Final author comments for manuscript cp-2016-35
Title: Ocean carbon cycling during the past 130,000 years – a pilot study on inverse paleoclimate record modelling
by author(s): C. Heinze et al.

RESPONSE TO REVIEWER#2:

We also would like to thank reviewer#2 for the expert review and the constructive comments for improving the manuscript. Below we cite the reviewer's remarks in italics and our direct responses in normal text.

Reviewer#2:
Heinze et al. use a coarse resolution ocean biogeochemical model to estimate the effect of changes in SST, terrestrial biosphere release, dissolution rate constant of POC and BSi, $CaCO_3$*:POC rain ratio, 3D oceanic velocity field, dust deposition and Redfield C/P ratio on sedimentary d13C, BSi and* $CaCO_3$*. A linear statistical model is then used to explore the parameter space. The parameters giving the best fit with a range of paleoproxy records are shown.*

(No response required.)

Reviewer#2:
This is a useful manuscript, which allows the study of a wide range of parameters, but with a "linear response" caveat.
The parameters for the full solution (rank 8) give a large decrease in $CaCO_3$*/POC, which the authors suggest is unlikely. They thus decrease the rank to 7, but obtain too large changes in SST. The final "best" solution is thus the rank 6. But with that solution, there is only little change in atmospheric* pCO_2*. Since the basis of the model is to reproduce a range of paleoproxy records, I am a bit surprised that no model data comparison is shown for the ranks 8, 7 and 6. Shouldn't at least correlation coefficients between model and proxy given for the 3 ranks?*

We have computed correlation coefficients between observations and predicted values from the linear response model for each paleoclimatic record employed in the fitting procedure for the three ranks considered (and also smaller ranks). We then summarised the findings in a diagram for full rank, rank 7, and rank 6, structured into tracer types and ranks. We plan to insert this figure as Figure 11. We plan to include the following text passage after page 17 line 24:
"Correlation coefficients between observations and predicted tracer values from the linear response model are given in Figure 11. While for a series of single records the correlation is good, for other single records the correlation is poor or even anti-correlations resulted. This is especially the case for the planktonic $\delta^{13}C_{planktonic}$ records. This deficiency can be in part explained through the coarse model resolution. If the regional extent of upwelling zones is different between model and reality also the respective surface tracers for paleo-productivity as recorded in the sediment cores will show respective differences."
(A respective figure caption will be added.)

Reviewer#2:
There is limited discussion on previous glacial/interglacial studies, particularly for recent studies, granted the approach used here is quite different.

We plan to add the following text in the discussion section before the start of the conclusion section, (i.e., after the text as suggested in the response to the previous referee comment):
"In previous studies on the glacial-interglacial changes in the ocean carbon cycle, often hypotheses involving one specific mechanism were presented or the multitude of potential mechanisms was reviewed. Studies were the simultaneous contributions from several processes to glacial carbon dynamics have been discussed are relatively scarce. Brovkin et al. (2007) employed an Earth system

model of intermediate complexity including oceanic and terrestrial biogeochemical modules to test the impact of simultaneous changes on the atmospheric CO_2 concentration. Their results are fairly consistent with those of this study. According to Brovkin et al. (2007), largest contributions to the CO_2 drawdown came from circulation and SST changes as well as from a strengthening of the biological pump through improved nutrient utilisation, while the land outgassing amounted to an atmospheric pCO_2 increase by 15 ppm. Rain ratio changes contributed to about 15 ppm, a process also cited as a less certain mechanism by Brovkin et al. (2007). In addition they report secondary changes of atmospheric pCO_2 due to weathering, sea level change, and changes in sedimentation (shallow water vs. deep water).

Recent studies focused again on the mineral dust hypothesis involving increased iron supply especially to the Southern Ocean (originally revived by Martin et al. (1994) and Berger and Wefer (1991)) and a respective regional strengthening of biological production and carbon export. Increased LGM aerosol iron flux to the Southern Ocean could be corroborated by Conway et al. (2015). With our approach, in a separate experiment (not shown in this study where we only consider dust for solution of sedimentary material) we also had tested increased ocean productivity and related surface nutrient drawdown due to changing dust deposition. The inverse approach did not favour this process. This is fairly consistent with the modelling study by Lambert et al. (2015) arriving at a direct effect of the iron induced biological pump strengthening of less than 10 ppm and delayed effect due to carbon burial and carbonate compensation by about 10 ppm.

