Clim. Past Discuss., 11, C827–C837, 2015
www.clim-past-discuss.net/11/C827/2015/

Climate of the Past Discussions

Interactive comment on "Trace metal evidence for a poorly ventilated glacial Southern Ocean" *by* M. Wagner and I. L. Hendy

M. Wagner and I. L. Hendy

wagne2me@cmich.edu

Received and published: 26 June 2015

Firstly we thank Anonymous Referee #1 for his or her thoughtful and detailed comments. Below we offer our response.

General comments: -We agree that the vertical water column structure suggested by the trace metal records is difficult to imagine. That is why we chose to leave this as an open question to be resolved by future work (page 17, lines 12-14). The interpretation here is uncertain. However, given that most work on glacial-interglacial changes in the Atlantic sector Southern Ocean derives from cores recovered from the Subantarctic Zone and Cape Basin, we feel that it is important to also present data from the Antarctic Zone to give a fuller picture of the region's oceanographic history and to address any potential sampling biases.

-The papers referenced that have previously published export production records mostly utilize Th-230 normalization. We have received mixed responses to normalization of trace metals to Th-230, which is one reason that this appears in the supplementary material. In the main text of the manuscript, we chose not to normalize Corg concentrations to Th-230 so as to highlight the similarities with Ag. Low-resolution Corg flux data is available for core RC13-254 (Anderson, R. F., Kumar, N., Mortlock, R. A., Froelich, P. N., Kubik, P., Dittrich-Hannen, B., and Suter, M.: Late-Quaternary changes in productivity of the Southern Ocean, Journal of Marine Systems, 17, 497-514, 1998.). Our Ag, Cd, and Corg records (Figures 3 and S1) are very much consistent with the pattern established by the earlier work (Anderson et al., 1998) (also see Figure R1-1). Silver and Cd concentrations record strong export production during the last glacial period and early deglaciation, as has been demonstrated by many previous studies. We acknowledge this shift on page 17, line 24. Whether Ag and Cd ever recorded the southward shift of the high productivity zone during deglaciation is unknown, because burndown has erased the record in the upper part of the core. (If we assume that burndown has not affected the core, then reduced Ag and Cd concentrations after ∼15 ka definitely are consistently with a southward shift of the high productivity zone.)

Organic carbon data have not been previously published for TN057-13-4PC. The pattern of organic carbon flux (Figure S2) is similar (though not identical) to the opal flux record published by Anderson et al. (2009), (Figure R1-2). Organic carbon flux is low until ∼17-18 ka (∼770-780 cm), at which time it increases and remains high until ∼5-7 ka (∼200-260 cm) when fluxes decrease. Our sampling intervals are not the same as those of Anderson et al. (2009), hence some of the detail in deglacial-age productivity changes does not appear in our record. Again, the patterns of Ag and Corg concentrations are very similar (Figure 4), as are Ag and Corg fluxes minus the large Ag flux peak at 840 cm core depth (Figure S2). We emphasize that in Figures 3 and 4 we primarily plot concentrations versus depth in the core, not versus sediment age.

We considered normalizing the data to Fe, Ti, or Al. However, for TN057-13-4PC the

CPD
11, C827–C837, 2015

data belong to Sam Jaccard and have not yet been published. Data for Fe, Ti, and Al at RC13-254 were published by Latimer and Filippelli (2001) and have been archived with the NOAA Paleoclimatology database. These data are lower resolution than what we collected for the trace metals. As a compromise, we included the % terrigenous material in Figures 3 and 4. This calculation was used by Latimer and Filippelli (2001) to estimate the terrigenous component, and we believe this adequately demonstrates that lithogenic input is a minor contributor to observed trace metal concentrations. However, if we interpolate the available data sets for both TN057-13-4PC and RC13-254, and normalize the trace metal concentrations to Al, we are confident that sediment dilution does not drive downcore patterns for RC13-254 (Figure R1-3). We acknowledge that normalizing to Al changes the temporal pattern of trace metal enrichments in TN057-13-4PC (Figure R1-4). Perhaps this should be expected given that the site received greater amounts of ice-rafted debris than RC13-254 would have (Kanfoush et al., 2000). The large peaks in Ag, Cd, and Re below ~750 cm (Figure 4) could plausibly be attributed to lithogenic input and we are open to a reinterpretation of this part of TN057-13-4PC.

