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Interactive comment on "The sensitivity of primary productivity to intra-seasonal mixed layer variability in the sub-Antarctic Zone of the Atlantic Ocean" *by* W. R. Joubert et al.

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Response to Reviewer1 on the manuscript "The sensitivity of primary productivity to intra-seasonal mixed layer variability in the Sub-Antarctic Zone of the Atlantic Ocean" – Joubert et al., Biogeosciences Discuss., 11, 1–24, 2014.

Reviewer's comments and author response are included in this response.

General Comments: This paper presents a very interesting dataset from an important but relatively under-sampled part of the Southern Ocean. It follows through on a line of analysis that is interesting but, in my view, is too narrow to fully put the processes considered into context, and consequently possibly exaggerates their overall importance.

Author response: Our goal was to highlight how synoptic scale variations in the MLD have the potential to induce additional Fe fluxes that can sustain productivity in the Sub-Antarctic Zone of the Southern Ocean. From the reviewer's comments, it appears that the role of light over Fe has emerged as more prominent and that alternative mechanisms (e.g. lateral advection) have not been given enough prominence. We thank the reviewer for providing us the opportunity to clarify our line of reasoning and in drawing our attention to alternate iron and light supplies. We address the reviewer's comments below and have modified the manuscript to account for them. The authors hope that the changes made are to your satisfaction.

Specific Comments:

Reviewer Comment 1: The paper introduction goes through arguments about iron and light limitation in the Southern Ocean. The suggestions that the Southern Ocean is generally light limited in summer, though referenced, are at odds with the small scale blooms seen downstream of islands and shallow sediment (eg see Fig 1 or several other references). These blooms are not associated with locally increased light levels. The blooms have short characteristic length scales, typical of ocean flow whereas light levels, due to their forcing, generally change over larger length scales typical of atmospheric variability. The analysis (and later calculation) of mixed layer depth, focusing on convective overturning and temperature differences, is appropriate for north of the Polar Front, but not the whole Southern Ocean.

Author Response1: We would like to address the perception of the reviewer that the Southern Ocean is generally light limited in summer. In the introduction we sought to highlight the complex interplay between water column irradiance and supply of limiting nutrients (dFe) into the mixed layer over the annual cycle. Phytoplankton blooms (or increases in biomass) reflect alleviation of these limiting factors. As such, an improved light environment is a driver of blooms associated with spring/summer shoaling of mixed layers, as well as sea-ice melt water (Arrigo et al., 2008; Fauchereau et al., 2011; Thomalla et al., 2011). Equally so, greater iron supply is invoked to explain the blooms associated with continental margins and downstream of topographic features (Moore and Abbott, 2000, Boyd and Ellwood, 2010). The introduction has been modified to address these comments. Furthermore, we agree with the reviewer that our analysis is appropriate equatorward of the Polar Front, and therefore we only focus on the SAZ region (see manuscript title and p4340 line12) and is not deemed appropriate for the whole Southern Ocean.

Reviewer Comment2: In the methods, it would be nice to know the density difference equivalent to the temperature difference used. Using a delta-T criterion is understandable given the use of XBTs, but a delta-sigma value is needed for comparison to values south of the polar front, where delta-T can't be used due to the dominant effects of salinity on density.

Author Respones2: We agree that Poleward of the Polar Front the salinity and temperature based density criteria are potentially more important than the temperature criteria to determine mixed layer depth. However, given that our analysis is limited to northward of the Polar Front, where temperature dominates and dS/drho $\sim$ 0, this comparison is not considered in the manuscript. We have, however, compared the MLD determination using both dT/dz and drho/dz and they match each other very well (see Figure1 attached here; r =0.86 p«0.01).

Reviewer Comment3: The assumption of O2/Ar being in steady state (requires steady conditions for 10 days, pg 4340, line 6) is not totally consistent with the timescale of MLD variability (2-5 deepening events per month, pg 4343, line 11). I'm not certain, but I would imagine non-steady state conditions would lead to higher values O2/Ar values being found in shallower mixed layers compared to deeper mixed layers.

