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To the Editor Climate of the Past (CP):

Our paper, "**Oceanic response to changes in the WAIS and astronomical forcing during the MIS31 superinterglacial**" is reviewed.

Please find enclosed point-by-point replies to the reviewer comments and suggestions. We greatly appreciate all comments and careful evaluation done by the anonymous reviewers, which will substantially improve the manuscript.

Sincerely,
Flavio Justino

Reviewer #1:

General comments:

The reviewer points to the relevance of the manuscript (MS) in the framework of Antarctic tipping point, insofar as the melting of West Antarctic Ice Sheet is concerned. This is a point which we had not explicitly mentioned, but it is an interesting one and we will include a statement on this in the revised MS. Moreover, the reviewer finds that modifications in sea-ice cover as discussed in the MS may shed some light on the potential impact of global warming in the extra-tropical latitudes.

The reviewer states, however, that the MS is written too fast and some sections needs better structure. We have modified the MS in this revised version where suggested by the reviewer. The reviewer also suggested co-authors should help improve the English. This will be taken care of.

A major concern of the reviewer is related to the model biases in the extra-tropical latitudes. This is an important point indeed. As discussed in several publications the representation of extra-tropical SST and sea-ice are currently among the largest limitations of Earth climate modeling.

Based on a CORE model intercomparison (Griffies, et al 2009 *Coordinated Ocean-ice Reference Experiment (CORES), 2009,Ocean Modelling, doi:10.1016/j.ocemod.2008.08.007)* we are finding that the Speedy-nemo biases are in the lower range as compared to other models. We will include this reference and a discussion of this point in the revised MS. In this intercomparison with driven ocean only simulations it was demonstrated that even in this idealized scenario generally models appear to have large biases in all fields (e.gSST, SSS, sea ice, zonal velocity in Equatorial Pacific sub-surface, their Fig 7 and 8).In particular, the models' AMOCs (Fig. 23) show substantial spread, but Kiel-ORCA performs very well. Speedy-NEMO, which is the ocean component used in our study, is a coupled ocean-atmosphere model that applies the same Kiel-ORCA ocean component. It gives us some confidence in our model that Kiel-ORCA is among the better models of the CORE model intercomparison. This is supported by a recent publication by Kucharski et al 2015 (cited in the MS).

As discussed in the MS our AMOC exhibits values that closely match observation, e.g. compared to Ferrari and Ferreira (2011) and Talley (2003) (cited in the MS). In the revised MS we will also point to the fact that higher resolution models with the same base as Speedy_NEMO estimate the AMOC well (Stepanov and Haines 2014 doi:10.5194/os-10-645-2014, Griffies, et al 2009 doi:10.1016/j.ocemod.2008.08.007, Sterl et al 2012 Cli. Dyn.). Consequently, a fair representation of the oceanic heat transport (OHT) should be expected under present day conditions because the majority of the OHT is driven by the AMOC.

The reviewer also argue that we admit that the OHT in our simulation is largely biased. However, this is a misunderstanding because the text in Page 4, Lines 25-30 in the original MS refers to the SPEEDO model instead of Speedy-NEMO. The former has in fact limitation in reproducing the AMOC. The statement was used to justify the use of a more complex ocean model utilized in our MS.

The reviewer suggested the inclusion of a figure showing modeled OHT versus observations. This is however not feasible because there are no observations of global OHT as such, but only hydrographical sections along individual latitude belts or indirect estimates from the residually-derived surface fluxes. Our Figure 4a matches very closely other model estimates and blended data (see Trenberth and Caron 2001, Trenberth and Fasullo 2017) for present day conditions, as shown in the figure below (included here, but not in the revised MS).

