Dear Dr. Langebroek,

Thanks for the constructive comments. The manuscript has been clarified and improved by taking your comments into account.

Notes: unless otherwise specified, line numbers refer to the non-updated manuscript version. The authors' comments are in blue, and the changes in the manuscript are in green.

General Comments

1. More discussion is needed on section 2 Antarctic ice-sheet geometry. There is a nice overview of literature, but no discussion on why the ice sheet configurations of the previous Miocene studies are discarded, and why Pollard's Oligocene configuration was used instead. You probably prefer to not use the configurations of Langebroek and Oerlemans, as they use rather simple model configurations. But why do you discard the geometry of Gasson et al.? Related: what forcing and boundary conditions are used in Pollard's simulations? How does that compare to the Middle Miocene?

As the reviewer mentions, the reason why Oerlemans and Langebroek's configurations were discarded is that they use rather simple model configurations. We wanted to provide a characterization of the Antarctic ice-sheet in two dimensions, i.e. varying with both latitude and longitude, and this is not available from Oerlemans or Langebroek's studies.
The scope of the current study was to provide Antarctic topography data consistent with published Antarctic ice volume estimates for the MMCO and MMG, and this was successfully accomplished. The configuration of Gasson et al. (2016) could be considered in future sensitivity studies, because uncertainties in the ice-volume estimates are high, but we consider the data from Pollard's simulations used here definitely suitable for the Middle Miocene since there is little to link those data to a specific time period (except for the Laskar orbits) (see below). Additionally, the distribution of ice in our study is comparable to that in Gasson et al. (2016): for the MMG, a continental scale ice-sheet exists in East Antarctica with ice thicknesses of ~3000-4000 m, although in West Antarctica there is less ice in Pollard's data; for the MMCO, the ice-sheets occupy similar positions, although they are less extensive in Pollard's data.
Regarding David Pollard's simulations, the physical model used is close to that described in Pollard and DeConto (2012), but with no marine ice physics, so that any floating ice is immediately removed. The bedrock-elevation boundary conditions are from the modern ALBMAPv1 dataset (Le

Brocq et al., 2010).

Climate forcing is obtained from a matrix of previous Global Climate Model (GCM) climates for various orbits, CO2 levels and ice sizes. The GCM used is GENESIS version 3 (as in Alder et al., 2011, except with a slab mixed layer ocean). Three Earth orbits are used, with eccentricity, precession and obliquity set corresponding to warm, intermediate and cold austral summers. Three CO2 levels are used, spanning the range in the long term run. Three Antarctic ice sizes (continental, ~half and no ice cover) are specified. 10-year mean equilibrated GCM climate solutions (i.e., monthly mean surface air temperatures and precipitation) are saved for all combinations of orbit, CO2 and ice size, yielding a matrix of 27 climates.

In the long-term ice-sheet run, the appropriate climate at any point in the run is obtained by linearly weighting the surrounding saved climates in the matrix, with the weights proportional to the current austral summer insolation, ice size and logarithm of CO2 level. This matrix-forcing method is discussed further in Pollard (2010). The annual surface mass balance at each point on the ice sheet is calculated from the monthly surface air temperatures and precipitation, using a simple box (zero-dimensional) seasonal surface-mass model that includes snow storage and refreezing of meltwater, and surface melting based on Positive Degree Days (Pollard and DeConto, 2012). The run is initialized with (essentially) no ice. Insolation is based on Laskar et al. (2004). The run is 12 Myr long, nominally from "37 Ma to 25 Ma", although there is little to actually link it to specific paleodates except the Laskar orbits. From 37 to 33 Ma, CO2 decreases linearly from 6xPAL to 2xPAL. From 33 to 25 Ma, CO2 increases linearly from 2xPAL to 10xPAL (where PAL= 280 ppmv). The configuration used to represent MMCO conditions corresponds to 34.8 Ma (CO2 = 3.8xPAL). The one representing MMG conditions, to 33 Ma (CO2 = 2xPAL).

Lines 82-99 (old numeration) have been rewritten.

2. Section 4 describing the different published atmospheric CO2 levels is somewhat difficult to follow. A figure showing all the different published records over the Middle Miocene, in combination with horizontal lines indicating your suggestion, would clarify this section. Additionally a discussion on why these values are all so different is needed.

