

## ***Interactive comment on “Ocean carbon inventory under warmer climate - the case of the LIG” by Augustin Kessler et al.***

### **Anonymous Referee #2**

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Review of Kessler et al. 2018

### General comments

This study aims to investigate an area of research about which we still know relatively little – the behaviour of the ocean carbon cycle during the last interglacial period. The authors do this by comparing two different climate states (125ka and 115ka) in an Earth System Model, contrasting the behaviour of the ocean carbon cycle between these two simulations. This study is a worthy addition to the published literature, but requires some major revisions, particularly in its explanation of the physical mechanisms driving the simulated changes in DIC.

Section 3.2 would benefit from a figure examining changes in Southern Ocean over-

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turning strength, looking at both the rate of deep water formation and how the wind-driven circulation changes between the two climate states (strength/ location of the Deacon cell, for example).

I am also surprised that, despite such a large change in SSW/NSW distribution in the Atlantic, the paper does not discuss the Atlantic meridional overturning circulation (AMOC). It is certainly relevant to the conclusions of the study if the two climate states have two different AMOC regimes or if the AMOC is well simulated at all and the impact this has (or doesn't have) on the results.

#### Specific comments

Please maintain one tense when writing – either past or present, but be consistent.

P2 L19 – The introduction is unusual, in that it spends a lot of time discussing the literature related to terrestrial carbon modelling for the Eemian, rather than focusing on the ocean. I question the relevance of this discussion, particularly as these papers are not discussed further in the context of the results presented within this study.

I would like to see a more robust introduction which discusses not only existing modelling studies of the ocean carbon cycle (eg: Menviel et al. 2012) but also what we might expect to find based on the proxy evidence that is referenced later in the Discussion (consider comparing to Yu et al. 2013). Considering the emphasis of the results on the change in the solubility pump, I would also like to see more written about expected changes in ocean circulation and what previous studies have found (eg. Born et al. 2010; Mokeddem et al. 2014)

Trends in atmospheric CO<sub>2</sub> are also discussed, but are not relevant to this study which compares two equilibrated climate states.

P5L24 – This could be a little clearer. Perhaps clarify that DIC<sub>dis</sub> and DIC<sub>sat</sub> equate to preformed carbon, or the solubility pump. This should be noted before these components of the solubility pump are deconstructed and their calculation described.

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P6L11 - “We will first describe”. Please be more explicit, change to something like “Section 3.1 will describe...”. Again, for “The second section”, please change to “Section 3.2” and also the sentence beginning with “Finally”.

P6L16 - “Simulated sea surface temperature (SST) during the 125ka experiment were warmer globally” with respect to what? Referencing Fig.1 would be appropriate here. I would also recommend a quick comparison to Hoffman et al. 2017 either here or in the discussion comparing the magnitude/ spatial pattern of SST change. This wouldn't require any new figures (particularly as the paper compares to PI SSTs) but simply a qualitative comparison.

P6L16 - “but the changes varied spatially and seasonally, affecting both the ventilation and the nutrient supply at the surface”. Please write in the present tense (change varied to vary). I would also like to see contours of  $\Delta_{\max}$  mixed layer depth (or some other metric to diagnose changes in convection/ upwelling) overlaid on Figure 1, or perhaps Figure 2. It would be interesting to see if, with the retreat of Antarctic sea ice in 125ka, the location of deep and intermediate water formation is shifting with respect to 115ka. Based on discussion later in the paper of the Ferrari et al. 2014 sea ice mechanism, it might also be useful to see changes in sea ice extent on these figures and how this is affecting mixed layer/ convective depth and also the location of the formation of these water masses.

P6L18 - “due to a weakening (strengthening) of the mixing process.”. Be explicit – do the authors refer to a flattening of the isopycnals resulting in reduced turbulent mixing?

P6L19 - “In the Atlantic, cooler SSTs are simulated during boreal winter and spring ( $\Delta\text{SST} < 0$ , Fig. 1a-b), which allow for more upwelled nutrients to the surface (Fig. 2a) via an increasing of the mixed layer depth.” - This is not true of the whole basin, be explicit where these changes occur. I would again re-iterate the usefulness of having changes in mixed layer depth/ convective depth contoured on these panels. The grammar of this sentence is also not quite right, please rephrase.

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P6L20 - "This higher concentration of nutrients increases the biological production (Fig. 2b) under more favourable warmer blooming season in summer in 125ka ( $\Delta\text{SST} > 0$ , Fig. 1c)." I would note that the authors should refer to 'export production' explicitly, rather than just 'biological production' which may be misunderstood as net primary productivity. Furthermore, the region of the ocean that coincides with increased export production in Fig. 2B is actually cooler in 125ka (Fig. 1c).

P6L23 – I find this sentence to be difficult to understand on first glance. Perhaps rephrase?