If we compare Ag/Al, Cd/Al, and opal fluxes in TN057-13-4PC, the trace metal-based productivity proxies (Ag and Cd) do a reasonably good job of following productivity recorded by opal flux (Figure R1-2). Importantly, normalization to Al only minimally changes the interpretation of sedimentary redox conditions. There is no change in interpretation for RC13-254, and in TN057-13-4PC there may be additional, short periods of increased oxygenation below ~700 cm. However, export production still primarily controls sedimentary redox conditions at this site.

-We understand the reviewer's concerns with normalizing trace metals to Th-230, although as noted Ag and Cd are probably reliable because they are delivered to sediments with biogenic particles. However, as we state in the Supplementary Information, sediment redistribution is a well-documented phenomenon in the Southern Ocean, and we felt that it was important to address this in some way. As recommended by the re-

CPD
11, C827–C837, 2015

viewer, we have now calculated sediment focusing factors for both cores (Figure R1-5, Table R1-1), and we will include these in the Supplementary Information.

Sediment focusing factors are highest for TN057-13-4PC below ∼760 cm core depth. Again, this may help to explain the large trace metal peaks, but does not substantially alter the interpretation of the record as a whole. Focusing factors are still significant (3.81) from ∼630-760 cm, but at this stage the high productivity zone had shifted south, and all productivity proxies (Ag, Cd, opal flux, and Corg flux) are consistent with enhanced export production. From the core top to ∼630 cm, encompassing the Holocene, the focusing factor is much closer to 1 (1.53).

Focusing factors are generally much lower and closer to 1 (or below 1) for RC13-254 above 172 cm. From 172-380 cm, the focusing factor is higher at 3.58. However, if anything, higher sedimentation rates may suppress Re accumulation because it diffuses into sediments. Elevated Re concentrations throughout this part of the core argue against sediment focusing driving trace metal accumulation. Silver and Cd concentrations are also sufficiently elevatedâĂŤin an open ocean environmentâĂŤsuch that they are difficult to explain by sediment focusing alone.

Specific comments:

We are prepared to revise our manuscript as detailed below.

Page 2, line 3: add “remineralized” before CO2

Page 2, line 5: change “predicts” to “requires”

Page 2, line 16: We like the word “arrangement.” Could the referee please explain the rationale for preferring the word “geometry?”

Page 2, line 21: We certainly do not intend to minimize the studies cited, but as far as we are aware, there is currently no comprehensive and universally accepted explanation for the location of the “missing” CO2 and the mechanism that redistributed carbon throughout its reservoirs.

CPD
11, C827–C837, 2015

Page 3, line 10: We agree with the referee that extended sea ice coverage could have altered the air-sea exchange of oxygen. Unfortunately, an analysis of the contribution of this phenomenon to reducing Southern Ocean oxygen levels is beyond the scope of this manuscript.

Page 5, line 13 to page 6, line 2: The referee is absolutely correct that lack of Ag and Cd cannot be uniquely attributed to low export production. Comparison to independent productivity proxies such as organic carbon or biogenic silica is required to assess whether high export production occurred in well-oxygenated waters. For this reason, organic carbon and opal flux are plotted in Figures 3 and 4 as well. However, given that Re is preserved in suboxic settings, it is unlikely that Re enrichments in the absence of Ag and/or Cd enrichments would occur under conditions of high export production and oxygenated conditions.

Page 10, line 2: We agree that it is a bit awkward to begin with a discussion of burndown. However, the discussion of burndown has had several "homes" throughout multiple rounds of revision and the current location at the beginning of Section 4 has so far been the best solution. There does not seem to be an ideal location for this discussion, although we feel that it is important to address this issue.

Page 11, line 10: We have not inferred lowest oxygenation in waters overlying site TN057-13-4PC at the LGM. At the LGM, we had inferred that export production primarily caused suboxic pore waters. Lowest oxygenation was inferred for site RC13-254 at the LGM.