The reviewer's suggestion is interesting, although we do not see the addition of a figure as a requirement for the comprehension of the CO2 section. Nevertheless, lines 162-168 (now lines 205-214) have been rephrased as follows to make the section more clear:

'We chose atmospheric CO_2 concentrations of 400 ppmv and 200 ppmv to represent the MMCO and the MMG respectively (Table 1). Although somewhat arbitrary, these values are within the range of published estimates. The 400 ppmv MMCO is in favourable agreement with Foster et al. (2012) (~392 ppmv at ~15.8 Ma) and Tripati et al. (2009) (~430 ppmv at ~15.1 Ma), although higher than Pearson et al. (2000) (~300 ppmv at ~16.2 Ma) and Pagani et al. (2005) (~300 ppmv at ~15 Ma), and lower than Kürschner et al. (2008) (> ~400-500 ppmv at ~15.5 Ma) and Retallack (2009) (~852 ppmv at ~15.6 Ma) maxima. The 400 ppmv estimate is also in good agreement with the most recent alkenone- and boron isotope-based pCO2 reconstructions for the MMCO by Zhang et al. (2013) and Greenop et al. (2014). The 200 ppmv MMG estimate is in good agreement with Foster et al. (2012) (~200 ppmv at ~12 Ma) and Pagani et al. (2005) (~200 ppmv at ~13 Ma), although higher than Pearson et al. (2000) (~140 ppmv at ~14.7 Ma) and Retallack (2009) (~116 ppmv at ~14.6 Ma), and lower than Tripati et al. (2009) (~340 ppmv at ~12 Ma) and Kürschner et al. (2008) (~280 ppmv at ~14 Ma) minima.'

The difference in the CO_2 estimates between the various studies arises most likely from method-related uncertainties and/or the relatively coarse temporal resolution of some of the datasets.

We added a note at line 185 (new numeration):
'The difference in the CO_2 estimates between the various studies arises most likely from method-related uncertainties and/or the relatively coarse temporal resolution of some of the datasets'.

3. Section 5.3, especially lines 204-214 are too detailed. Please make this section more concise. Maybe "We used ArcGIS to convert ... to ..."

The text at lines 204-214 (old numeration) has been shortened:
'South East Asian paleogeography was modified based on Hall's (2012) reconstruction constrained at 15 Ma (Fig. 3). Hall's data, available as a georeferenced image, were converted into grid format using ArcGIS. Qualitative height/depth values were assigned to the different geographic features: ~2800 m for volcanoes, ~1000 m for highlands, ~250 m for land, ~-22 m for carbonate platforms, ~-200 m for shallow sea, <-4000 m for deep sea, and ~-5500 m for trenches. After embedding the data into the MMCO global dataset, minor manual smoothing was applied at the margins of the embedded region. Here, shallow bays were removed and single, shallow grid points surrounded by much deeper grid points were deepened to the adjacent depth. In total, these modifications affected ~0.5% of the total number of grid points.'

4. Concerning the global topography/bathymetry section: a difference plot to the Herold et al reconstruction (or at least additional information on this) would be highly relevant.

A new figure has been added (and a reference to it at line 243 (new numeration)).