P6L26-27 – I would like to see further explanation regarding these 'ocean tunnels', particularly given that our current understanding of ocean dynamics in this region would suggest that intermediate water formed in the South Atlantic sector would take a very indirect route towards the equator, diminishing this signal (flowing north in the Malvinas current, until it is deflected eastward by the Brazil current, before some proportion is entrained into the Benguela Current and reaches the tropics). A reference or two would be sufficient here.

I'm also curious if the authors investigated changes in equatorial/ low latitude winds, as the decrease in export production in the Eastern equatorial Pacific may also be in part due to a weaker Equatorial Undercurrent.

P6L29 – Southern ocean upwelling is largely wind-driven and southern ocean density structure is controlled primarily by salinity rather than temperature. Changes in SSS are mentioned later on P7L30, but it is worth noting here that the change in the Southern Ocean's density structure is not purely due to an increase in SST, which is implied here.

P7L5 - "Despite latitudinally homogeneous forcing..." Not sure what this means? The difference between the two climate states should only be the concentration of greenhouse gases and orbital forcing (which should affect high-latitude insolation). This difference in insolation is zonally homogeneous, but certainly differs with latitude.

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P7L32 - 'As a net result, the water mass becomes younger in the SO because of a southward retraction of SSW and southward incursion of more and younger NSW.'. I think this isn't phrased quite correctly. The water mass becomes younger because of a retreat in Antarctic sea ice extent and influx of meltwater, (presumably) an increase in wind-driven upwelling/ mixing and an increase in buoyancy which in turn LEADS to a retraction of SSW.

P8L3 - 'into the interior during the warmest period (Fig 3b).' - please refer to it explicitly as 125ka, or simply add it afterwards (ie: into the interior during the warmer period (125ka – Fig 3b))

P8L3 - 'northward in the Indian, the' - please add Ocean/ Basin.

P8L4 - 'Indian deep water must also decrease (increase)' why is increase included in brackets here? There is no point of comparison.

P8L8 - 'the eastern side waters of the basin are simulated to be older in 125ka by as much as 300 years older.' remove 'older' at the end of the sentence.

P8L8 - 'This older water masses are created in the Pacific SO and are predominantly affected by the strong increase in SST, increasing therefore the stratification' - 'This' should be 'These' and 'increasing therefore the stratification' makes no grammatical sense. Please rephrase.

P8L9 - 'In the northern hemisphere the younger waters are due to cooler SST (Fig. 1).' I'm sceptical that a slight cooling in the surface sub-tropical and equatorial Pacific would produce a sufficient increase in circulation to decrease the water mass age of the North Pacific basin down past a depth of ~1000m. I suggest investigating the meridional overturning streamfunction for the Pacific, but more importantly, identifying a mechanism to explain why the deep North Pacific is so much younger. I suspect that, similar to the Southern Ocean, a reorganisation of water masses has simply resulted in this region of the deep ocean to be better ventilated, and has very little to do with

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SST in the North Pacific.

P8L16 - 'They are significantly different and basin specific responses of deep water ventilation rates and water mass distribution to uniform changes in forcing.' This sentence is not at all clear (what does 'they' refer to?), please rephrase.

P8L32 - 'The  $\Delta$ DIC tot of the Indian basin resembles that of the Atlantic at depth, where the soft-tissue and disequilibrium components simulate the strongest decrease (Fig. 5c, green and purple bars). However, the saturation component depicts persistent negative  $\Delta$ DIC below 1000 m depth, thereby accounting for the second most important component of the decrease throughout the water column.' These two sentences could lead to confusion, as the authors initially state that the Indian Ocean resembles the Atlantic where the soft-tissue pump and disequilibrium components are responsible for the greatest decrease in DIC, however the very next sentence correctly identifies that the saturation component is in fact the second most important component. Please rephrase to enhance clarity.

P9L9 - 'zonally averaged' I'm curious if there is a reason why these plots do not show zonally integrated values of DIC? While I'm sure this would not change the interpretation of the results, it is, in my opinion, the more appropriate depiction of  $\Delta$ DIC. This is particularly true when each panel should be representing the components of the sum total change in panel a) of each figure.

P9L13 - 'At depth, the changes in SSW and NSW lead to a decrease in younger water masses, hence less remineralized organic matter.' I find this confusing – shouldn't older deep water masses contain more remineralised DIC due to their decreased ventilation rate?

P9L15 - 'Positive change in  $\Delta$ DIC tot also arises' where?

P9L18 - 'The latter' It is unclear what is being referred to here.

P9L19 - 'The NSW water mass, formed in the North Atlantic, is generally more subject

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to biological production during its near surface northward transport before sinking into the interior than the SSW' please provide references to support this claim.