Inspired by the suggestion of temperature-dependent export production of Laws et al. (2000), Matsumoto et al. (2007) quantify in a further single mechanism study the effect of temperature dependent remineralisation on the atmospheric CO_2 using an ocean biogeochemical model. According to their findings, an LGM atmospheric CO_2 decline by 30 ppm would be possible through this process. In our study, the parameter change of the POC remineralisation rate with temperature forcing did not result in a similarly likely drawdown when tested in the inverse approach against evidence from the sedimentary record. Rather our work suggests that simple temperature and pCO_2 dependent changes of ocean physics as well as biogeochemistry do not straightforwardly translate into atmospheric CO_2 changes and respective sedimentary imprints, but that the problem is more complicated.

The Southern Ocean has been established to be one of the key regions for regulating glacial-interglacial carbon dynamics. Apart from processes involving dissolved iron and nutrients, especially the physical dynamical processes - and hence stratification, deep water production, upwelling, water mass formation, and lateral advection - have been considered in conjunction with the physical/chemical and biological carbon pumps. Special attention has been placed on a northward shift of the westerlies wind forcing at the LGM as compared to today (Toggweiler et al. (2006); Watson and Garabato (2006); Watson et al. (2015)). The general idea is that a northward shift of Southern Ocean upwelling leads to reduced CO_2 outgassing and enhanced carbon export to the deep waters resulting in a deep ocean accumulation of organic matter from the surface and hence a vertical "fractionation" of carbon as well as nutrients as described already by Boyle (1988a) and Boyle (1988b)). This general view is corroborated also by recent proxy data findings (for the Southern Ocean by Gottschalk et al., 2014; also for the North Atlantic by Hoogakker et al., 2015). Refined Southern Ocean dynamics could also improve the results of our studies, but we have been limited to the flow fields available. In general, Southern Ocean flow field and tracer simulations show traditionally a large intermodel spread (Broecker et al. (1998); Roy et al. (2011); Orr (2002)). One of the reasons is the complex interplay of sea-ice as well as wind forcing and also the subgrid-scale parameterisation of convection events which occur on narrow regional scales in reality (Gordon (1978)). Still, simulating the Southern Ocean flow field and mixing remains a key challenge even for the modern ocean (Farneti et al. (2015): Downes et al. (2015); Mignot et al. (2013); Abernathey et al. (2016))."

Reviewer#2:
Figures: Some lines fall out of the y axis range in figures 6 and 7. I understand this is to highlight the fact that $CaCO_3$/POC and SST parameters are going outside the expected range, but aesthetically it is not the best. Also text and lines are sometimes one on top of each other.

Technically improved figures will be provided.

Reviewer#2:
Typos: There are a few typos throughout the text and some sentences could be simplified or rewritten for a better flow. Some typos are listed below: p. 6 "EPICA" p15, L16 "on" iof "om" Legend figure 3: "experiment"

The language issues will be addressed together with the respective remarks by Reviewer#1.

REFERENCES:

Abernathey, R., Cerovecki, I., Holland, P., Newsom, E., Mazloff, M., and Talley, L.: Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning, *Nature Geoscience*, doi:10.1038/NGEO2749, advanced online publication, in press, 2016.

Adkins, J., McIntyre, K., and Schrag, D.: The salinity, temperature, and delta O-18 of the glacial deep ocean, *Science*, 298, 1769–1773, doi:10.1126/science.5 1076252, 2002.

Anklin, M., Barnola, J., Beer, J., Blunier, T., Chappellaz, J., , Clausen, H., Dahljensen, D., Dansgaard, W., Deangelis, M., Delmas, R., Duval, P., Fratta, M., Fuchs, A., Fuhrer, K., Gundestrup, N., Hammer, C., Iversen, P., Johnsen, S., Jouzel, J., Kipfstuhl, J., Legrand, M., Lorius, C., Maggi, V., Miller, H., Moore, J., Oeschger, H., Orombelli, G., Peel, D., Raisbeck, G., Raynaud, D., Schotthvidberg, C., Schwander,
J., Shoji, H., Souchez, R., Stauffer, B., Steffensen, J., Stievenard, M., Sveinbjornsdottir, A., Thorsteinsson, T., and Wolff, E.: Climate instability during the last interglacial period recorded in the grip ice core, *Nature*, 364, 203–207, 1993.

