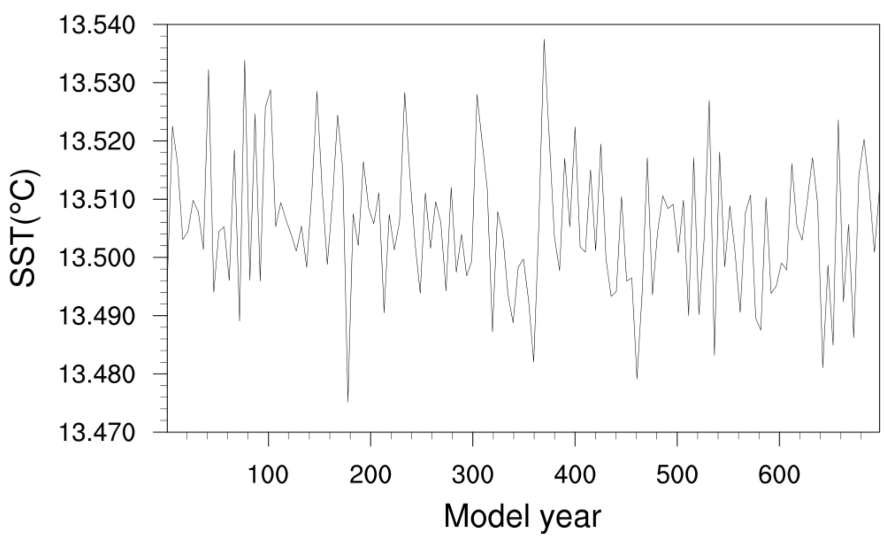
Reply to general comments

1. *Some more information on the experimental setup would be desirable. How is the ocean initialized, e.g. are World Ocean Atlas ('Levitus') data used? This is in particular of interest since the authors claim that their model ocean is in equilibrium after only 100 years of spin up whereas other modeling groups perform multi-century (Delworth et al., 2006) or even multi-millennial (Müller et al., 2018) spin-up runs to significantly reduce the temperature drift in the ocean where clearly a drift is still visible after 300 or 500 years (Delworth et al., 2012, Fig. 1; Delworth et al., 2006, Fig. 3). Such a drift is best visible in timeseries of the global mean temperature for the surface but also deeper ocean layers, which unfortunately are not provided by the authors and should be added. It is essential for other modelling centres to provide at least a number or even better a timeseries of the TOA radiation (im)balance.*

Reply:

Thanks for these comments. Climate drift is common in the numerical models, which tends to be model dependent (Gupta et al., 2013). Since the simulation improvements of SST in the ECHAM5-NEMO3.6 are remarkable, it has been questioned whether this is caused by climate drift that happens to improve the SST simulation in the selected time period. The OGCM NEMO3.6 is initialized with the default model configuration from the present time climatology, including the World Ocean Atlas (WOA) data. The global SST time series of the ECHAM5-NEMO3.6 with five-year running average are provided below



The SST fluctuations displayed in the figure are confined within 0.1°C, of the same magnitude as Huang et al. (2014) who have evaluated the ICM coupled model based on ECHAM5.4 and NEMO2.3. In the selected time period (model year

101~200), the SST fluctuation shows a similar pattern as other time span. It's definitely better to integrate the three CGCMs for much longer time span, but the computational cost is high and thousands of years' realization is time-consuming. Since the most efficient way to ameliorate the unrealistic nonlinear oscillation in a weather model is through flux adjustment, which nevertheless produces undesirable results, it may be acceptable to evaluate the model performance based on the quasi-equilibrium state.

2. *For both the Atmosphere (ECHAM5 and ECHAM6) and the ocean models (NEMO, MPI-OM) very little information is provided on the technical details except for the configuration of the coupler (e.g., which parametrizations are active, which model options are switched on or off, how are the model components initialized, is nudging or restoring used in the ocean or atmosphere, model tuning)*

Reply:

Thanks for these comments. Because the models have different parameterizations and even different dynamical structures, it is less useful to provide the technical details about the parameter settings that does little help for the inter-model comparison. By emphasizing on model parameterization differences, it seems to say that the inter-model differences are resulted from the intrinsic characteristics of each component model. Since the simulation deficiencies are always model-dependent, there is no need to investigate the key mechanisms that shape the inter-model differences. This is completely opposite to the purpose of this paper. I'm afraid that the reader's attention will be diverted by those kinds of information and thus I did not provide many details.

