trends and strongly reflected in the RMSE values within each water mass. That is why we only show statistically significant trends.

To clarify further, we'll change lines 14-15 of page 7 (section 3.3) to:

“We show the value of the root mean square error (RMSE or square root of the variance of the residuals), which can be interpreted in large part as unexplained variance caused by short-time scale processes including the different seasonal timings of the cruises. RMSE has the same units as the response variable.”

P1, line 11: Is this the correct symbol for neutral density (also at other places in the manuscript)?

No, it's not. Thanks for noticing. The epsilon will be changed to a gamma throughout the reviewed manuscript.

P2, line 6 “ : : : and ultimately upwell close to the Antarctic Shelf” I think this only holds for part of this water, and possibly not even the major part. Please change the wording to take that into account.

The referee is right. We'll modify the text in page 2 lines 5-6 to:

“...and ultimately upwell between the Southern ACC Front and the Polar Front.”

P2, line 11 I suggest a modified sentence: Within the eastward flow of the ACC major water exchange between the three ocean basins takes place.

Thanks. We accept this modification.

P2, line 16 Because of twice the word “that” in this sentence I suggest : : : water mass properties and this may complicate : : :

Thanks. We’ll correct this.

P2, line 19 I think it is fair to cite older work of observationalists here, which actually laid the basis for this knowledge.

You are right. Two more references will be added:
“Sabine et al., 2004; Gruber et al., 2009”

P3, line 12-13 Change to : : : reported an increase in CANT uptake : : :

Thanks. We’ll correct this.

P3, line 16 delete “of the”

Thanks. We’ll correct this.

P3, line 23 Change to : : : one of the most revisited sections in the Southern Ocean.

Thanks. We’ll correct this.

P3, line 23-25 This sentence is an anacoluthon. Please correct.

Sorry for that. The sentence will recover the missing verb:

“Trends in oxygen (O_2), nutrients, and the carbon system parameters, i.e., DIC, total alkalinity (TA), anthropogenic carbon (C_{ANT}), total pH (pH_T) and % aragonite saturation (Ω_{AT}) were estimated for the period 1995-2011, when both DIC and TA measurements are available.”

P3, line 31 This concerns surface waters, I presume. Please add that term.

Yes, you are right. We’ll change line 31 in page 3 (section 2) to:

“separates warm, salty subtropical surface waters from cooler and fresher sub-Antarctic surface waters.”

P4, line 30 Is there a reference for this?

Yes, it was included in the previous phrase. The reference (*Rintoul, 1998*) will be added in this phrase as well.

P5, line 13-15 You only give the precision for DIC and TA measurements. Please also supply the accuracy, which is much more important here. It should be less good than the precision.

Thanks for noticing. We’ll change the phrase to:

“The precisions and accuracy of DIC and TA measurements improved slightly on more recent sections, and for all sections were better than $\pm 2 \mu\text{mol kg}^{-1}$, for both variables, based on analysis of duplicate samples and certified reference material”.

P6, line 2 combined with and

Thanks. We'll correct this.

P7, line 12 : : : defined by their $\text{I}\check{\text{S}}\text{n}$ condition (Table 2).

Thanks. We'll add this.

P8, line 8-9 “Nevertheless, long-term trends in O₂ due to circulation and remineralization processes have not yet been reported.” This is not correct. See:

Matear, R. J., A. C. Hirst, and B. I. McNeil (2000), Changes in dissolved oxygen in the Southern Ocean with climate change, *Geochem. Geophys. Geosyst.*, 1, 1050, doi:10.1029/2000GC000086. (cited in the present manuscript)

van Heuven SMAC, Hoppema M, Jones EM, de Baar HJW, 2014. Rapid invasion of anthropogenic CO₂ into the deep circulation of the Weddell Gyre. *Phil. Trans. R. Soc. A* 372: 20130056. <http://dx.doi.org/10.1098/rsta.2013.0056>

We agree with the referee that this phrase is not correct and that our summary of previous work on this issue was not complete. The intention was to indicate that statistically significant trends *different from zero* in surface waters had not been reported, rather than that no investigations had occurred. With respect to the two studies mentioned, we accordingly note that neither found statistically significant trends in surface waters (except in the deepest layer of waters in the Weddell Sea in Van Heuven et al., 2014).

