Nutrient utilization and diatom productivity changes in the low-latitude SE Atlantic over the past 70 kyr: Response to Southern Ocean leakage

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1 Response to Editor

Two reviewers provided constructive comments and recommendations for the publication. The reviewers gave positive comments about the value of the data and the interesting interpretations. Queries around use of 2 specific for isotope work have been addressed in the author replies, including clarifying that the isotope data is not 'species-specific'. Further concerns about citing contextual information for the area has been addressed, as well as those related to the processes being explored with the simple model.

Many thanks to the editor for the thorough review of our article. We are happy to respond to the further comments below. We have uploaded a new version of the manuscript with changes to address the comments from the two reviewers and the editor highlighted in red, blue and cyan respectively.

1) Links between what is happening in the Benguela upwelling system and in the Southern Ocean, the source of the DSi. At present the data and it's interpretation are presented without reference to knowledge of any changes in SO circulation / productivity, which may offer support or explanation to the patterns the authors propose. It may be that such data does not exist (e.g. at the resolution the authors work here) but the text in section 3.1 is very focussed only on the Benguela system, e.g. lines 174-175 notes "a decrease in the DSi concentration of the supplied water...": is there data from the Southern Ocean marine archives which could predict/explain why this would happen or is it a signal driven by the local (upwelling) circulation changing? Do other Benguela sites offer support/explanation?
line 183-184: as for my previous comment, are there other data sets which support or explain why this supply changed?

This is an important limitation, and this issue is discussed in our previous publications (Romero et al., 2003; Romero, 2010; Romero et al., 2015; Shukla and Romero, 2018). However, our understanding of SO nutrient dynamics over these

timescales has so far limited by the lack of published, similarly high-resolved record of diatom production south of the Polar Front for the past 70 kyr.

We have made this point on line 39 onwards:

"However, as yet there are no published archives of silicon cycling under full glacial conditions south of the subantartic front. Furthermore, very few archives have been published over this time period from lower latitudes…"

Instead, we have to rely on information gleaned from core sites in the lower latitudes.

We postulate that intermittent, SO-originated pulses of DSi into the BUS between 70 kyr and ca. 30 kyr led to the upwelling of Si-rich waters off Namibia (Romero et al., 2003; Romero, 2010; Romero et al., 2015). This nutrient scenario was triggered by the equatorward transport of Si-enriched waters of Antarctic origin, either by (i) direct mixing or by (ii) the advection of Subantarctic Mode Waters (whose present-day Si content is low relative to surrounding water masses; Matsumoto et al., 2002) that invaded the middle to lower thermocline of subtropical coastal upwelling areas (Sarmiento et al., 2004). The equatorward leakage of DSi followed intervals of lowered diatom productivity in the SO south of the Subantarctic Front due of varying physical and biological conditions (sea ice cover, winds, Fe input; Matsumoto et al., 2014). Two possible drawbacks of this sub-Milankovitch scale leakage scenario are (i) the lack of a diatom reconstruction south of the Subantarctic Front showing millennial-scale variability, and (ii) the prediction of glacial increases and interglacial decreases of Si leakage. Additional evidence for a non-glacial, sub-Milankovitch Si leakage is provided by increased opal burial recorded in the eastern equatorial Pacific between 40-60 kyr, attributed to extended sea ice around Antarctica (as already discussed in the introduction).
Another possible link between SO and the BUS is provided by the weak anti-correlation between the size and concentration of *F. kerguelensis'* valves at GeoB3606-1 during the late MIS3 (Shukla and Romero, 2018). This could have resulted from the higher Fe availability through dust flux during 70–30 kyr in the SO (i.e., Mahowald et al., 2005; Martínez-García et al., 2014), which might have caused increased growth rates of diatoms and a decrease in the silicate-to-nitrate uptake ratio of diatoms (Matsumoto et al., 2002; Brzezinski et al., 2002; Matsumoto et al., 2014). The magnitude of any silicic acid leakage is largely dependent on the behavior of AAIW and SAMW (Crosta et al., 2007) which is largely unknown for glacial-interglacial period (Kohfeld et al., 2013). Although we are not able to provide a convincing explanation of the intensity changes of AAIW or SAMW in our *F. kerguelensis* valve size data (which was anyway beyond the scope of that work), both the valve size and concentration *F. kerguelensis* in core GeoB3606-1 suggest decreased silicate:nitrate uptake of diatoms in presence of higher iron availability through dust flux (Takeda, 1998; Hutchins and Bruland, 1998).

We have added the following to line 207 onwards:

"A weak anti-correlation between the size and concentration of F. kerguelensis valves at GeoB3606-1 during the late MIS3 (Shukla and Romero, 2018) could indicate an increase in growth rates of these diatoms resulting from a higher Fe availability in the SO due to an enhanced supply of dust (Martínez-García 210 et al., 2014). Alleviation of Fe limitation in the SO could also have caused a decrease in the DSi-to-nitrate uptake ratio of diatoms and, so, a relative enrichment of DSi in SO waters exported to the lower latitudes (Brzezinski et al., 2002). Although upwelling conditions in surface waters overlying the lower slope off SW Africa became less favourable for diatom production, the strength of the trade winds remained strong during MIS2 (Shi et al., 2001), indicating that lower latitude dust supply is a secondary control on diatom activity in the Late Quaternary in the SE Atlantic."