Author Response3: We agree with the reviewer that biological oxygen saturation (O2/Ar ratio) would certainly change with depth and is not in steady-state. The steady state requirement is necessary to convert the instantaneous O2/Ar ratio measurement to a net community production flux in units of mmolO2 m-2 d-1. NCP is a time inte-

grated product which is highly dependent on the piston velocity through the wind speed. Thus overall NCP is less affected by vertical gradients in NCP. In the manuscript we present both O2/Ar ratio and NCP which effectively show the same relationship, however, O2/Ar ratio has more data due to data loss from the wind speed product. Furthermore, a weighted wind speed history is used convert O2/Ar ratio to NCP which attenuates with time so that the majority of the weight within the first 10 days of the wind speed history. This integration of the wind speed brings the number of events (2 – 5 per month) well within the event scale discussed in the manuscript. Finally, non-steady state conditions could entrain under saturated waters to be introduced into the productive surface water, and subsequently introduce a bias in O2/Ar ratio and NCP it would need to entrain under-saturated water. Dissolved oxygen water profiles of the water column shows the water column is well mixed with respect to oxygen in the upper 100 m of the water column in the SAZ region.

Reviewer Comment4: The results start with an analysis of the relationship between O2/Ar and MLD. The ranges given (pg 4341, lines 10-11) should use the same percentile so as to be comparable.

Author Response4: Both O2/Ar ratios and calculated NCP flux data are presented, to show the loss of data when calculating NCP from O2/Ar ratios, due to the sporadic nature of the satellite wind product. The aim was not to compare O2/Ar with NCP for which a percentile comparison may be appropriate. Our goal rather was to examine whether O2/Ar ratios and NCP showed a similar relationship with MLD, despite the smaller NCP dataset.

Reviewer Comment5: The inference that deep mixed layers to the south limit primary production is not consistent with the elevated chl-a values found in the far south of the transect in/south of the Polar Front (manuscript figures fig 1, fig 2c) where mixed layers are deeper and incoming irradiance is lower (manuscript fig 3).

Author Response5: Although elevated Chl-a are observed near in the Polar Frontal

Zone north of the Polar Front (manuscript Fig 2C), Net Community Production measurements (and O2/Ar ratios) in this region were particularly low (see manuscript Fig 2b). Hence, despite comparable chlorophyll concentrations, our inference that deep mixed layers limit primary production in the PFZ is not at odds with the data. Manuscript Fig 1 is a summer climatology that includes the spring- early summer bloom (Thomalla et al., 2011) at the PFZ – this study focuses particularly in the post spring bloom – persistence of summer bloom (Swart et al., 2014). It is noted that chlorophyll values are high in the PFZ but may reflect the climatological summer conditions rather than in increase in biomass associated with increased net community production. Advective convergent flow mechanisms are potentially responsible for the elevated chl-a concentrations at frontal positions. This paper however addresses the variability in NCP in the SAZ in relation to mixed layer depth variability.

Reviewer Comment6: The 'threshold' value of 45m identified is, in my view, used too strongly through the paper and at times morphs into a 'critical value' (pg 4344, line9) which it isn't (there is definitely no peak at 45m – pg 4342, line 1 should be 'below which' rather than 'where' after the 'threshold'). I don't agree that the relationship is 'strongly non-linear' (pg 4347, line 5).

Author Response6: We agree that the word 'threshold' is too strong to be used here and so we have altered the text as follows: The word "threshold" is changed to "45 m minimum light requirement". The text on g 4342 is changed to "below which" as recommended by the reviewer. Change "strongly non-linear" to "quasi non-linear".

Reviewer Comment7: The increased chl-a near the Polar Front is due to advection of iron downstream from South Georgia (on average there is a monotonic decrease of chl-a along the downstream flow), suggesting that spatial variations in iron availability are more important in setting chl-a values in summer than light, even away from the large blooms. Relevant to this study, it is likely that downstream advection from the South American shelf area is important. Along with this, lateral exchange between the circumpolar waters (N replete, Fe limited) and South Atlantic waters (N limited,

potentially elevated Fe concentrations – this should be stated) may also help sustain production in the SAZ.