Model initialization is started from the climatology basic state recalculated with the AMIP run input data from 1981 to 2010. In the revised manuscript, parameter settings for greenhouse gases and aerosols have been supplemented as follows:

'The CO2 value is set to default 353.9 ppm in the user manual. Other greenhouse gases like NO2 also follows the default present time setting so that they are consistent with each other. The aerosol settings use the climatology compiled by S. Kinne without any complementation of volcanic aerosols.'

Model retuning is left for further studies due to time limitation and high computational cost. In order to unify the model settings to the utmost, nudging hasn't been applied on any component model. After all, model integration will be much slower when nudging is used. Power spectrum of the Niño3.4 index in section 4.7 of the revised manuscript shows similar variational trends for each CGCM that coincide with the reanalysis counterpart. It can thus prove that the improvement of the cold tongue simulation is not achieved by restoring in the OGCM, otherwise the SST variability will be heavily suppressed. Although the ECHAM5-NEMO3.6 shows weak variability especially at inter-decadal scales for SAM and SOI, it is not caused by restoring in the AGCM. In fact, I don't find a way to specify the restoring in the control run configuration of the ECHAM5. Section 4.7 that introduces system variabilities of the CGCMs has been pasted below for convenience.

'**4.7 Model variability of ENSO and SAM**

In the coupled ocean-atmosphere system, global climate variability has been driven by the El Niño-Southern Oscillation (ENSO) and the southern annular mode (SAM, also called the Antarctic Oscillation) (Philander, 1990; Wallace and Thompson, 2002). It is therefore necessary to examine the model variability by applying spectra analysis on relevant indices. The CGCM simulations of the three indices are generally consistent with the theoretical red noise (Markov) spectrum (figure omitted). The Niño3.4 index is defined as the SST anomalies averaged over the NINO34 region (5°N-5°S,170°W - 120°W). It shows high variance in 2-7 years' period that documents the ENSO peaks in the HadISST reanalysis (Fig. 8a). All of the CGCMs reproduce similar variations of the Niño3.4 power spectra. The ECHAM6-NEMO3.6 presents weak variabilities at the interannual and interdecadal scale, whose periodic peaks are about one year less than the reanalysis counterpart. The ECHAM5-NEMO3.6 shows a better spectral distribution that best coincides with the reanalysis at the interannual scale. However, it still suffers a weak variability at the interdecadal scale and the periodic peak is even half a year less than that of the ECHAM6-NEMO3.6. The MPI-ESM instead takes on an intensified interannual variability, which stays strong at the interdecadal scale. The Southern Oscillation Index (SOI) is calculated based on the differences in sea level pressure anomalies between Tahiti and Darwin in Australia. In comparison to the Niño3.4 spectra, the SOI exhibits similar peaks at the interannual scale in the ERA-20c reanalysis (Fig. 8b). Nevertheless, all the CGCMs reproduce weak variabilities at the interannual and interdecadal scales. The ECHAM6-NEMO3.6 presents the best simulation with a significant increase in variance around 4 years' period, while the ECHAM5-NEMO3.6 shows the weakest variability at the interannual scale. It implies that the AGCM replacement has an opposite effect on the Niño3.4 and SOI variabilities. The MPI-ESM also show reduced variance from the annual scale and above, quite the opposite to that in the Niño3.4 case. Since the model biases of ENSO variability may be attributed to thermocline feedback and zonal wind variations (Borlace et al., 2013), the reversed changes in the variabilities of Niño3.4 and SOI can be caused by the related oceanic and atmospheric processes. The SAM index is calculated following Gong and Wang (1999) by the differences of normalized monthly zonal mean sea level pressure at 40°S and 65°S. Variations of SAM tend to be more flattened than those of SOI in the ERA-20c reanalysis (Fig. 8c), with prominent fluctuations from biannual to interannual scales. Compared with the reanalysis counterpart, all CGCMs show more power at interannual time scales that represents a robust modulation of the SAM, which is possibly attributed to the semi-annual oscillation (SAO) (Hurrell and van Loon, 1994) and circulation anomalies over Antarctica (Thompson and Solomon, 2002). The ECHAM6-NEMO3.6 presents stronger decadal variability than that of the reanalysis data, while the ECHAM5-NEMO3.6 exhibits weaker low-frequency variability. Since the high variance in low-frequency band represents the upward trend of SAM index at decadal scale (Raphael and Holland, 2006), updating the AGCM can result in a drastic change of long-term climate variability in southern hemisphere. In contrast, the MPI-ESM shows the SAM variability very close to the reanalysis counterpart from 1 year and above, indicating that the OGCM feedback to the atmosphere can lead to a better representation of the inter-decadal variability.