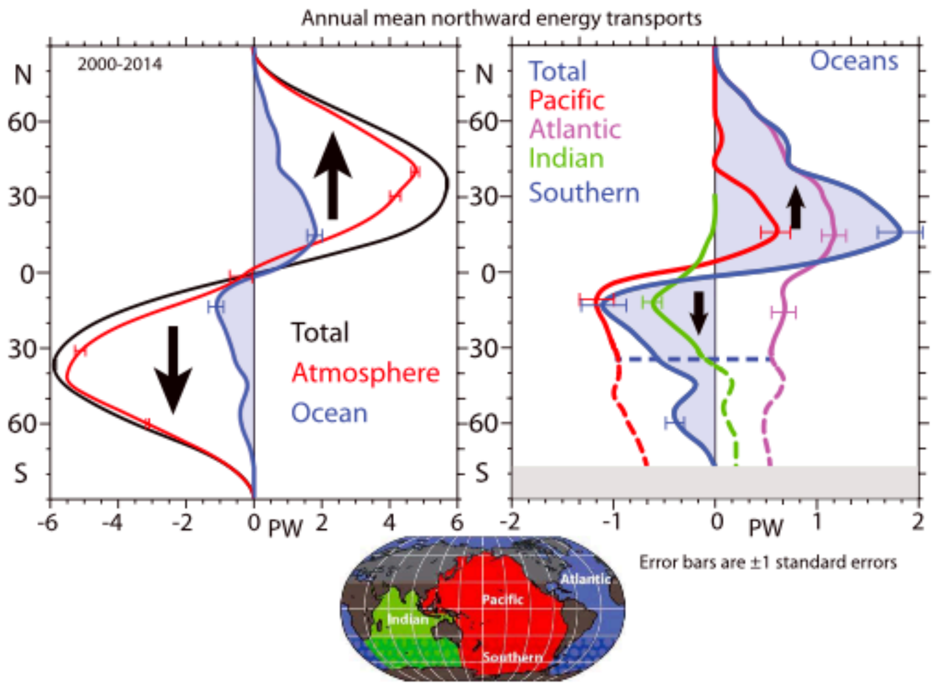


Figure 3. Northward energy transports: The annual and zonal means of the northward energy transports for 2000–2014 in PW for (left) the total Earth system (black), the atmosphere (red) and the ocean (blue). (right) The ocean component broken down into the contributions from the Atlantic (violet), Pacific (red), and Indian (green) Oceans which combine south of 35°S to give the southern ocean value, as given in the small map below. For dOHC/dt, data only through 2013 are considered. The error bars are ±1 standard deviation.

Therefore, we do not intend to include such a comparison in the revised MS We will mention in the revised MS that the peak of Atlantic OHT varies in position and magnitude among estimates in energy balance approximations and in climate model results.

As suggested by the reviewer, the revised version includes t-test statistics for differences between the CTR simulation and the sensitivity experiments. This is shown at the end of this document.

Comments annotated in the PDF file by the reviewer:

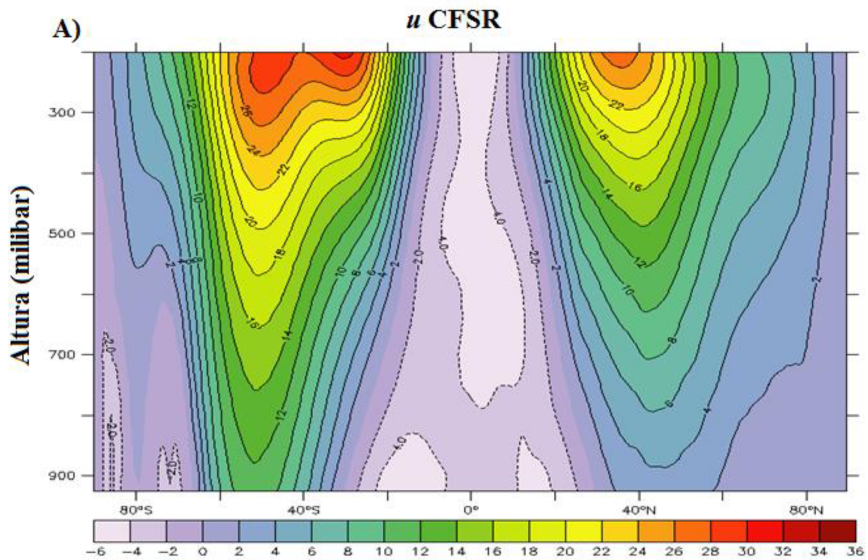
1. PAGE 1. In fact there exists changes of the MOC and OHT in both Atlantic and Pacific, but in the latter they are stronger. This will be modified in the abstract.

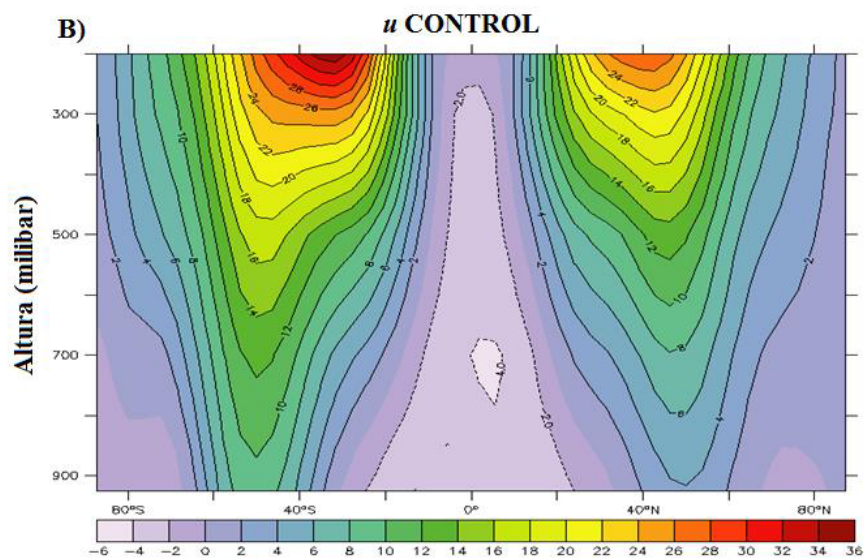
2. PAGE 1. We have explained the mechanisms responsible for changes in the PMOC (Figure 5 flowchart in original MS). We do not have reason to believe that these changes are related to the model biases due to its resolution. Speedy-NEMO is run in a reasonable resolution for a global model in particular in the tropics where most of the OHT is transported. The same applies for changes in sea-ice in the sensitivity experiments.
3. PAGE 2. The sentence will be modified to: "Additionally, 325 ppm characterizes the CO2 concentration by the year 1950 which does not include the increase in CO2 due to human emission in the end of the 20th century.
4. PAGE 3 -1. The analyses have been conducted for the last 100 years of a 1000 year -long simulation.