In order to clarify this, we'll change the text in 3.3 to (new text is underlined):

“The term $\frac{\partial \text{DIC}^{\text{BIO}}}{\partial t}$ can be influenced by changes with time of alkalinity due to changes in the rate of carbonate precipitation/dissolution and of AOU due to changes in the rate of remineralization and in circulation. In the present study only surface waters of the SR03 section present changes DIC^{BIO} between 1995 and 2011. Numerous studies have reported a strong influence of biological communities in the seasonal cycle of dissolved O₂ in surface waters (Bender et al., 1996; Moore and Abbott, 2000; Sambrotto and Mace, 2000; Trull et al., 2001a). Interannual variability in O₂ in upper layers of the Southern Ocean have also been related to changes in the entrainment of deeper waters into the mixed layer due to the mixed layer depth variability (Matear et al., 2000; Verdy et al., 2007; Sabine et al., 2008; Sallée et al., 2012). Although some studies found long-term decreases in O₂ due to circulation in deep waters of the Weddell Sea (van Heuven et al., 2014*) and for the first 1000 m of the global ocean (Helm et al. 2011**), significant long-term trends in O₂ due to circulation and remineralization processes have not yet been reported for surface waters of the Southern Ocean.”

*van Heuven, S., Hoppema, M., Jones, E.M., de Baar, H.J.W.: Rapid invasion of anthropogenic CO₂ into the deep circulation of the Weddell Gyre. *Phil. Trans. R. Soc. A* 372: 20130056. <http://dx.doi.org/10.1098/rsta.2013.0056>, 2014.

** Helm, K. P., Bindoff, N.L., and Church, J.A.: Observed decreases in oxygen content of the global ocean, *Geophys. Res. Lett.*, 38, L23602, doi:10.1029/2011GL049513, 2011.

We'll also add some comments in section 5, (after first paragraph in page 13) in order to acknowledge previous efforts:

“In terms of the change in oxygen, Helm et al. (2011) found an average decrease in the concentration of O₂ between 100 and 1000 m from 1970 to 1992 of $\sim -0.23 \mu\text{mol l}^{-1}$ for the Southern Ocean (27% of the estimated global average change, $-0.93 \pm 0.23 \mu\text{mol l}^{-1}$). Considering the volume of the first 1000 m of the water column of the Southern Ocean to be $19400 \cdot 10^9 \text{ l}$ (obtained using ETOPO1 doi:10.7289/V5C8276M) and the volume of the first 1000 m of the SR03 section to be $2700 \cdot 10^9 \text{ l}$, the

decrease of O₂ found by Helm et al. (2011), if constant in time, would correspond to a decrease of ~ -1.7 μmol l⁻¹ yr⁻¹. We only found changes in oxygen within the surface water mass layers (STCW, AASW and AASW_{upw}) that approximately fill the first 300 m of the water column of the SR03. Then, the decrease of ~ -1.7 μmol l⁻¹ would correspond to an average change of O₂ of ~ -0.32 μmol kg⁻¹ yr⁻¹ for surface waters of the SR03. This means that values of ~ 0.20 μmol kg⁻¹ yr⁻¹ due to circulation processes can be expected in $\frac{\partial DIC^{BIO}}{\partial t}$ for surface waters, which is comparable to the average of our findings (Table 5), $0.32 \pm 0.24 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$ and could indicate that the change in O₂ is related to circulation processes.”

The last paragraph of section 5 is clearly a conclusion, and should thus be moved to the Conclusions section.

We agree. Thanks. We will move this paragraph.

P15, line 13 delete one “repeat”

Thanks. We’ll correct this.

P16, line 8 uses stepwise MLR (delete “and”)

Thanks. We’ll correct this.

P18, lines 16-17 This sentence is incomplete.

We’ll complete the sentence:

“A battery of OMP analyses were done with varying values of R_N between 9 and 10 in increments of 0.2, R_P between 120 and 145 in increments of 5, and R_{Si} between 0 and 8 in increments of 2.”

P23, line 8 When using data from GLODAPv2, please cite GLODAPv2 manuscript, Olsen et al 2016 ESSD.

The references will be added:

*Key et al., 2015; Olsen et al., 2016 in section 3.1
Lauvset et al., 2016 in section A.3 page 23*

P24, line 31 delete info near end of line

Thanks. We’ll correct this.

P25, line 24 Deep-Sea (hyphen)

Thanks. We’ll correct this.

P27, line 6 Deep-Sea (hyphen)

Thanks. We’ll correct this.

P27, line 22 add NCAR technical note

Thanks. We’ll correct this.

P27, line 26 Law et al. as shown here is the Discussions paper. There is also a final paper in Geosci. Model Dev. from 2017.

The reference will be changed to Law et al. (2017):

“Law, R. M. et al.: The carbon cycle in the Australian Community Climate and Earth System Simulator (ACCESS-ESM1) Part 1: Model description and pre-industrial simulation, Geosci. Model Dev., 10, 2567–2590, <https://doi.org/10.5194/gmd-10-2567-2017>, 2017.”

P32, line 11 Comptes Rendus Geoscience

Thanks. We'll correct this.

P32, line 26 Mechanisms (typo)

Thanks. We'll correct this.

Table 2 caption: references (typo)

Thanks. We'll correct this.

PF is defined in the caption but does not occur in Table 2

Thanks. We'll correct this.