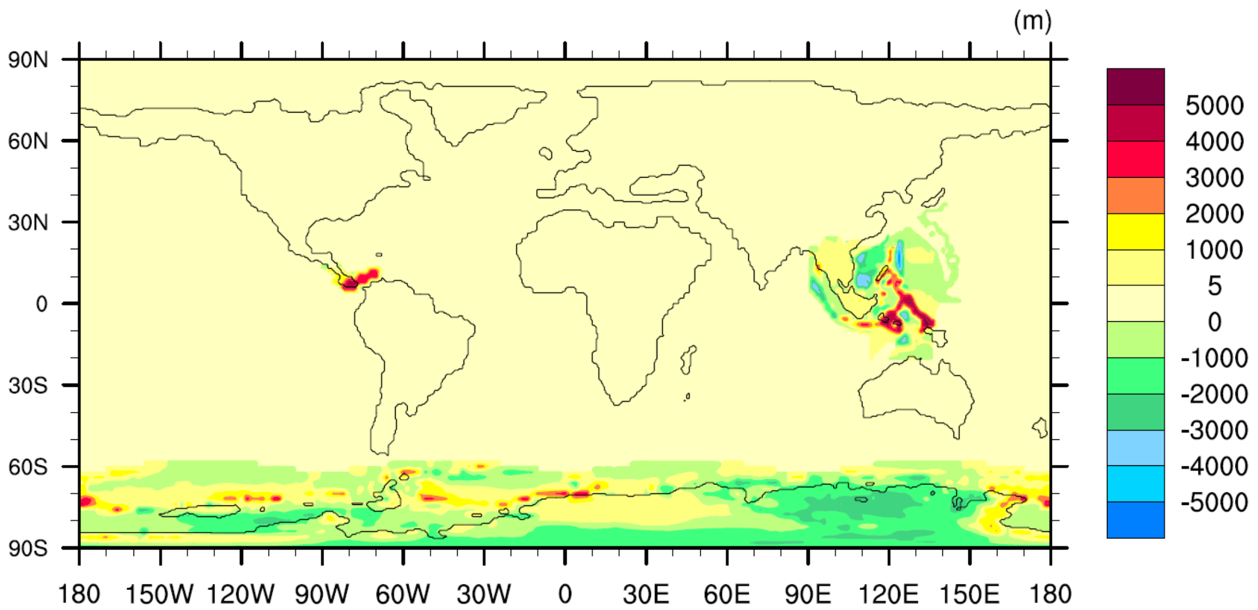

Figure S1: Difference between MMCO and the topography/bathymetry by Herold et al. (2008), in meters. Sea level is 4 m higher in the MMCO dataset (subsection 5.2), the Indonesian Throughflow barriers are shallower (subsection 5.3), the Panama seaway is narrower (subsection 5.4), and the Antarctic topography/bathymetry is based on David Pollard's data (subsection 5.1) and consistent with MMCO ice volume estimates.

5. Now my biggest concern: The description of the vegetation (Section 6). This section is very lengthily, and to be honest not very useful. In many subsections the vegetation patterns from literature are stated, but then subsequently ignored because you prefer to have a low resolution, simple, distribution. I have no problem with the latter, but I then do not see the use of discussing in detail the vegetation in each continent. I also do see that vegetation might be an important boundary condition, and suggest applying an offline vegetation model (e.g. BIOME4) in order to get a more consistent vegetation pattern within your model set-up. This could then be compared and discussed with previous studies, also previous modelling studies (for example Bradshaw et al., 2012).

Although a detailed discussion on the vegetation of each region is not indispensable for the comprehension of this manuscript, we think that it is important to show how exactly we decided what vegetation to assign to each region.

Subsections 6.1-6.9 have thus been moved to the Appendix (Sect. 10), in case the reader was interested in those details. A reference to the Appendix has been added at line 360 (new numeration).

The reviewer's suggestion of using the output from an offline vegetation model as a boundary condition is very interesting (e.g., the ones described in Henrot et al., 2017), although here our aim was to provide boundary conditions based on palaeobotanical data. The vegetation output from an offline vegetation model is based on a climatic forcing. In our study the approach was the opposite: using vegetation data to be able to produce a climatic output. An alternative for GCMs including a dynamic vegetation component would be to use our Middle Miocene vegetation dataset to initialize the vegetation model. Nevertheless, we consider that, although coarse, our dataset provides a fair characterization of Middle Miocene global vegetation patterns.

A note has been added at line 355 (new numeration).

6. The final part, the model simulations, are interesting, but need discussion:

a. How is the grid extended to reach higher southern latitudes? Does this mean that the resolution is lower in the Miocene simulations compared to the PI simulation? How do you make difference plots then (regridding?)? Does this have an impact on the results?

The Miocene grid is a dipole grid created from scratch using the CCSM3 setup tools described in Rosenbloom et al. (2011) and defined by the following parameters: dyeq=0.25 (meridional grid spacing at the equator, in degrees), dsig=20 (Gaussian e-folding scale at equator), and jcon=45 (rows of constant meridional grid spacing at poles).
In some areas the Miocene grid presents a slightly coarser resolution than the PI grid, since both grids have the same number of grid points (384x320) and the Miocene grid reaches further south than the PI grid (~87°S vs ~79°S).
Difference plots are made by regridding from the PI grid onto the Miocene grid. The method used is the "patch recovery" method (http://www.ncl.ucar.edu/Applications/ESMF.shtml), which gives better approximations than the "bilinear" method. We do not think interpolation has any significant effect on the results.

The reviewer's comment has been addressed in the manuscript at lines 549-556 (new numeration).

b. Are the simulations run long enough? What are the trends in the deep ocean (temperatures, salinity, …)?