Archer, D. and Maier-Reimer, E.: Effect of deep-sea sedimentary calcite preservation on atmospheric CO_2 concentration, *Nature*, 367, 260–263, doi:10.1038/367260a0, 1994.

Armstrong, R., Lee, C., Hedges, J., Honjo, S., and Wakeham, S.: A new, mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals, *Deep-Sea Research Part II*, 49, 219–236, 2002.

Barker, S., Chen, J., Gong, X., Jonkers, L., Knorr, G., and Thornalley, D.: Icebergs not the trigger for North Atlantic cold events, *Nature*, 520, 333+, doi:10.1038/nature14330, 2015.

Berger, W. and Keir, R.: Glacial-Holocene Changes in Atmospheric CO_2 and the Deep-Sea Record, pp. 337–351, American Geophysical Union, Washington, D.C., doi:10.1029/GM029p0337, J.E. Hansen and T. Takahashi (Eds.), Geophysical Monograph 29, 1984.

Berger,W. and Wefer, G.: Productivity of the glacial ocean - discussion of the iron hypothesis, *Limnology and Oceanography*, 36, 1899–1918, doi:10.4319/lo.1991.36.8.1899, 1991.

Bond, G., Broecker, W., Johnsen, S.,McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G.: Correlations between climate records from North Atlantic sediments and Greenland ice, *Nature*, 365, 143–147, doi:10.1038/365143a0, 1993.

Boyle, E.: Vertical oceanic nutrient fractionation and glacial interglacial CO_2 cycles, *Nature*, 331, 55–56, doi:10.1038/331055a0, 1988a.

Boyle, E.: Glacial interglacial deep ocean circulation contrast, *Chemical Geology*, 70, 108–108, doi:10.1016/0009-2541(88)90504-9, 1988b.

Broecker, W.: Ocean chemistry during glacial time, *Geochimica et Cosmochimica Acta*, 46, 1689–1705, doi:10.1016/0016-7037(82)90110-7, 1982.

Broecker, W., Peacock, S., Walker, S., Weiss, R., Fahrbach, E., Schroeder, M., Mikolajewicz, U., Heinze, C., Key, R., Peng, T.H., and Rubin, S.: How much deep water is formed in the Southern Ocean?, *Journal of Geophysical Research-Oceans*, 103, 15 833–15 843, doi:10.1029/98JC00248, 1998.

Broecker, W. and Peng, T.: Carbon cycle - 1985 Glacial to interglacial changes in the operation of the global carbon cycle, *Radiocarbon*, 28, 309–327, 1986.

Brovkin, V., Ganopolski, A., Archer, D., and Rahmstorf, S.: Lowering of glacial atmospheric CO_2 in response to changes in oceanic circulation and marine biogeochemistry, *Paleoceanography*, 22, doi:10.1029/2006PA001380, 2007.

CLIMAP Project Members: The surface of the ice-age Earth, *Science*, 191, 1131–1137, 1976.

CLIMAP Project Members: Seasonal Reconstruction of the Earth’s surface at the Last Glacial Maximum, *Geol. Soc. Am. Map Chart Ser.*, 36, 1981.

Conway, T., Wolff, E., Roethlisberger, R., Mulvaney, R., and Elderfield, H.: Constraints on soluble aerosol iron flux to the Southern Ocean at the Last Glacial Maximum, *Nature Communications*, 6, doi:10.1038/ncomms8850, 2015.

Cutler, K., Edwards, R., Taylor, F., Cheng, H., Adkins, J., Gallup, C., Cutler, P., Burr, G., and Bloom, A.: Rapid sea-level fall and deep-ocean temperature change since the last interglacial period, *Earth and Planetary Science Letters*, 206, 253–271, doi:10.1016/S0012-821X(02)01107-X, 2003.

Dansgaard, W., Johnsen, S., Clausen, H., Dahljensen, D., Gundestrup, N., Hammer, C., Hvidberg, C., Steffensen, J., Sveinbjornsdottir, A., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250-kyr ice-core record, *Nature*, 364, 218–220, doi:10.1038/364218a0, 1993.