   PAGE 3 -2. As demonstrated in Fig 4 supp. material, our coupled model is able to reproduce the main sites of deep water formation in the SH.

   PAGE 3 -3, 4. The manuscript focuses on annual mean changes of the MIS31 climate. Discussion of the seasonal cycle, though very important, is out of the scope of the paper.

   PAGE 3 -4, 5. To address the reviewer comment that our vertical wind structure and the jet is shifted southward as compared to those of reanalysis, we show below the zonal wind profile.





Here it is seen that despite limitation in our atmospheric component of the coupled model, Speedy is suitable for our study. Additional analyses are provided in http://users.ictp.it/~kucharsk/speedy8_clim.html.

PAGE 3 -6. We will include in the conclusion limitations of our analyses as well as caveats related to the modeling framework.

PAGE 4 -1. Statement will be modified according to reviewer suggestion.

PAGE4 -2. No, we have not included changes in the initial salinity field in response to the WAIS collapse. This has been treated similarly previously in Justino et al (2014 Cli. Dyn.). This is supported by Aiken and England (2008) who demonstrated limited response of the climate system to the freshening implied by Antarctic sea ice melt.

Moreover, Vaughan and Spouge (2001) argued that an outflow rate associated with WAIS melting is not realistically attainable, making it difficult to implement in a rose experiment. However, changes in temperature around Antarctica might be expected by adding freshwater. This has been included in the revised MS.

The MS focuses on analyzing the climate response to changes in the Antarctic topography due to WAIS collapse, insofar mechanical changes in orography lead to modified atmospheric lapse-rate.

PAGE 4 -3. All figures will be modified accordingly

PAGE 4 -4. The sentence will be removed.

PAGE 4 -5. Yes, Speedy-NEMO can properly capture the sites of deep water formation in the Northern Hemisphere as shown in Figure 3a. This is also true in the Southern Hemisphere as shown in the supplementary material Figure 4. This will be pointed out in the revised MS.

PAGE 4 -6. The statement will be removed as suggested to Section 2.1.

PAGE 5 -1. References will be added to observations and modeling based studies (Stepanov and Haines 2014 doi:10.5194/os-10-645-2014, Griffies, et al 2009 doi:10.1016/j.ocemod.2008.08.007, Sterl et al 2012 Cli. Dyn.)

PAGE 5 -2. Reference will be included, Mathiot et al. 2010
http://dx.doi.org/10.1016/j.ocemod.2010.07.001

PAGE 5 -3,4 Brackets will be included and Figure 2 will be modified

PAGE 5 -5. In conditions of reduced sea-ice thickness there is an increase in the heat flux from the ocean to the atmosphere further increasing the convective mixing. The exchange of heat and mass between the atmosphere and ocean is strongly modulated by sea ice and vice-versa.

PAGE 5 -6. We are aware that seasonal analyses of the MIS31 sea-ice characteristics are important for understanding the global climate. However, in our analyses of MIS31, our main focus is climatic features that vary on long time-scales, such as AMOC, PMOC and OHT. A thorough discussion of seasonal changes is beyond the scope. We will explain this shortly.

PAGE 5 -7. Reference to Yin and Berger (2012) will be added

PAGE 5 -8. Paragraph will be removed

PAGE 6 -1. Surface temperature refers to SST or land surface temperature. This will be clarified.