The temperature trends in the deep ocean (at 4-5 km depth) are < 0.14, 0.15, and 0.17 °C/100 years in the PI, MMCO, and MMG cases, respectively. At that same depth range, the salinity trends are <0.01, 0.007, and 0.01 psu/100 years for PI, MMCO, and MMG, respectively. These values represent quasi-equilibrium conditions and we consider them sufficiently small for the focus of this study.

The reviewer's comment has been addressed in the manuscript at lines 565-568 (new numeration).

c. The comparison of the precipitation needs to be rewritten. The lower/higher precipitation along the coast of South America seems to be due to the movement of the continents. Maybe more interesting would be to discuss the apparent shift in the ITCZ. Why?

We checked again the absolute precipitation maps (see Figure S2) and the Miocene experiments present lower precipitation rates than PI along the northwest coast of South America. Nevertheless, the difference of 5-6 mm/day we suggested is too high, and as the reviewer noted, linked to the movement of the continents.

The text has been modified by replacing 'up to 5-6 mm/day lower' with '3-4 mm/day lower' at line 572 (new numeration). We also added a paragraph on the ITCZ. Please, check lines 575-579 (new numeration) for more details. Additionally, a new figure (Fig. S2) has been added (please, see below).

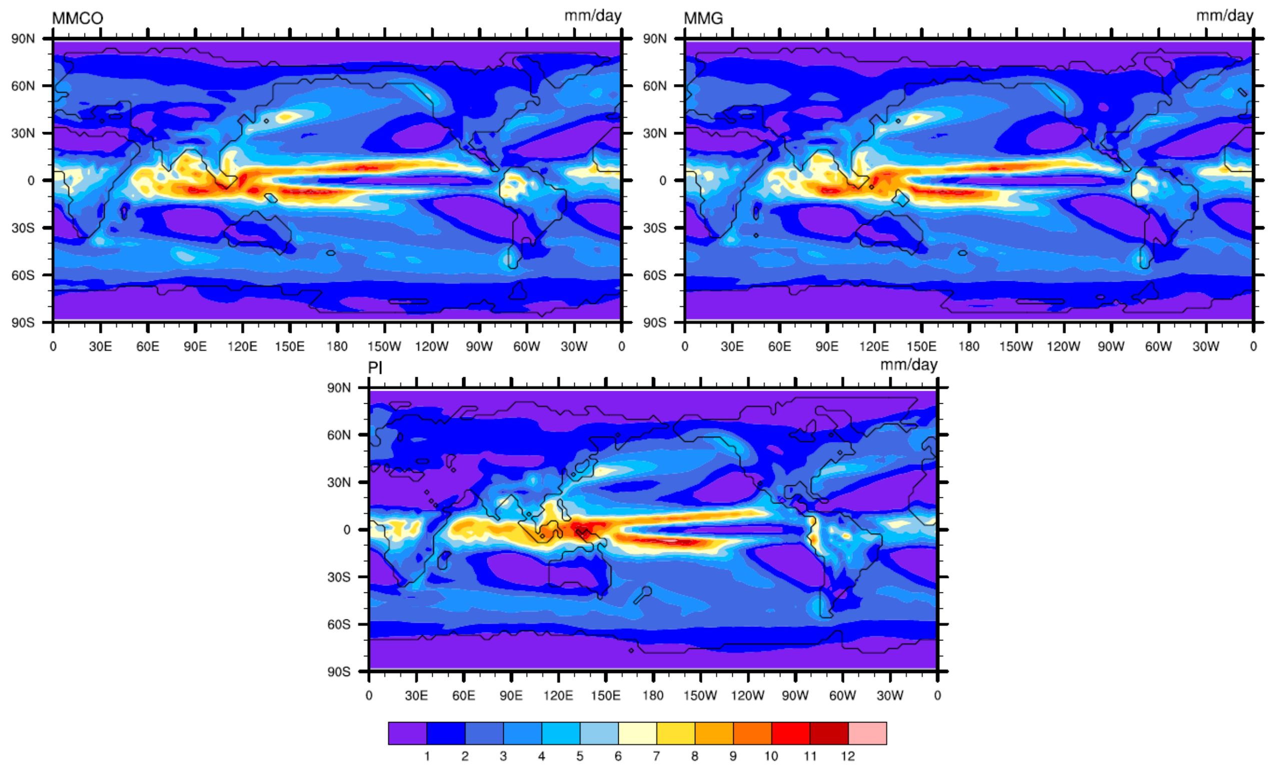

Figure S2: Precipitation for MMCO, MMG, and PI, in mm/day.

d. Also the temperature comparison lacks discussion. Why is the MMG simulation warmer than PI? CO2 is lower (200 ppm), right? How different is the Antarctic ice sheet compared to today? Is the cooling in the Pacific caused by changes in gateways/geography/topography? Please discuss.