Page 11, line 15: We appreciate the referee's input on this. Again, we felt that it was important to address the possibility of oxidative burndown, especially because the issue was raised by previous authors (e.g., Rosenthal, Y., Boyle, E. A., Labeyrie, L., and Oppo, D.: Glacial enrichments of authigenic Cd and U in Subantarctic sediments: A climatic control on the elements' oceanic budget?, Paleoceanography, 10, 395-413, 1995).

CPD
11, C827–C837, 2015

Page 12, line 3-22: We agree that site RC13-254 shows a typical SAZ-type behavior during the last glacial period and in fact this interpretation has been put forward previously (Anderson et al., 1998; Kumar et al., 1995); we do not dispute this in our manuscript. Our trace metal data indicate that glacial Southern Ocean deep waters were additionally affected by lower oxygen concentrations compared to present. It is implausible that enhanced export production alone can account for the observed trace metal concentrations. Ideally, trace metal concentrations could be related quantitatively to dissolved oxygen concentrations. Without such a relationship, our best option is to compare downcore trace metal concentrations to modern-day environments. Trace metal concentrations similar to those of glacial RC13-254 are found in modern sediments underlying coastal upwelling regions with oxygen-depleted bottom waters and high surface productivity (e.g., parts Arabian Sea, Morford and Emerson, 1999; Chile margin, Böning et al., 2005; parts Mexican margin, McKay and Pedersen, 2008; Nameroff et al., 2002). We note this comparison more generally on page 11, lines 23-27.

Page 14, line 12: The correlation with the South Atlantic ventilation ages is very bad (R2 = 0.014) and the correlation with the North Atlantic ventilation ages is also poor (R2 = 0.38).

Page 15, line 10: We only meant to highlight that similarly high Re concentrations were observed at another site, and RC13-254 is not unique in this way. We did not intend to reinterpret this site. To clarify, we can amend the sentence this way: "A lower-resolution Re record from PS2489-2 corroborates the pattern from RC13-254 of lower Re concentrations/lower ventilation ages during MIS 3 and higher Re concentrations/higher ventilation ages during MIS 2, although Martínez-Garcia et al. (2009) attribute elevated Re concentrations during glacial intervals to enhanced export production and Corg remineralization."

Page 16: We disagree that the discussion related to 14C is out of place. Carbon-14 ventilation ages are some of the best evidence available for substantiating our conclu-

CPD
11, C827–C837, 2015

sion of lower oxygen concentrations and enhanced glacial CO2 storage in Southern Ocean deep waters. Moreover, greater storage of glacial CO2 (and lower oxygen concentrations) in LCDW-equivalent waters necessitates consideration of the global deep ocean in providing a convincing explanation of glacial-interglacial CO2 changes, because modern LCDW is exported to all three major ocean basins. Our intent is to take a slightly different approach to resolving the glacial-interglacial CO2 conundrum by viewing the ocean as a connected whole, rather than in pieces such as the Southern Ocean, Atlantic basin, etc.

Page 16, line 24: Burke and Robinson (2012) do not suggest that net transfer occurred only through upwelling, and neither do we. Please see the Supporting Online Material for Burke and Robinson (2012).

Page 17, lines 16-20: This is true that these factors also affect Ag, Cd, Re, and Mo. This highlights the need for multi-proxy studies that can provide added confidence in interpretations. However, many studies rely heavily on authigenic U, and Frank et al. (2000) are somewhat cautious in using authigenic U.

Supplement, lines 15-16: We can add the words “and authigenic” as pointed out.

Interactive comment on Clim. Past Discuss., 11, 637, 2015.