We have expanded the discussion of the late MIS2 to include more information about SO records on line 214 onwards:

"The decreased delivery of DSi into the SE Atlantic around 17 kyr led to the floral shift at GeoB3606-1 (Fig. 2E). Higher CaCO3 (lower opal) values at GeoB3606-1 from late MIS2 to the mid/late Holocene (Romero et al., 2015) indicate a shift in predominant nutrients toward Si-depleted waters. Following the lessened sea ice cover in the SO (Crosta et al., 2005), and the lowered input of Fe south of the Polar Front due to weakened wind intensity during the last deglaciation (Kohfeld et al., 2005; Sijp and England, 2008), DSi was mainly consumed in waters south of the Subantarctic Front and became mostly trapped in underlying sediments (Brzezinski et al., 2002; Bradtmiller et al., 2009). This scenario corresponds to the present-day dynamics of production and sedimentation of biogenic particulates in the southern BUS (Romero and Armand, 2010), where coccolithophorids dominate primary production over diatoms."

2) lines 66-67: since there has been a revision to the radiocalibration curves since the McKay et al. 2016 publication could the authors please clarify here which calibration model was used to generate the calendar ages? (rather than the reader having to seek out the original age model papers)

The age model we used here is that of McKay et al., 2016, and the calibration process is now detailed on line 69:

"The radiocarbon ages of all samples were converted into calendar years, and a new age model (McKay et al., 2016) was created using the OXCAL 4.2 program with the marine calibration curve MARINE13 (Reimer et al., 2013)."

3) response to R1 regarding SST and upwelling: "reduced SST reconstructions" could be read as "fewer SST data points". "...reduced SSTs as reconstructed from alkenone archives" might be more clear? The authors may also consider line 160-161: "Cooler SSTs indicate a pulse of upwelling..."?

Many thanks for these suggestions. We have changed these lines as requested.

4) response to R2 regarding Fe fertilisation: the authors note an addition on Line 205 to address this concern. Although this addition refers to ‘dust supply’ it does not indicate whether this refers to the concern about Fe fertilisation which was expressed by the reviewer. Could the authors consider clarifying here if they are arguing for a lack of Fe fertilisation when they refer to dust, or are they referring to DSi and/or Fe supply?

Dust supplies to surface waters have been suggested to alleviate both Si and Fe limitation. We have clarified that we were referring to both possibilities on line 181

"In addition to upwelling of marine sources, strong trade winds could also have promoted diatom productivity through the supply of DSi and trace nutrients to surface waters via dust, given the drier conditions on land…”

Additional references added to the manuscript:

Bradtmiller, L.I., Anderson, R.F., Fleisher, M.Q., Burckle, L.H. 2009. Comparing glacial and Holocene opal fluxes in the Pacific sector of the Southern Ocean. Paleoceanography 24, PA2214, doi:10.1029/2008PA001693.

Crosta, X., Shemesh, A., Etourneau, J., Yam, R., Billy, I., Pichon, J.J., 2005. Nutrient cycling in the Indian sector of the Southern Ocean over the last 50,000 years. Global Biogeochemical Cycles 19, doi:10.1029/2004GB002344.

Kohfeld, K.E., Le Quéré, C., Harrison, S.P., Anderson, R.F., 2005. Role of Marine Biology in Glacial-Interglacial CO2 Cycles. Science 308, 74-78.

Martínez-García, A., Sigman, D.M., Ren, H., Anderson, R.F., Straub, M., Hodell, D.A., Jaccard, S.L., Eglinton, T.I., Haug, G.H., 2014. Iron fertilization of the Subantarctic Ocean during the last ice age. Science 343, 1347–1350. http://dx.doi.org/10.11 science.1246848.

Sijp, W., England, M.H., 2008. The effect of a northward shift in the southern hemisphere westerlies on the global ocean. Progress in Oceanography 79, 1–19.

Reimer, P. J., et al. (2013), IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP, Radiocarbon, 55(4), 1869–1887

Other references cited in this response:

Brzezinski, M.A., Pride, C.J., Sigman, D.M., Sarmiento, J.L., Matsumoto, K., Gruber, N., Rau, G.H., Coale, K.H., 2002. A switch from Si(OH)4 to NO3 depletion in the glacial Southern Ocean. Geophysical Research Letters 29, doi:1510.1029/2001GL014349.

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Mahowald, N.M., Baker, A.R., Bergametti, G., Brooks, N., Duce, R.A., Jickells, T.D., Kubilay, N., Prospero, J.M., Tegen, T., 2005. Atmospheric global dust cycle and iron inputs to the ocean. Glob. Biogeochem. Cycles 19. http://dx.doi.org/10.1029/2004GB002402.

Matsumoto, K., Sarmiento, J.L., Brzezinski, M.A., 2002. Silicic acid leakage from the Southern Ocean: A possible explanation for glacial atmospheric pCO2. Global Biogeochem. Cycles 16, doi:10.1029/2001GB001442.

Matsumoto, K., Chase, Z., Kohfeld, K., 2014. Different mechanisms of silicic acid leakage and their biogeochemical consequences. Paleoceanography 20, 238–254, doi:210.1002/2013PA002588.

Romero, O.E., Armand, L.K., 2010. Marine diatoms as indicators of modern changes in oceanographic conditions. In: Smol, J.P., Stoermer, E.F., (Eds.), The diatoms: Applications for the Environmental and Earth Sciences (2nd Ed.). Cambridge University Press, U.K.

Sarmiento, J.L., Gruber, N., Brzezinski, M.A., Dunne, J.P., 2004. High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 427, 56–60.

Takeda, S., 1998. Influence of iron availability on nutrient consumption ratio of diatoms in oceanic waters. Nature 393, 774–777.