Indeed, CO2 is lower in the MMG simulation than in the control run (MMG: CO2 = 200 ppmv, PI: CO2 = 280 ppmv). Nevertheless, SST's are higher for MMG (18.04°C) than for PI (16.85°C). Potential causes for a MMG climate warmer than PI could be the lower extent of ice-sheets (the Antarctic ice-sheet is smaller and the northern Hemisphere free of ice-sheets in the MMG run), or the different vegetation cover (Knorr et al., 2011). However, unambiguously disentangling the effects of each of the different boundary conditions would require performing a series of sensitivity experiments, which was beyond the scope of the current study. Here our aim was testing the idoneity of the current boundary conditions as input data in GCMs for MMCO and MMG experiments.
In the MMG experiment the Antarctic ice-sheet has a volume of 23 million km^3, hence lower than present-day (27 million km^3, according to Fretwell et al., 2013).

This point has been addressed at lines 592-598 (new numeration).

e. During this discussion please list again the differences between the Miocene simulations (400 vs 200 ppm; different Antarctic ice sheet and vegetation). What is the climate sensitivity of this model? A 200 ppm decrease in CO2 would cause a reduction in temperature of about 2-4°C? Why is there only a difference of 1.6°C? Is the difference larger when you take the global mean surface air temperature? And how much of the cooling is due to the ice expansion (and related albedo changes)? Please discuss.

The climate sensitivity of CCSM3 is discussed in Kiehl et al. (2006), where two different approaches are used, one based on results from a slab ocean run with fixed CO2 and the other one based on a fully coupled run with increasing CO2 rates. The results obtained are 2.47°C and 1.48°C, respectively.
When, instead of SSTs, surface air temperatures (at 2 m height) are considered, our results show mean global values of 16.38°C, 13.88°C, and 12.16°C for the MMCO, MMG, and PI, respectively. This implies a decrease of 2.5°C between the MMCO (CO2= 400 ppmv + small Antarctic ice-sheet) and MMG (CO2= 200 ppmv + expanded ice-sheet), which is in good agreement with the CCSM3 climate sensitivity values suggested in Kiehl et al. (2006). A decrease of 1.6°C in SST's would also be in agreement with Kiehl et al. (2006).
Quantifying how much of the cooling is due to ice expansion is a very interesting suggestion, although it would require performing a series of sensitivity studies, with fixed CO2 and varying Antarctice ice volume, which were beyond the scope of the current study. Here our aim was testing the idoneity of the current boundary conditions as input data in GCMs for MMCO and MMG experiments.

The reviewer's comment has been addressed at lines 584-588 (new numeration).

Specific Comments

1. The start of Section 3 is somewhat confusion, because of the connection between Antarctic ice volume (defined for the Middle Miocene at the end of Section 2) and sea level. Maybe it would be better to start Section 3 with lines 132-136, followed by the discussion of other literature values.

Lines 132-136 have been moved to the top of the section. However, those lines have been slightly rephrased because they contained a reference to Equation (1), which had not been defined yet.

Lines 112-118 were removed because they had become redundant.

2. Why is the topography over Greenland so high in the Middle Miocene? It looks much higher than a present-day isostatically rebounded topography.

Our values are based on Herold et al. (2008). In that study, the topography over Greenland is "reduced by 2300 m" compared to present-day and "isostatically corrected by 1651 m", which means that it is 649 m lower than at present-day. We compared our topography to Bamber et al. (2001) present-day isostatically rebounded topography (Figure 5 in Bamber et al., 2001). We agree with the reviewer that our topography is a bit higher, reaching maximum values of ~2400 m, versus maximum values of ~2000 m in Bamber et al. (2001). Nevertheless, we believe that Herold's values are still a good approximation of an ice-free Greenland topography.

Technical Comments

-Line 12: add "successfully" to applied.

Added.

-Lines 20-21: rewrite. δ18O could also reflect a combined change in ice volume and temperature.