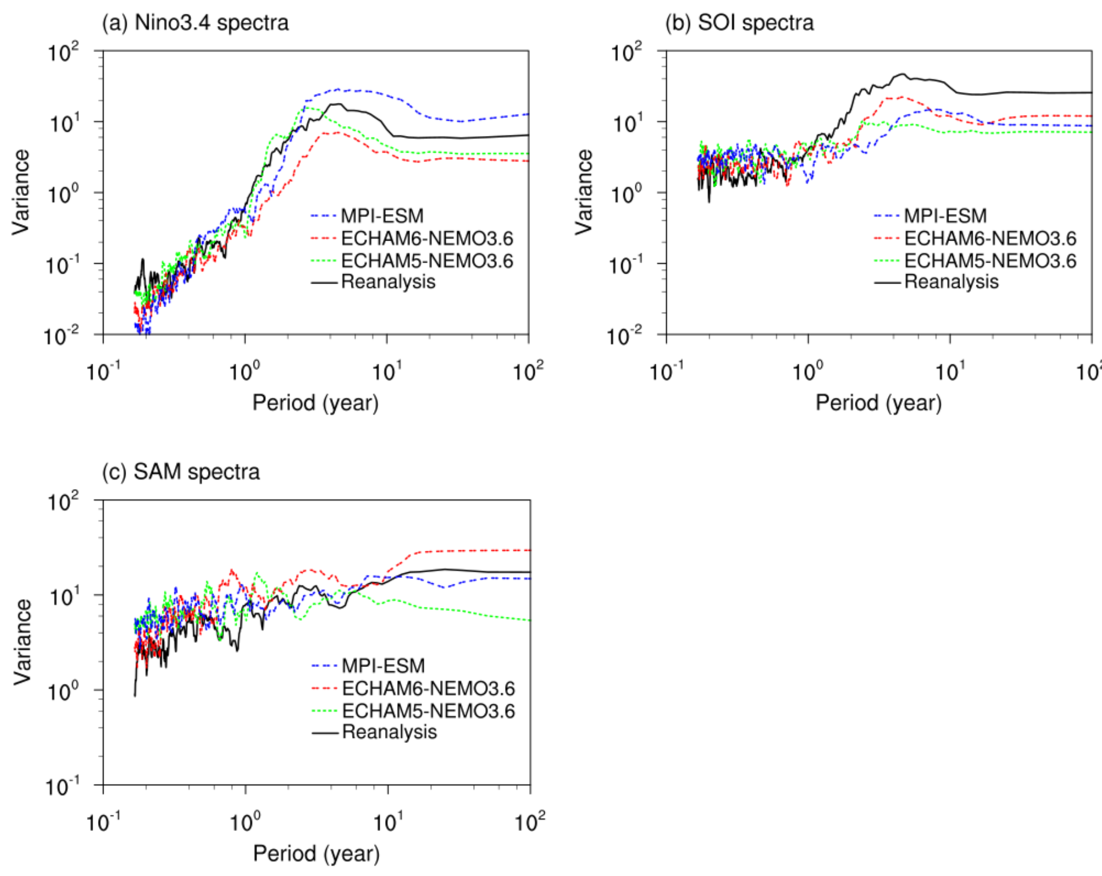


Figure 8: Power spectra of (a) Niño3.4 index, (b) SOI, (c) SAM index. Solid line denotes the calculation results of reanalysis data, green dotted line denotes the ECHAM5-NEMO3.6 simulation, red dotted line denotes the ECHAM6-NEMO3.6 simulation, and blue dotted line denotes the MPI-ESM simulation.'