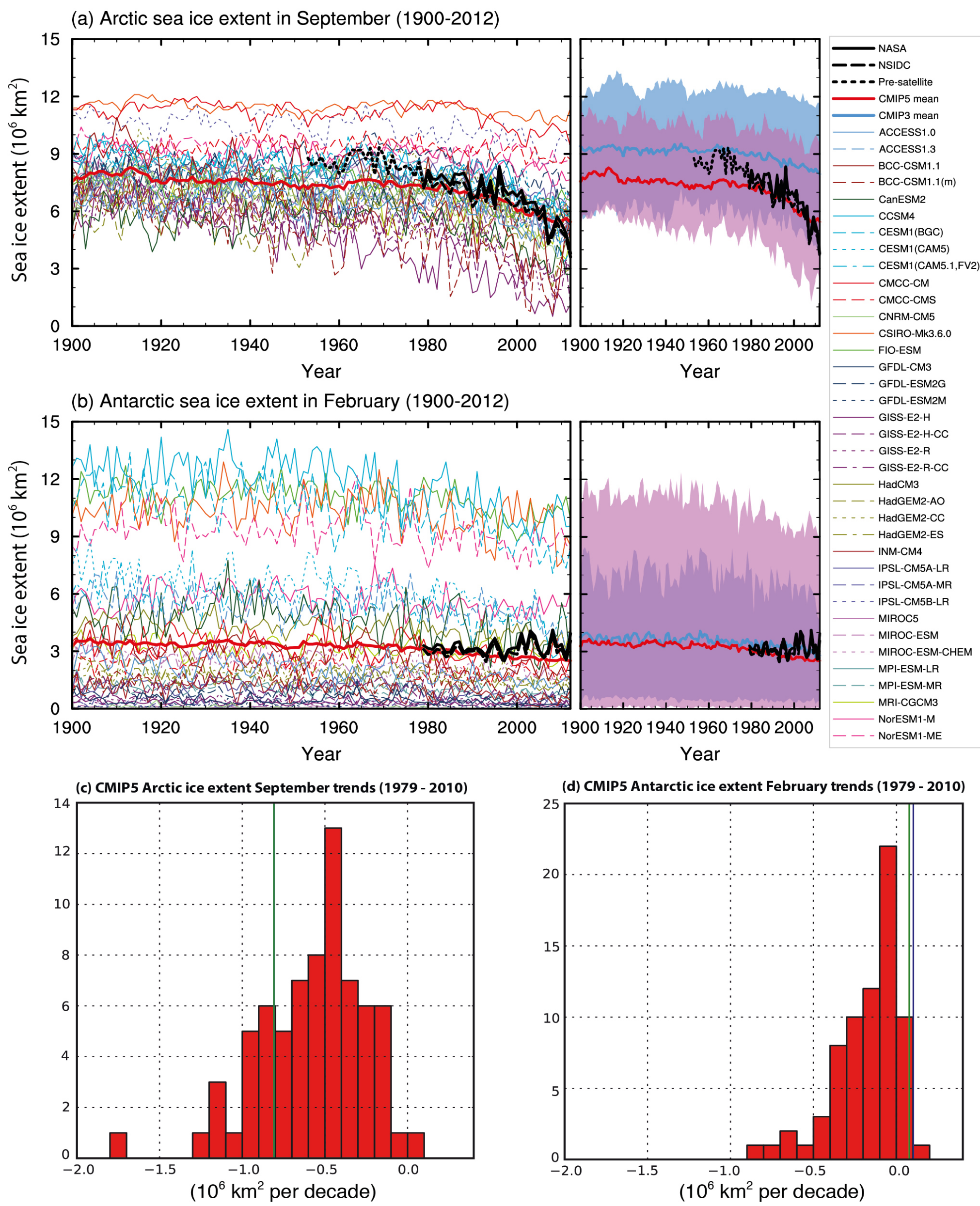
PAGE 6 -2. This statement is important because it emphasizes the astronomically driven air-sea interaction which is a crucial mechanism related to changes in SST. The reviewer has requested to include temperature values in the dots and squares shown in Figure 2c. This is not practical because the original reconstructions exhibit large uncertainties in the equatorial temperatures, as they been inferred from changes in the Walker circulation. The same applies for the polar region though the inference for cooling/warming is based on different processes. Wet et al 2016, EPSL argued that "we hesitate to draw conclusions on the absolute temperature values reached during the studied interval due to the calibration issues, numerous interesting features are apparent based on relative temperature changes." Highlighting the complexity of proxy-model data intercomparison

PAGE 6 -4. The statement will be re-phrased.

PAGE 6 -5. The reviewer argues that the model bias can limit the reliability of our findings. It is well known that all coupled models exhibit limitations in particular over the polar regions, as assessed by the IPCC AR5 (shown in the figure below).

Evaluation of sea ice in models is hampered by insufficient observations of some key variables (e.g. ice thickness). Nevertheless, particular climate anomalies resulting from inclusion of distinct boundary conditions may be primarily assumed to be climate-driven. Though, we will emphasize in the revised version limitations in our simulation of sea–ice in the Weddell Sea.

PAGE 6 -6. We compared the sea-ice extent in all experiments MIS31,TOPO and AST. This is important to provide to the reader an evaluation of the individual impacts of implementing the boundary conditions. Moreover, this can shed light on non-linear effects of the joint forcing (TOPO + AST) applied in the MIS31 run.



(Top and middle rows) Time series of sea ice extent from 1900 to 2012 for (a) the Arctic in September and (b) the Antarctic in February, as modelled in CMIP5 (coloured lines) and observations-based (NASA; Comiso and Nishio, 2008) and NSIDC; (Fetterer et al., 2002), solid and dashed thick black lines, respectively). The CMIP5 multi- model ensemble mean (thick red line) is based on 37 CMIP5 models (historical simulations extended after 2005 with RCP4.5 projections). Each model is represented with a single simulation. The dotted black line for the Arctic in (a) relates to the pre-satellite period of observation-based time series (Stroeve et al., 2012). In (a) and (b) the panels on the right are based on the corresponding 37-member ensemble means from CMIP5 (thick red lines) and 12-model ensemble means from CMIP3 (thick blue lines). The CMIP3 12-model means are based on CMIP3 historical simulations extended after 1999 with Special Report on Emission Scenarios (SRES) A2 projections. The pink and light blue shadings denote the 5 to 95 percentile range for the corresponding ensembles. Note that these are monthly means, not yearly minima. (Adapted from Pavlova et al., 2011.) (Bottom row) CMIP5 sea ice extent trend distributions over the period 1979–2010 for (c) the Arctic in September and (d) the Antarctic in February. Altogether 66 realizations are shown from 26 different models (historical simulations extended after 2005 with RCP4.5 projections). They are compared against the observations-based estimates of the trends (green vertical lines in (c) and (d) from Comiso and Nishio (2008); blue vertical line in (d) from Parkinson and Cavalieri (2012)). In (c), the observations-based estimates (Cavalieri and Parkinson, 2012; Comiso and Nishio, 2008) coincide.