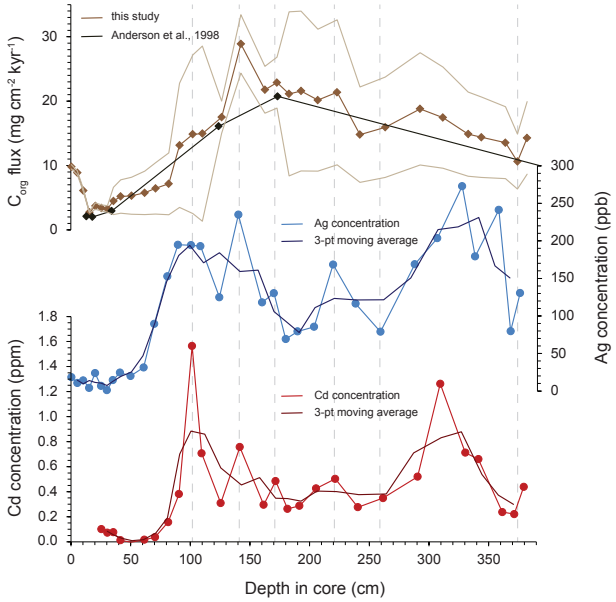

Figure R1-1

Fig. 1. Figure R1-1

Full Screen / Esc
Printer-friendly Version
Interactive Discussion
Discussion Paper

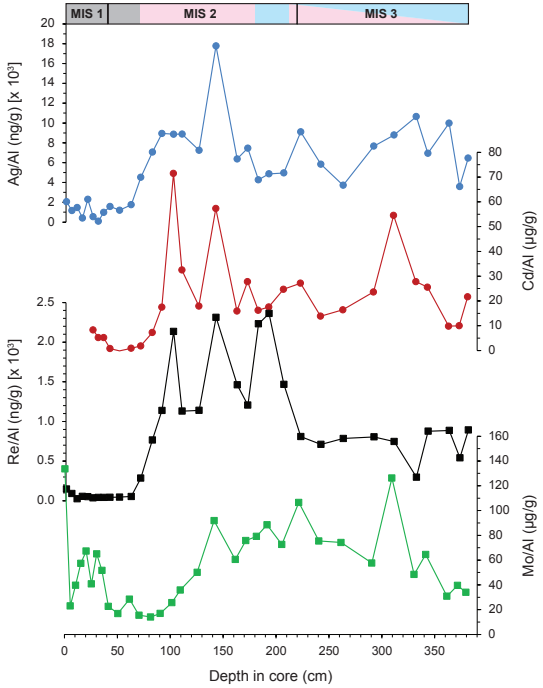

Figure R1-3

Fig. 2. Figure R1-3

Full Screen / Esc
Printer-friendly Version
Interactive Discussion
Discussion Paper

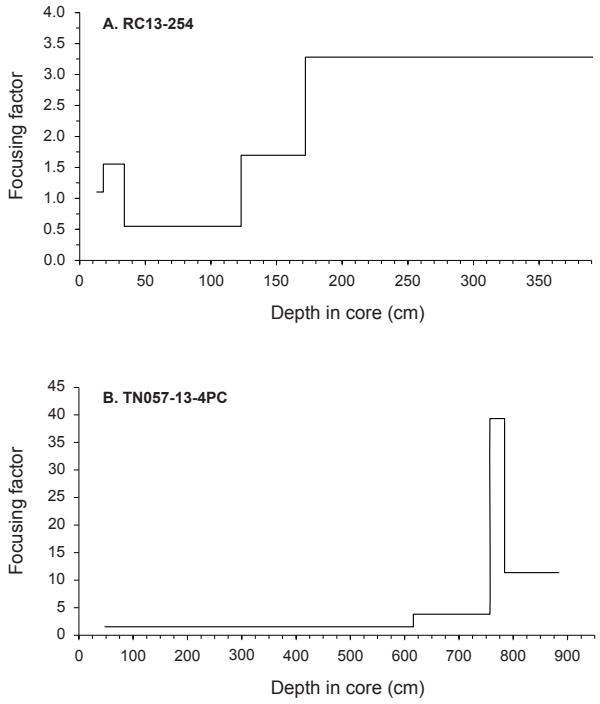

Figure R1-5

Fig. 3. Figure R1-5

CPD
11, C827–C837, 2015

Depth (cm)	Focusing factor
RC13-254[a]	
18	1.10
34	1.55
123	0.55
172	1.69
432	3.58
TN057-13-4PC[b]	
616	1.53
757	3.81
784	39.34
884	11.36

[a]Dry bulk density = 0.34 g cm^{-3} after Latimer and Filippelli (2001)
[b]Dry bulk density from Kanfoush et al. (2002)

Fig. 4. Table R1-1

CPD
11, C827–C837, 2015