Author Response7: We agree with the reviewer that resupply of iron likely sustains productivity in the SAZ. However, since the regional variations in MLD on intra-seasonal timescales will clearly modify the light environment (Figure 3) this should also affect rates of production. Thus synoptic deepening and shoaling of the MLD modulates both the supply of Fe and the availability of light. This mechanism can produce Fe fluxes able to support production in the SAZ (sections 3.2 and 4.2). In making these estimates we do not exclude lateral fluxes of Fe, but simply show that they are not necessary at first order in this region. Nevertheless, understanding how local Fe supply on seasonal (Tagliabue et al., 2014) and intra-seasonal (this work) timescales interacts with remote Fe input from lateral advection remains an important question for future work. We hope that with more Fe data from forthcoming GEOTRACES campaigns the role of lateral Fe input can be better constrained in the future. We have modified the discussion to reflect these comments.

Reviewer Comment8: On pg4336, line 13 the system is described as at times 'iron replete'. Although iron addition stimulates growth, the relatively low chl-a values (all <1 mg m-3) suggest that there was still significant limitation on phytoplankton growth – iron limitation is a sliding scale. Author Response8: We would like to thank the reviewer for pointing out this nuance. We have since changed "Iron replete" in the text to "under potentially increased iron conditions".

Reviewer Comment9: The estimation of vertical iron supply (equation 3) puzzled me. Firstly I'm not sure what element of the integral is a function of z and I'm not sure why the 45m value seems to be being used to define a ferricline depth across all latitudes. Surely this should vary depending on the normal range of MLD variation (deeper mixed layers bringing iron up from deeper depths and leading to a deeper ferricline). Overall it seems to be set up to find high values where the MLD varies each side of 45m and not otherwise. I'm not convinced that all assumptions that go into such a formulation are valid and, as discussed above, there are other plausible reasons for this region of enhanced production that should be considered (eg at pg 4345, line 26-27).

Author Response9: The goal of this section was to understand how synoptic oscillations in the MLD around $\sim$ 45 m might impact Fe supply. We chose to use 45m as an indicator MLD since it presents as a threshold in the MLD (Figure 2a and b) and is representative of typical MLDs in the SAZ (Figure 3b). Equally we sought to understand how the frequency of MLD deepening events and their magnitude might impact synoptic Fe fluxes. At present our understanding of the seasonal Fe supply neglects this contribution (Tagliabue et al., 2014). Available dissolved Fe data from the region is used with different assumptions regarding whether the MLD reservoir is depleted or not (left and right panels of manuscript Figure 6). This is important as we lack constraints on the seasonal cycle of Fe in this region (Tagliabue et al., 2012) and the lack of a data constraint on the seasonal minima may bias the calculated Fe flux. Thus we estimate the synoptic Fe flux to be 98 – 599 nmolFe m-2 d-1across uncertainties for the number of deepening events, their magnitude and whether the MLD Fe reservoir is fully depleted or not. We note that we are not seeking to provide the actual fluxes present, but to assess across bounds of uncertainty whether synoptic fluxes have the potential to be important in sustaining NCP in the SAZ. As noted in Response 7 the role for lateral advection of Fe (that is, however, difficult to assess quantitatively at present) is added to the text. Ultimately we would of course wish to see Fe supply placed into the context of local and remote factors and seasonal and synoptic time-scales.

Reviewer Comment10: Overall, I don't believe that the data presented supports any general conclusion about light limitation and I'm also uncertain about the specific calculations of iron fluxes and the (limited) range of other values they are compared against.

Author Response10: We would argue that we are not proposing light limitation and have sought to clarify this issue in the responses above and in the revised manuscript. We are however, providing the first evidence for synoptic scale fluctuations in NCP and suggesting how parallel MLD variations that modify the light environment and support

additional Fe fluxes may explain them. This is important as, at present, our understanding of seasonal Fe supply and demand neglects the role of synoptic scale events. These issues should be investigated further with a dedicated process study.