PAGE 7 -1, 2, 3. We will provide new figures, but kept the subsection "*Changes in MOC and OHT.*" Reference will be included (Stouffer et al 2007).

PAGE 7 -4. Stronger mean winds refer to comparison to annual mean conditions, this occurs for instance in winter months. This may also apply for the sensitivity experiments in comparison to CTR simulation. This will be better explained.

PAGE 7 -5,6. New figure and the statistical significance of differences will be provided for Table 1.

PAGE 7 -7. The reviewer is right, there is no clear evidence indicating a shallower cell in the TOPO. The statement will be removed.

PAGE 7 -8,9,10. The paragraph is modified.

PAGE 7 -11. We will implement in the revised MS as suggested: "changes in topography of the WAIS, shown in Figures 2 and 3, have no significant impact and therefore AST and MIS 31 show very similar results. Thus we choose to show only results for MIS 31."

PAGE 7 -12. The reviewer is right, we have not discussed changes in the main site of NADW formation between CTR and MIS31. To clarify this we will include in the revised MS: "The joint effect of the astronomical and WAIS topography forcings in the MIS31 climate is to increase density flux in the Labrador Sea and the North Atlantic in the MIS31, as compared to the CTR counterpart (Figure 3c). Another source of NADW formation during the MIS31 interglacial is located in the Norwegian Sea, as shown in Figure 3f."

PAGE 7 -13. All figures have been redone including t-test statistics. This has shown that our statement on the intrusion of AABW in the North Atlantic included in the original MS is valid.

PAGE 14 -1. Statement will be removed.

PAGE 14 -2. In fact, superficial transport does not decrease. In CTR simulation the zonal mean flow in the North Atlantic is southward between 20N-Equator (Fig. 3d) whereas in MIS31 it shifts northward with maximum between 20N-40N. This will be clarified in the revised MS.

PAGE 14 -3. The reviewer suggestion will be included.

PAGE 14 -4 Figure will be included in the supplementary material.

PAGE 14 -5. This paragraph shows the initial mechanisms related to the formation of the PMOC. The flowchart (supp. Material Fig 4) explains in more detail the climate interaction related to the PMAC formation.

PAGE 14 -6. Paragraph will be modified to include the reviewer suggestion.

Reviewer #2

The main comment raised by the reviewer concerns the possibility of comparing our MIS31 simulation with similar experiments of MIS1 and 5e. We recognize that seeing our MIS31 experiments in relation to these two other interglacials would add to the manuscript value. However, this will require another set of experiments specifically 6 additional runs. We regret that at this stage is not feasible to proceed as suggested by the reviewer, as new modeling experiments could not be conducted in due time. Because an AOGCM is used, demanding computational time and complexity in interpreting global results make this task un-attainable. In fact, it is for the first time that such experiments have been performed with a full rather than a slab oceasn model. We will leave this interesting comparison to a potential follow up publication. However, all other comments by this reviewer are addressed.

We will modify the introductory section to better define the manuscript focus. Also we will emphasize clearer that our study is an improvement of previous ones conducted with slab ocean models. Indeed, this is the first study conducted with an AOGCM to evaluate the

MIS31 interglacial, performed to disentangle individual climate responses to astronomical and WAIS topography forcings.

We will add the suggested references, and their main findings in the Introduction.