3. *The most prominent feature of no North Atlantic cold SST bias in a 2 ocean model coupled to ECHAM5 in their ECHAM5-NEMO3.6st configuration is not properly discussed. This bias has been around for decades in coupled climate models at the given resolution, and numerous papers discuss it. None of this work is mentioned or compared to. See also our detailed comments on Figure 3 below.*

Reply:

> Thanks for these comments. The ECHAM5-NEMO3.6 and ECHAM6-NEMO3.6 uses the same configuration for the OGCM, and in the ECHAM6-NEMO3.6 the cold biases are still there in North Pacific and North Atlantic. Zhang & Zhao (2015) suggested that the cold SST bias in Atlantic caused the same cold bias in North Pacific through WES feedback and NAM originating in tropical and extra-tropical Atlantic. In our study, the AMOC biases are not so much different between the two CGCMs, while the NPMOC (MOC in North Pacific) exhibits bigger inter-model differences. Therefore, the experiment results suggest an inverse cause-and-effect relationship between the cold SST biases in North Pacific and North Atlantic, through the air-sea interaction. Investigation on the mechanisms will be discussed in an ongoing research. The AMOC comparison has been pasted below:

'Since the upper cell of Atlantic meridional overturning circulation (AMOC) plays a significant role in delaying warming signals from anthropogenic greenhouse gases and responding to climate change (Marshall et al., 2014; Buckley and Marshall, 2016), model bias analysis is still focused on the upper ocean levels. The overall magnitude of AMOC bias is less than that of NPMOC with significantly reduced biases near the sea surface (Fig. 10), which is consistent with those of surface currents among the three CGCMs. The ECHAM6-NEMO3.6 shows exiguous bias near the ocean surface, but presents strong biases in the mesopelagic zone of subtropical areas, bringing more heat to higher latitudes (Fig. 10a). Likewise, the ECHAM5-NEMO3.6 exhibits strong circulation biases rotating clockwise in the thermocline that intensifies poleward heat transport (Fig. 10b). In the upper ocean levels, the AMOC poleward transport is a little more enhanced than that of the ECHAM6-NEMO3.6. With similar bias patterns of the AMOC, the ECHAM5-NEMO3.6 and the ECHAM6-NEMO3.6 have opposite SST biases in North Atlantic (Figs. 3a and 3c), which implies that the air-sea feedback including WES feedback and NAM as suggested by Zhang & Zhao (2015) takes the responsibility. The MPI-ESM experiment shows negative biases in tropical Atlantic from the sea surface to the bathypelagic zone, indicating that the overturning circulation has been restrained. There is a narrow positive bias in the subtropical Atlantic, but its strength has been limited by the negative biases nearby. One consequence of the weak AMOC is the decrease of SST in North Atlantic due to less heat supply from the tropics (Fig. 3e). The overturning circulation is enhanced in the middle latitudes with one centre located north of 35ºN and another centre around 55ºN at the depth of 1200m. It still promotes the poleward heat transport and results in warm SST biases in subpolar region (Fig. 3e). The AMOC biases in the MPI-ESM piControl experiment are similar as those in the MPI-ESM experiment, with more negative biases in tropical Atlantic. Comparing the AMOC biases between the MPI-ESM and the ECHAM5-NEMO3.6, it can be seen that the SST cold biases in North Atlantic are partially attributed to decreased MOC in the thermocline of tropical and extra-tropical oceans. However, the air-sea interaction also takes account of the SST variations in consideration of the SST differences between the ECHAM5-NEMO3.6 and the ECHAM6-NEMO3.6. Zhang & Zhao (2015) suggested that the cold SST bias in Atlantic caused the same cold bias in North Pacific through different mechanisms originating in tropical and extra-tropical Atlantic. Because the differences of NPMOC are bigger than those of AMOC between these two newly developed CGCMs, it suggests an inverse cause-and-effect relationship between the cold SST biases in North Pacific and North Atlantic where the former takes the lead.