Technical corrections: pg 4337, line 25: sub-seasonal; pg 4338, line 5: i.e. -> e.g.; pg 4341, line 14: elevated; pg 4342, line 1: +/- 20.4 is too precise; pg 4346, line 11: results; pg 4347 line 17: add 'of' after persistence; Fig 2c: figure doesn't match caption;

Author Response: Technical corrections have been corrected.

References: Arrigo, K. R., van Dijken, G. L., & Bushinsky, S. (2008). Primary production in the Southern Ocean, 1997–2006. Journal of Geophysical Research, 113(C8), C08004. doi:10.1029/2007JC004551. Fauchereau, N., Tagliabue, A., Bopp, L., & Monteiro, P. M. S. (2011). The response of phytoplankton biomass to transient mixing events in the Southern Ocean. Geophysical Research Letters, 38(17), L17601, doi:10.1029/2011GL048498. Thomalla, S. J., Fauchereau, N., Swart, S., & Monteiro, P. M. S. (2011). Regional scale characteristics of the seasonal cycle of chlorophyll in the Southern Ocean. Biogeosciences, 8(10), 2849–2866. doi:10.5194/bg-8-2849-2011. Tagliabue, A., Mtshali, T., Aumont, O., Bowie, a. R., Klunder, M. B., Roychoudhury, a. N., & Swart, S. (2012). A global compilation of dissolved iron measurements: focus on distributions and processes in the Southern Ocean. Biogeosciences, 9(6), 2333–2349. doi:10.5194/bg-9-2333-2012. Moore, J. K., & Abbott, M. R. (2000). Phytoplankton chlorophyll distributions and primary production in the Southern Ocean. Journal of Geophysical Research, 105(C12), 28709. doi:10.1029/1999JC000043. Boyd, P. W., & Ellwood, M. J. (2010). The biogeochemical cycle of iron in the ocean. Nature Geoscience, 3(10), 675–682. doi:10.1038/ngeo964. Tagliabue A., J-B. Sallee, A. Bowie, M.Levy, S.Swart, P.W.Boyd, 2014, Surface water iron supplies in the Southern Ocean sustained by deep winter mixing, Nature Geoscience, 7, 314 – 320, doi:10.1038/ngeo2101.

Interactive comment on Biogeosciences Discuss., 11, 4335, 2014.

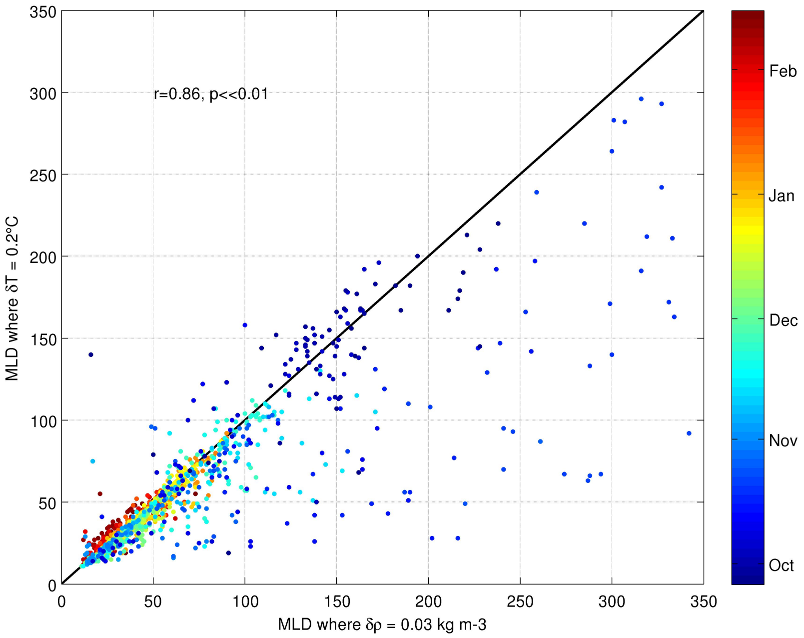

Fig. 1. A strong positive correlation between MLD determined from temperature and density criteria were observed from glider data in the Atlantic Sub-Antarctic Zone