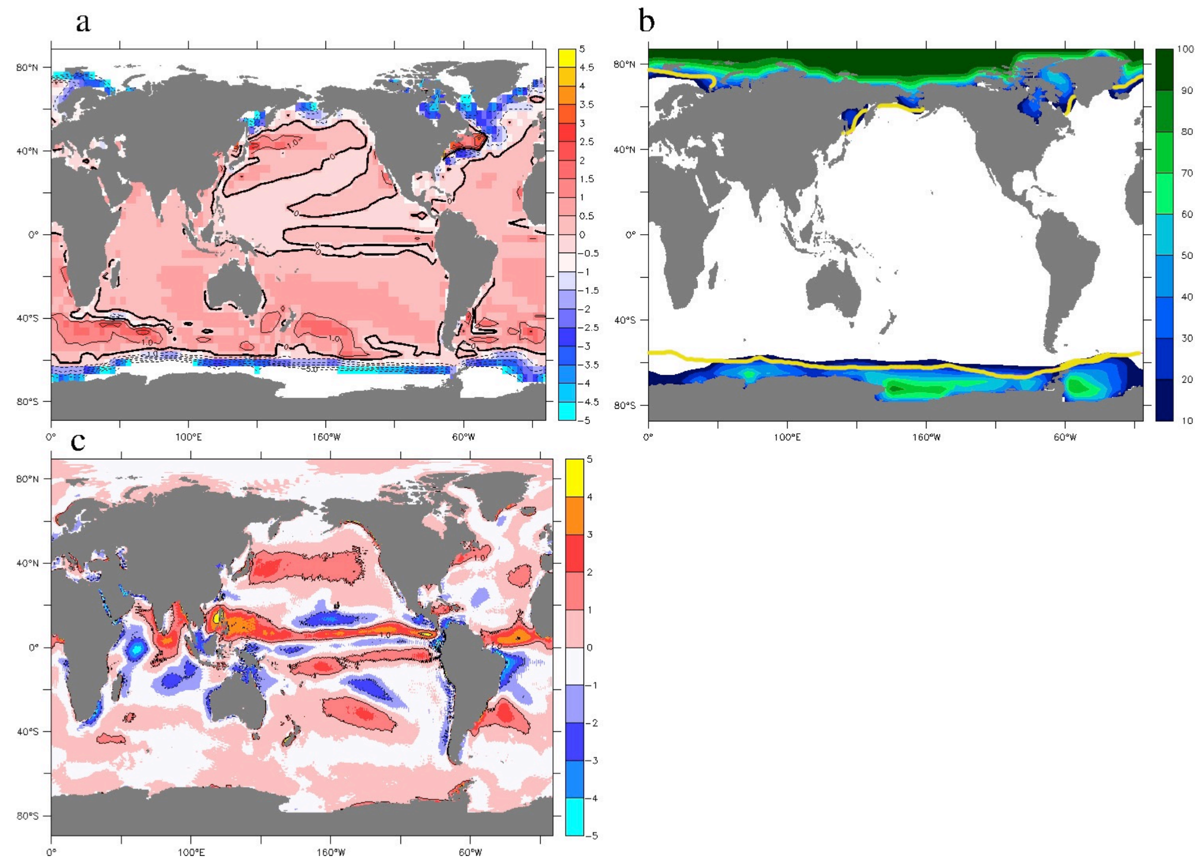
We will include a paragraph on the CO2 uncertainties during MIS31, and their potential impact on our results which assume present day CO2.

There are unfortunately no observations of global OHT as presented in the MS, we have therefore, compared with indirect estimations. This point was raised also by reviewer #1, and in our reply to her/him we explain in some more detail why we will refrain from including such a comparison.

Regarding the paleo-model inter-comparison shown in Figure 2c, we will argue that the MIS31 interval lacks extensive reconstructions, and those available do not provide magnitudes, but rather in general express whether the climate state was cooler or warmer than the present climate. This is our reason for showing red squares (warming) and blue squares (cooling) together with modeled temperature anomalies.

* Regarding to CO_2, CH_4 and N_2O concentration.

It has been proposed by Hoenisch et al. (2009) that the MIS31 has the highest partial pressure of CO_2 of the mid-Pleistocene, by about 325 ppm. However, according to their Figure 1, the CO2 concentration could vary between 300 and 350 ppm during the MIS31, due to propagated error of the individual pH, SST, salinity, and alkalinity. The uncertainty in the atmospheric composition may lead to overestimation in the NH warming as simulated in our study. Changes in CO_2 by about +50 ppm may be associated with +0.3K change in globally averaged surface temperature. In fact, this alteration in temperature is within the uncertainties of the climate sensitivity (Bindoff et al. 2013). The CH_4 (800 ppb, Loulergue et al. 2008) and N_2O (288 ppb, Schilt et al. 2010) concentrations are similar to Coletii et al. (2015).



(a) Surface temperature differences (!C) between the CTR and the NOAA-OI-surface temperature-V2 . The white shading indicates surface temperatures -1.8!C. (b) Sea-ice cover in the CTR (shaded in %) and the sea ice (yellow line)based on HadISST. (c) Time-averaged E - P flux differences (mm day−1) between the control simulation and the ERAI.