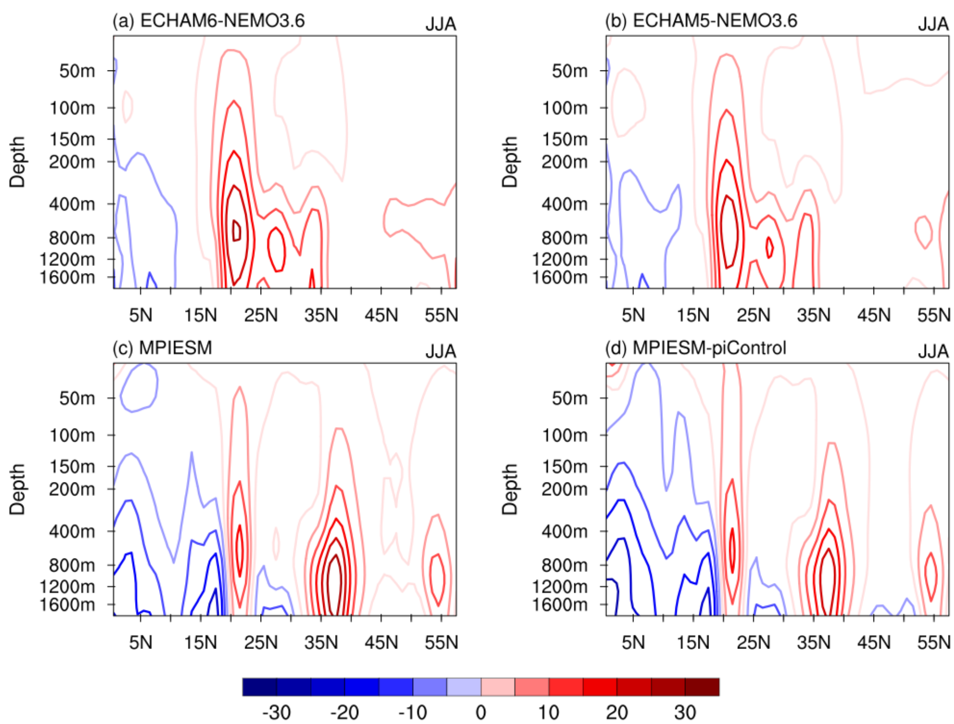


Figure 10: Model biases of AMOC in summer, (a) ECHAM6-NEMO3.6, (b) ECHAM5-NEMO3.6, (c) MPI-ESM, (d) MPI-ESM piControl, Unit: Sv.'

4. *No figures or information on the stability of the control simulation (e.g., timeseries of surface air temperature, TOA radiation budget, etc.) are provided which are crucial to evaluate coupled GCM performance.*

Reply:

Thanks for these comments. As in the question No.1, we have ensured that no remarkable climate drift appears in model integration with the SST time series. It is obviously better to provide all the information, but it also increases the length of the article which is already long enough. At the very beginning, we believed that it was necessary to integrate the CGCMs for thousands of years. But later in a LASG (The State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics) annual conference, via the personal contact with some researchers in the Institute of Atmospheric Physics (IAP), we were told that 200-300-year realization was enough for the CGCM experiment. Since the long-term integration was time-consuming and less cost-effective, we followed their advice to analyze the model results after 100-year realization and hence no time series of these quantities were provided.