Downes, S., Farneti, R., Uotila, P., Griffies, S., Marsland, S., Bailey, D., Behrens, E., Bentsen, M., Bi, D., Biastoch, A., Boening, C., Bozec, A., Canuto, V., Danabasoglu, E. C. G., Danilov, S., Diansky, N., Drange, H., Fogli, P., Gusev, A., Howard, A., Ilicak, M., Jung, T., Kelley, M., Large, W., Leboissetier, A., Long, M., Lu, J., Masina, S., Mishra, A., Navarra, A., Nurser, A., Patara, L., Samuels, B., Sidorenko, D., Spence, P., Tsujino, H.,Wang, Q., and Yeager, S.: An assessment of Southern Ocean water masses and sea ice during 1988-2007 in a suite of interannual CORE-II simulations, *Ocean Modelling*, 94, 67–94, doi:10.1016/j.ocemod.2015.07.022, 2015.

Dwyer, G., Cronin, T., Baker, P., Raymo, M., Buzas, J., and Correge, T.: North-Atlantic deep-water temperature-change during the late Pliocene and late quaternary climatic cycles, *Science*, 270, 1347–1351, doi:10.1126/science.270.5240.1347, 1995.

Farneti, R., Downes, S., Griffies, S., Marsland, S., Behrens, E., Bentsen, M., Bi, D., Biastoch, A., Boening, C., Bozec, A., Canuto, V., Chassignet, E., Danabasoglu, G., Danilov, S., Diansky, N., Drange, H., Fogli, P., Gusev, A., Hallberg, R., Howard, A., Ilicak, M., Jung, T., Kelley, M., Large, W., Leboissetier, A., Long, M., Lu, J., Masina, S., Mishra, A., Navarra, A., Nurser, A., Patara, L., Samuels, B., Sidorenko, D., Tsujino, H., Uotil, P., Wang, Q., and Yeager, S.: An assessment of Antarctic Circumpolar Current and Southern Ocean meridional overturning circulation during 1958-2007 in a suite of interannual CORE-II simulations, *Ocean Modelling*, 93, 84–120, doi:10.1016/j.ocemod.2015.07.009, 2015.

Gordon, A.: Deep Antarctic convection west of Maud Rise, *Journal of Physical Oceanography*, 8, 600–612, doi:10.1175/1520-0485(1978)008<0600:DACWOM>2.0.CO;2, 1978.

Gottschalk, J., Skinner, L., Lippold, J., Vogel, H., , Frank, N., Jaccard, S., and Waelbroeck, C.: Biological and physical controls in the Southern Ocean on past millennial-scale atmospheric CO_2 changes, Nature Communications, 7, doi:10.1038/ncomms11539, 2016.

Griffiths, J. D., Barker, S., Hendry, K. R., Thornalley, D. J. R., van de Flierdt, T., Hall, I. R., and Anderson, R. F.: Evidence of silicic acid leakage to the tropical Atlantic via Antarctic Intermediate Water during Marine Isotope Stage 4, *Paleoceanography*, 28, 307–318, doi:10.1002/palo.20030, 2013.

Hoogakker, B., Elderfield, H., Schmiedl, G., McCave, I., and Rickaby, R.: Glacial-interglacial changes in bottom-water oxygen content on the Portuguese margin, *Nature Geoscience*, 8, 40–43, doi:10.1038/NGEO2317, 2015.

Klaas, C. and Archer, D.: Association of sinking organic matter with various types of mineral ballast in the deep sea: Implications for the rain ratio, *Global Biogeochemical Cycles*, 16, doi:10.1029/2001GB001765, 2002.

Lambert, F., Tagliabue, A., Shaffer, G., Lamy, F.,Winckler, G., Farias, L., Gallardo, L., and Pol-Holz, R. D.: Dust fluxes and iron fertilization in Holocene and Last Glacial Maximum climates, *Geophysical Research Letters*, 42, 6014–6023, doi:10.1002/2015GL064250, 2015.

Laws, E., Falkowski, P., Smith, W., Ducklow, H., and McCarthy, J.: Temperature effects on export production in the open ocean, *Global Biogeochemical Cycles*, 14, 1231–1246, doi:10.1029/1999GB001229, 2000.

Martin, J., Coale, K., Johnson, K., Gordon, S. F. R., Tanner, S., Hunter, C., ELROD, V., Coley, J. N. T., Barber, R., Lindley, S., Watson, A., Vanscoy, K., Law, C., Liddicoat, M., Ling, R., Stanton, T., Stockel, J., Collins, C., Anderson, A., Bidigare, R., Ondrusek, M., Latasa, M., Millero, F., Lee, K., Yao, W., Zhang, J., Friedrich, G., Sakamoto, C., Chavez, F., Buck, K., Kolber, Z., Greene, R., Falkowski, P., Chisholm, S., Hoge, F., Swift, R., Yungel, J., Turner, S., Nightingale, P., Hatton, A., Liss, P., and Tindale, N.: Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean, *Nature*, 371, 123–129, doi:10.1038/371123a0, 1994.