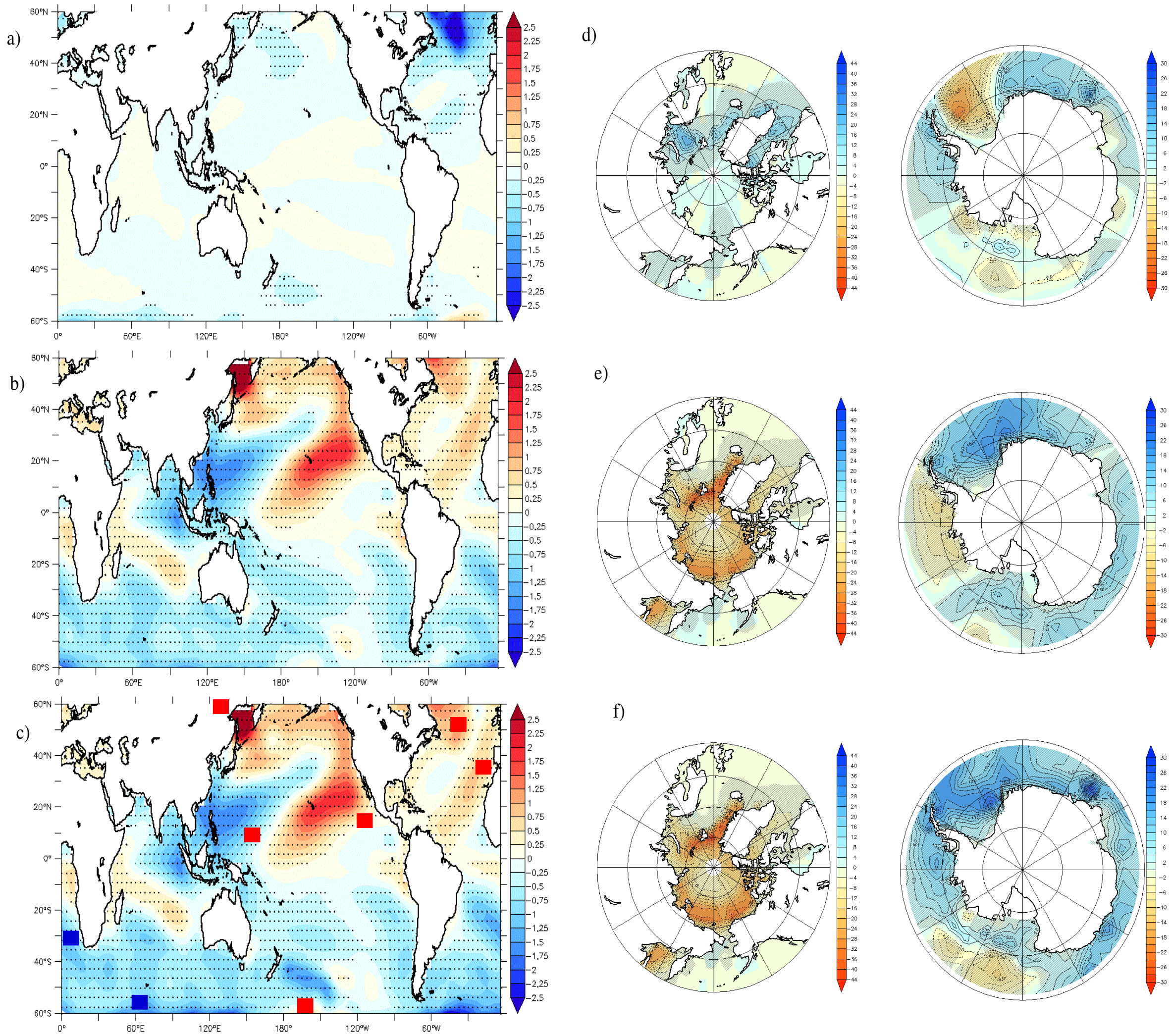


Figure 2. Surface temperature differences (C) between (a) TOPO, (b) AST, and (c) MIS31 compared to the CTR. Sea-ice differences (%) between the runs (d, e, f) Land-ocean reconstructions are shown as red squares (warmer MIS31 conditions) and blue squares (colder MIS31 conditions) as compared to CTR simulation. Dotted areas are significant at 95% based on t-test statistics.