P9L25 - 'due to weaker ventilation induced by stronger SSTs in the Labrador and Nordic sea.' please reference Fig. 1 here. Also, 'stronger' is an inappropriate word here, consider replacing with something like 'warmer'.

P9L28 – Indian \*Ocean.

P9L35 - 'Changes in the bottom water DIC soft can be attributed primarily related to the difference in the disequilibrium effect due to stronger carbon export in the Southern Ocean (Fig. 2b) and to a slight decrease in the saturation component. ' Remove 'related'.

P10L10 - 'This lower organic remineralization arises from an increase of the ventilation around 30 °N and a potential increase of the upwelling generating younger water masses (Fig. 3c)' This sentence is misleading – there isn't increased ventilation at 30N, rather, water masses at 30N are better ventilated (likely via some pathway that results in upwelling in the Southern Ocean). Please rephrase to avoid confusion. Also, if I understand this correctly, ' This lower organic remineralization' refers to the decrease in DICsoft rather than an actual decrease in the remineralization rate in the ocean. If this is the case, consider rephrasing this to something along the lines of 'this decrease in biogenic carbon ...'.

P10L11 - 'This is in good agreement with the increased carbon export production (Fig. 2b)' But export production is largely unchanged or negative in the Pacific Ocean according to Fig. 2b.

' , inducing positive  $\Delta$ DIC tot near the surface, and with the cooler SST depicted in Fig. 1' Negative SSTs are only evident in Boreal winter and spring – does this outweigh the effect of considerably warmer SSTs in summer and autumn?

P10L21 - 'This SSW mainly composes the Pacific interior ocean.' please rephrase.

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P10L30 - 'Significant decreases of the ocean carbon' replace 'of the' with 'in'.

P10L31 – This is a good summary, but I would suggest that instead of saying 'Most of this decrease', give the exact %.

I would also like to see an extra sentence at the end of this summary paragraph highlighting the mechanisms responsible for the change in ocean ventilation. This could include AMOC strength, changes in SSW/NSW, changes in AABW/IW formation, sea ice changes etc.

Comparison to proxies regarding water masses is good, though I would suggest one or two extra studies that could be referenced during the discussion (please see list at the end of this document).

P11L24 - 'A sense of the scale of the changes model simulations can be gained through comparison to previous modelling efforts where atmospheric CO<sub>2</sub> was not fixed.' this sentence does not make sense, please rephrase.

I'd also like to see comparisons to Menviel et al. 2012 here.

P12L1 - 'obtained a difference in atmospheric CO<sub>2</sub> concentration and terrestrial carbon storage of about 40 PgC and 350 PgC, respectively' If you refer to an atmospheric concentration, then please change the 40 PgC to ppm equivalent, or alternatively, rephrase to refer to "atmospheric and terrestrial carbon storage" instead. The authors should also be clearer here: is this +350Pg and -40Pg? Similarly, the following line claims that a change in ocean carbon of 310 Pg corresponds well to your findings of -314.1 PgC. These values are opposite, is the former supposed to be -310?

P12L4 - 'However, the changes in CO<sub>2</sub> concentration in the atmosphere that they simulated steadily increases' This is poorly worded and gives impression that the rate of change of atmospheric CO<sub>2</sub> is varying somehow. Please rephrase. Something along the lines of "However, their simulated atmospheric CO<sub>2</sub> steadily increases over this period".

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P12L31 - 'The ongoing global warming raises questions about the oceanic carbon sink and its efficiency under a warmer climate condition.' Be specific. 'Ongoing anthropogenic warming...' and remove 'The' from the start of the sentence.

P12L32 - 'In this study, we use a fully-coupled NorESM' please change 'a' to 'the' (unless of course there is more than one version of Nor-ESM, which should then be stated).

P13L1 - 'We focus on the differences that occurred in 125ka in comparison to 115ka, specifically the differences at global and basin scales.' This is vague – be explicit that you're looking at changes in the ocean carbon cycle.

P13L2 - 'Thereby, to our knowledge, it is the first attempt in elucidating the biogeochemical and physical processes that are responsible for the ocean carbon inventory changes under warmer climate conditions during the LIG.' Please see Menviel et al. 2012.

P13L24 - 'The western Pacific is influenced by water masses coming from the Pacific Southern Ocean, with a warmer SST that hinders the ventilation and increases the residence time of the interior water masses on the eastern side of the basin.' On P8L6, the authors state that the Western Pacific is ventilated by water originating from the Atlantic. Either this section or that in section 3.2 needs to be clarified/ corrected.

Minor typographical errors/ suggestions

Please capitalise names of basins/ hemispheres throughout the manuscript.

P1L7 - "We find a considerable weaker ocean dissolved..." this sentence does not make grammatical sense. I would suggest changing it to "We find considerably reduced ocean dissolved..."

L14 - "...restricting the extend of DIC rich southern sourced water reducing the storage of biological remineralized carbon at depth." Typo. 'extend' should be 'extent'.