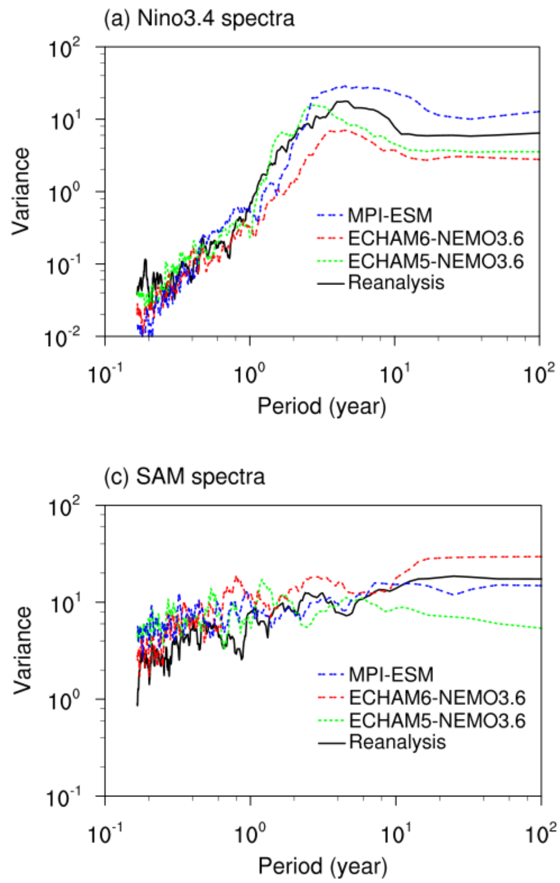
5. *A new coupled model system is presented and key ocean parameters such as the Atlantic Meridional Overturning circulation (MOC) or important coupled atmosphere ocean variability patterns (e.g., ENSO, NAO), their difference amongst the different GCM configurations and their possible impact on the SST bias are not discussed and should be added to the paper.*

Reply:

Thanks for these comments. The AMOC and Model variability have been analyzed and compared among the three CGCMs in section 4.7 and section 5.2 of the revised manuscript.

'**4.7 Model variability of ENSO and SAM**

In the coupled ocean-atmosphere system, global climate variability has been driven by the El Niño-Southern Oscillation (ENSO), the southern annular mode (SAM, also called the Antarctic Oscillation) and the Indian Ocean dipole (IOD) (Philander, 1990; Wallace and Thompson, 2002; Saji et al., 1999). It is therefore necessary to examine the model variability by applying spectra analysis on relevant indices. The CGCM simulations of the three indices are generally consistent with the theoretical red noise (Markov) spectrum (figure omitted). The Niño3.4 index is defined as the SST anomalies averaged over the NINO34 region (5°N-5°S,170°W -120°W). It shows high variance in 2-7 years' period that documents the ENSO peaks in the HadISST reanalysis (Fig. 8a). All of the CGCMs reproduce similar variations of the Niño3.4 power spectra. The ECHAM6-NEMO3.6 presents weak variabilities at the interannual and interdecadal scale, whose periodic peaks are about one year less than the reanalysis counterpart. The ECHAM5-NEMO3.6 shows a better spectral distribution that best coincides with the reanalysis at the interannual scale. However, it still suffers a weak variability at the interdecadal scale and the periodic peak is even half a year less than that of the ECHAM6-NEMO3.6. The MPI-ESM instead takes on an intensified interannual variability, which stays strong at the interdecadal scale. The Southern Oscillation Index (SOI) is calculated based on the differences in sea level pressure anomalies between Tahiti and Darwin in Australia. In comparison to the Niño3.4 spectra, the SOI exhibits similar peaks at the interannual scale in the ERA-20c reanalysis (Fig. 8b). Nevertheless, all the CGCMs reproduce weak variabilities at the interannual and interdecadal scales. The ECHAM6-NEMO3.6 presents the best simulation with a significant increase in variance around 4 years' period, while the ECHAM5-NEMO3.6 shows the weakest variability at the interannual scale. It implies that the AGCM replacement has an opposite effect on the Niño3.4 and SOI variabilities. The MPI-ESM also show reduced variance from the annual scale and above, quite the opposite to that in the Niño3.4 case. Since the model biases of ENSO variability may be attributed to thermocline feedback and zonal wind variations (Borlace et al., 2013), the reversed changes in the variabilities of Niño3.4 and SOI can be caused by the related oceanic and atmospheric processes. The SAM index is calculated following Gong and Wang (1999) by the differences of normalized monthly zonal mean sea level pressure at 40°S and 65°S. Variations of SAM tend to be more flattened than those of SOI in the ERA-20c reanalysis (Fig. 8c), with prominent fluctuations from biannual to interannual scales. Compared with the reanalysis counterpart, all CGCMs show more power at interannual time scales that represents a robust modulation of the SAM, which is possibly attributed to the semi-annual oscillation (SAO) (Hurrell and van Loon, 1994) and circulation anomalies over Antarctica (Thompson and Solomon, 2002). The ECHAM6-NEMO3.6 presents stronger decadal variability than that of the reanalysis data, while the ECHAM5-NEMO3.6 exhibits weaker low-frequency variability. Since the high variance in low-frequency band represents the upward trend of SAM index at decadal scale (Raphael and Holland, 2006), updating the AGCM can result in a drastic change of long-term climate variability in southern hemisphere. In contrast, the MPI-ESM shows the SAM variability very close to the reanalysis counterpart from 1 year and above, indicating that the OGCM feedback to the atmosphere can lead to a better representation of the inter-decadal variability.