We added this text:
'or a combination of both'.

-Line 25: change "would have been" to "were".

Changed.

-Line 28: explain "important".

A reference to Section 3 has been added. In this section, sea level fall published estimates for the Middle Miocene Climate Transition are reviewed in detail.

-Line 40: add "e.g." before references. Using an intermediate complexity climate and ice sheet model, Langebroek et al. (2010) showed that a combination of pCO2 decrease and orbital forcing causes an Antarctic ice sheet expansion that can explain the majority of the benthic δ18O increase.

Added at line 47(new numeration), although slightly rephrased:
'Langebroek et al. (2010), for example, using an isotope enabled ice-sheet–climate model forced with a pCO2 decrease and varying time-dependent orbital parameters, modeled an increase in δ18O of sea water in good agreement with published MMCT estimates.'

-Line 54: change "data" to "boundary conditions".

Changed.

-Line 61: change "studies" to "sediment core data".

'Studies' has been replaced with 'sediment core studies'.

-Line 67: change "simulations" to "study".

Changed (now line 77).

-Line 93: "This estimate" instead of "This 6 estimate".

Done (now line 95).

-Line 104: change "very few" to "little".

Changed.

-Line 190: change "Some" to "Additional". And make clear in this sentence that the modifications will be discussed below.

Done.

A comment has been added at line 191 (now line 243):
'(see discussion below in subsections 5.1–5.4)'.

-Line 198: "64" where does this number come from?

The 64 m present-day sea-level equivalent value is in good agreement with Vaughan et al. (2013) (58.3 m for the Antarctic ice-sheet and 7.36 m for the Greenland ice-sheet).

The following text has been added at line 251 (new numeration):
'This present-day estimate is in good agreement with Vaughan et al. (2013) (58.3 m for the Antarctic ice-sheet and 7.36 m for the Greenland ice-sheet).'

-Line 448: what does "T42x1" mean? Especially the "x1"?

T42 is the atmosphere horizontal grid, a Gaussian grid with 64 points in latitude and 128 points in longitude (~2.8° resolution). The notation T42 refers to the spectral truncation level. x1 is the ocean horizontal grid, a dipole grid with 384 points in latitude and 320 points in longitude. The zonal resolution of the ocean horizontal grid is ~1°, the mean meridional resolution is ~0.5°, refined around the equator (~0.3°). The notation x1 refers to the nominal zonal resolution. T42x1 is the model configuration employing the T42 and x1 grids.

Lines 448-453 (old numeration) have been modified as follows:
'The atmosphere horizontal grid employed in the PI run, T42, is a Gaussian grid with 64 points in latitude and 128 points in longitude (~2.8° resolution). The notation T42 refers to the spectral truncation level. The land and atmosphere models share the same horizontal grid. The ocean horizontal grid, x1, is a dipole grid with 384 points in latitude and 320 points in longitude. The zonal resolution of the ocean horizontal grid is ~1°, the mean meridional resolution is ~0.5°, refined around the equator (~0.3°). The notation x1 refers to the nominal zonal resolution. The ocean and sea–ice components share the same horizontal grid. The atmosphere and ocean vertical grids have 26 and 40 vertical levels, respectively. This model grid configuration is known as T42x1.'

-Line 459: rephrase to "were set to PI following Otto-Bliesner".

Rephrased.

-Line 471: change "observed" to "simulated".

The word "observed" does not appear in the text anymore. We rewrote that part of the text in relation to the reviewer's comment: 6 c).

-Line 477: change "complete compilation" to "complete set".

Changed.

-Line 481: change "treated" to "discussed".

Changed.

-Figure 1: caption: change "total elevation" to surface elevation". Colours: The colour scale is not great. By colouring 0 to -1000 white, it seems to belong to land, while it is actually ocean. Please change this. Also ice thickness cannot be negative, please update colour bar.

Done.

-Figure 4: Please make the order of the abbreviations in the caption consistent with the order in the colour bar.

Done.

Additional modifications:

-Line 73 (now line 83):
In Langebroek et al. (2010) the model is isotope-enabled, but in Langebroek et al. (2009) it is not.

We have thus rephased 'Langebroek et al. (2009) used a coupled isotope-enabled ice-sheet–climate model' as 'Langebroek et al. (2009) used a coupled ice-sheet–climate model'.

We hope we have addressed all your comments.

Yours sincerely,

Amanda Frigola and co-authors.

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