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Furthermore, consider rephrasing as follows “...restricting the extent of DIC rich southern sourced water, thereby reducing the storage of biological remineralized carbon at depth.

P1L20 - “If the anthropogenic greenhouse...” remove ‘the’.

P1L23 – consider rephrasing “For this, the changes in the the warm Eemian period may be considered as an analog for a future warmer climate.” to “The changes in the the warm Eemian period may therefore be considered an analog for a future warmer climate.

P3L26 – prescribed should be prescribes.

P3L27 - “(>100m depth)” should this not be <100m depth? Or are you referring to the sinking rate of the particles that have left the euphotic zone?

P3L31 - ‘vertical advection’: convection?

P4L24 - ‘the dissolved inorganic carbon’. ‘the’ is not necessary.

P5L25 – Remove ‘mostly’ - vague language.

P6L13 - ‘Each analysis have’ - please rephrase.

P7L2 - ‘southern hemisphere’ should be Southern Hemisphere.

P7L17 - ‘translates to a stronger ventilation rate age and’ remove ‘age’.

P7L22 - ‘since the SST in the SO is rather warmer in 125ka’ remove ‘rather’.

P7L26 - ‘byFerrari et al. (2014)’ space missing

P7L26 - ‘study,Luo et al...’ space missing.

P8L27 - ‘main contributors for the weaker carbon inventory’ replace weaker with reduced.

P9L3 - ‘simulating a strong positive difference of about +18 PgC’ strong with respect to

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what? I would suggest removing such descriptive words.

P9L6 - 'However, the saturation component has also a considerable influence' 'has also' should be 'also has'.

P9L29 - 'Only in the region that may correspond to the AAIW the simulated 4DIC tot are positive (Fig. 7a, red shade).' Poor grammar, please rephrase.

P11L6 - 'has been previously been inferred' remove second 'been'.

P11L27 - 'but at slightly weaker decrease than in our study.' grammatically incorrect. Please rephrase.

P12L8 - 'our model study shows an heterogeneous response' 'a' not 'an'.

P12L10 - 'Such heterogeneous response of the biogeochemical divide have also been highlighted by Moore et al. (2018) for future projections under warmer climatic conditions.' Consider rephrasing to 'Such a response...' and '...has also been highlighted...'

P12L11 - 'This implies that changes in the biogeochemical divide could somewhat be similarly impacted from past and future anthropogenic CO<sub>2</sub> forcings' Poorly phrased, please correct.

P12L12 - "Reconstruct and understand the pattern and signs of past responses of large scale productivity to climate forcing are therefore critical for assessing not only the sign but also the sensitivity of different regions to climate change." Poorly phrased, please re-write.

P12L15 - 'Factors that could influence ocean carbon storage including sea level, riverine input of nutrients, and atmospheric dust loading, which are all set to preindustrial levels in our simulations, but may have been different in the LIG.' remove 'which', otherwise sentence does not make grammatical sense.

P12L23 - 'Our quasi-equilibrated model simulations for 115ka and 125ka, also lack ice sheet and the corresponding freshwater input variability, do not address such shorter-

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term changes that could affect the ocean carbon inventory (Stocker and Schmittner, 1997).’ \*and do not address.

P13L32 - ‘a priori’ typically written in italics, though this is only a suggestion.

## References

Few references include a doi. Please add them wherever available.

Table 1: ‘southern sources water’ correct to ‘sourced’ I’m also curious as to why values for NSW were not also included in this table and discussed in the manuscript.

Figure 2. The authors refer to this box as a ‘turquoise rectangle’ here but as a green rectangle elsewhere in the manuscript. Please be consistent and change one or the other.

Figure 4. Please include units for the neutral density contours in the caption.

Figure 5. Again, I question the utility of averaging over 500m intervals rather than summing. Particularly when dealing with bulk differences. Is there a reason for this?

## Recommended references

Menviel et al. 2012 - Simulating atmospheric CO<sub>2</sub>, 13C and the marine carbon cycle during the Last Glacial–Interglacial cycle: possible role for a deepening of the mean remineralization depth and an increase in the oceanic nutrient inventory

Yu et al. 2013 - Responses of the deep ocean carbonate system to carbon reorganization during the Last Glacial–interglacial cycle

Born et al. 2010 Sea ice induced changes in ocean circulation during the Eemian

Born et al. 2011 Late Eemian warming in the Nordic Seas as seen in proxy data and climate models

Hoffman et al. 2017 Regional and global sea-surface temperatures during the last interglaciation

Mokeddem et al. 2014 Oceanographic dynamics and the end of the last interglacial in the subpolar North Atlantic

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Interactive comment on Clim. Past Discuss., <https://doi.org/10.5194/cp-2018-77>, 2018.

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