Matsumoto, K., Hashioka, T., and Yamanaka, Y.: Effect of temperature-dependent organic carbon decay on atmospheric pCO_2, *Journal of Geophysical Research - Biogeosciences*, 112, doi:10.1029/2006JG000187, 2007.

Matsumoto, K., Sarmiento, J., and Brzezinski, M.: Silicic acid leakage from the Southern Ocean: A possible explanation for glacial atmospheric pCO_2, *Global Biogeochemical Cycles*, 16, doi:10.1029/2001GB001442, 2002.

Mignot, J., Swingedouw, D., Deshayes, J., Marti, O., Talandier, C., Seferian, R., Lengaigne, M., and Madec, G.: On the evolution of the oceanic component of the IPSL climate models from CMIP3 to CMIP5: A mean state comparison, *Ocean Modelling*, 72, 167–184, doi:10.1016/j.ocemod.2013.09.001, 2013.

Olsen, S., Shaffer, G., and Bjerrum, C.: Ocean oxygen isotope constraints on mechanisms for millennial-scale climate variability, *Paleoceanography*, 20, doi:10.1029/2004PA001063, 2005.

Orr, J.: Global Ocean Storage of Anthropogenic Carbon (GOSAC), Tech. rep., IPSL/CNRS, Saclay, France, EC Environment and Climate Programme (Contract ENV4-CT97-0495), 2002.

Ridgwell, A.: An end to the rain ratio reign?, *Geochemistry Geophysics Geosystems*, 4, doi:10.1029/2003GC000512, 2003.

Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Zeebe, R. E., and Morel, F. M.: Reduced calcification of marine plankton in response to increased atmospheric CO_2, *Nature*, 407, 364–7, doi:10.1038/35030078, http://tinyurl.sfx.mpg.de/u77b, 2000.

Roberts, J., Gottschalk, J., Skinner, L., Peck, V., Kender, S., Elderfield, H.,Waelbroeck, C., Riveiros, N., and Hodell, D.: Evolution of South Atlantic density and chemical stratification across the last deglaciation, *Proceedings of the National Academy of Sciences of the United States of America*, 113, 514–519, doi:10.1073/pnas.1511252113, 2016.

Roy, T., Bopp, L., Gehlen, M., Schneider, B., Cadule, P., Froelicher, T., Segschneider, J., Tjiputra, J., Heinze, C., and Joos, F.: Regional Impacts of Climate Change and Atmospheric CO_2 on Future Ocean Carbon Uptake: A Multimodel Linear Feedback Analysis, *Journal of Climate*, 24, 2300–2318, doi:10.1175/2010JCLI3787.1, 2011.

Skinner, L., Shackleton, N., and Elderfield, H.: Millennial-scale variability of deep-water temperature and delta O-18(dw) indicating deepwater source variations in the Northeast Atlantic, 0-34 cal. ka BP, *Geochemistry Geophysics Geosystems*, 4, doi:10.1029/2003GC000585, 2003.

Toggweiler, J., Russell, J., and Carson, S.: Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages, *Paleoceanography*, 21, doi:10.1029/2005PA001154, 2006.

Watson, A. and Garabato, A.: The role of Southern Ocean mixing and upwelling in glacial-interglacial atmospheric CO_2 change, *Tellus Series B-Chemical and Physical Meteorology*, 58, 73–87, doi:10.1111/j.1600-0889.2005.00167.x, 2006.

Watson, A., Vallis, G., and Nikurashin, M.: Southern Ocean buoyancy forcing of ocean ventilation and glacial atmospheric CO_2, *Nature Geoscience*, 8, 861+, doi:10.1038/NGEO2538, 2015.

Winguth, A., Archer, D., Duplessy, J., Maier-Reimer, E., and Mikolajewicz, U.: Sensitivity of paleonutrient tracer distributions and deep-sea circulation to glacial boundary conditions, *Paleoceanography*, 14, 304–323, doi:10.1029/1999PA900002, 1999.

Zondervan, I., Zeebe, R., Rost, B., and Riebesell, U.: Decreasing marine biogenic calcification: A negative feedback on rising atmospheric pCO_2, Global Biogeochemical Cycles, 15, 507–516, doi:10.1029/2000GB001321, 2001.