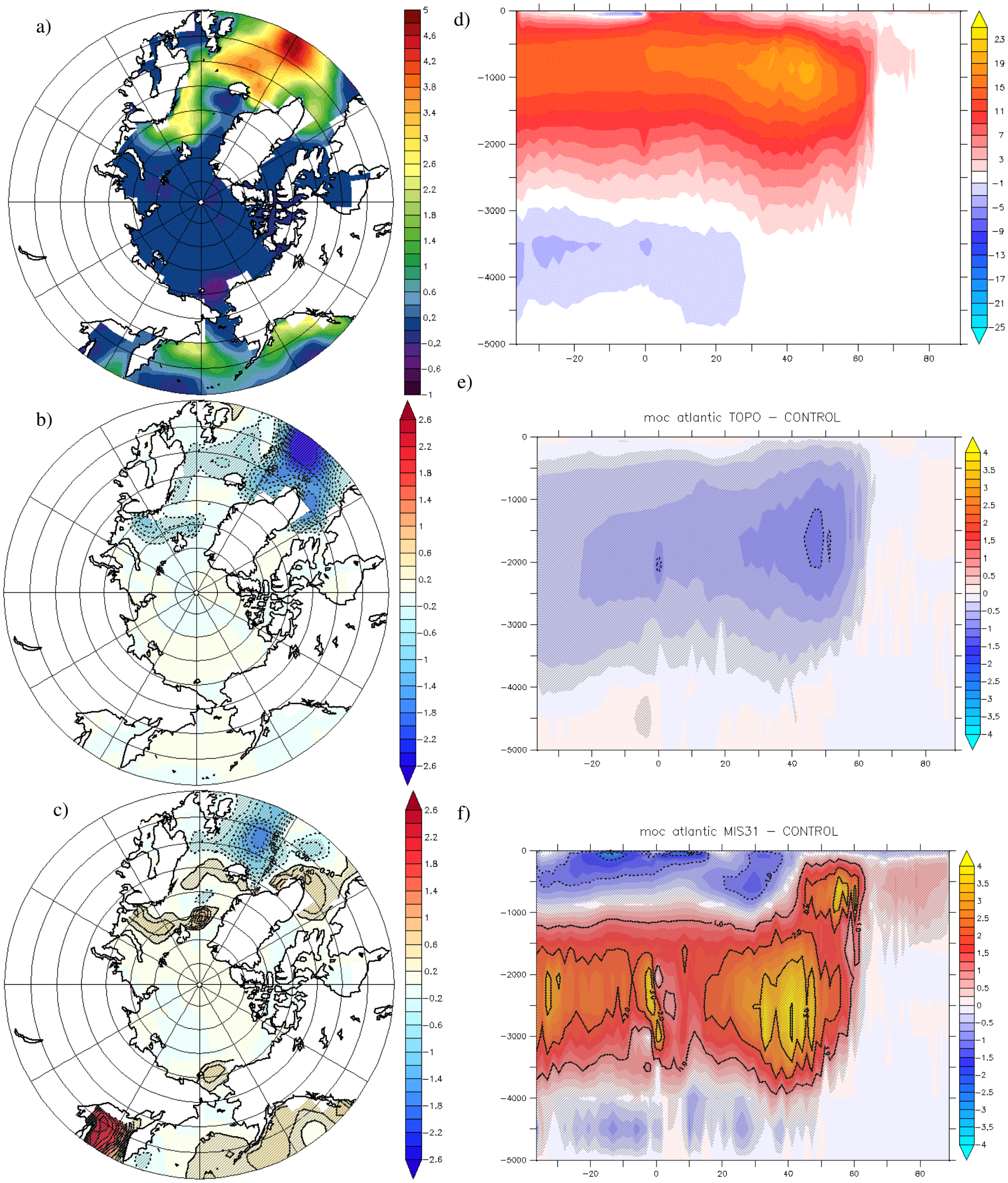


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Figure 3. Density flux for CTR (a, 10^{-6} kg m^{-2} s^{-1}) and differences between the sensitivity experiments and CTR (b) TOPO, (c) MIS31.(d) Time-averaged MOC (Sv) in the CTR and differences between the CTR and (e) TOPO and (f) MIS31. Hatched areas are significant at 95% based on t-test statistics.

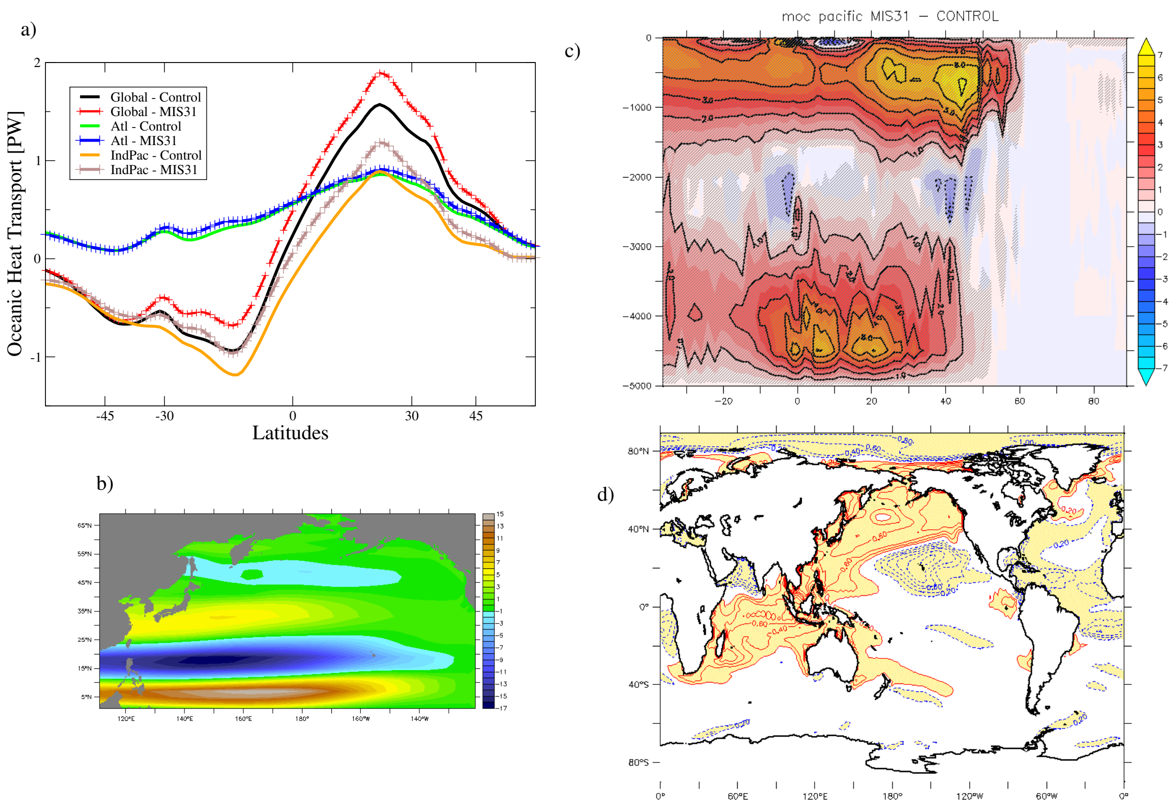

Figure 4. (a) OHT (PW) for CTR (solid line) and MIS31 (dashed-crossed line). (b) Sverdrup transport differences (Sv) between the MIS31 and CTR. (c) Differences between the MIS31 and CTR MOC in the Pacific ocean (shaded, Sv), and contour shows the Pacific MOC in CTR. (d) Surface salinity differences between MIS31 and CTR. Hatched (Yellow) areas are significant at 95% based on t-test statistics in c (d).