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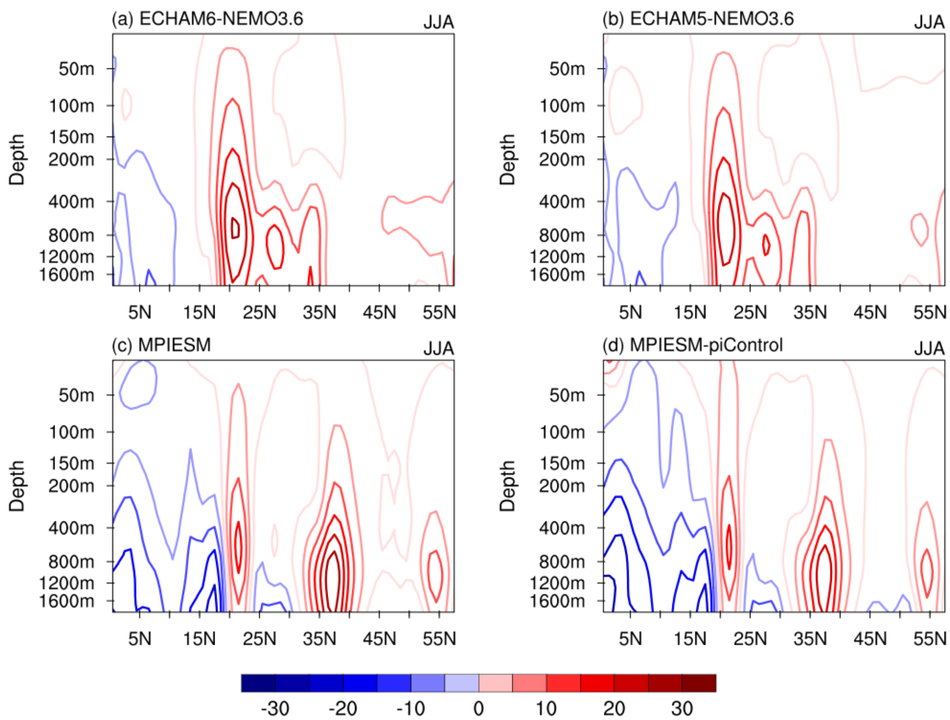

Figure 10: Model biases of the AMOC in summer, (a) ECHAM6-NEMO3.6, (b) ECHAM5-NEMO3.6, (c) MPI-ESM, (d) MPI-ESM piControl, Unit: Sv.

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6. *In our opinion, the pattern correlation method (table 1, with pattern correlations always below 0.4) cannot be used to explain the inter-model differences as it completely ignores both the physical dependencies of the parameters used in the correlation as well as the impact of ocean dynamics and coupled ocean-atmosphere feedbacks onto the SST bias in a GCM. In addition, the presented pattern correlation values are very low.*

Reply:

Thanks for these comments. Since one main purpose of this paper is to investigate the effects of changing component models on the coupled system, which inevitably involves inter-model comparison with different parameterization schemes and even dynamical structures. Although this is less rigorous than normal approaches to study the model characteristics, we take a bold step forward to study the model response with different configurations so as to overcome the predicament of model development that tends to improve the simulation quality by blindly updating the parameterization schemes. The robustness of pattern correlation has been increased when the area of computation is narrowed down to Pacific (Tab. 2 in the revised manuscript). Low correlation values seem less convincing, but the top three ranking variables that facilitate the attribution analysis have well passed the 99.9% Student-t test. A larger number of grid points are involved that makes the threshold value relatively small. The ranking of coupling variables provides an insight into the causation of inter-model differences, which is not used in its absolute sense.

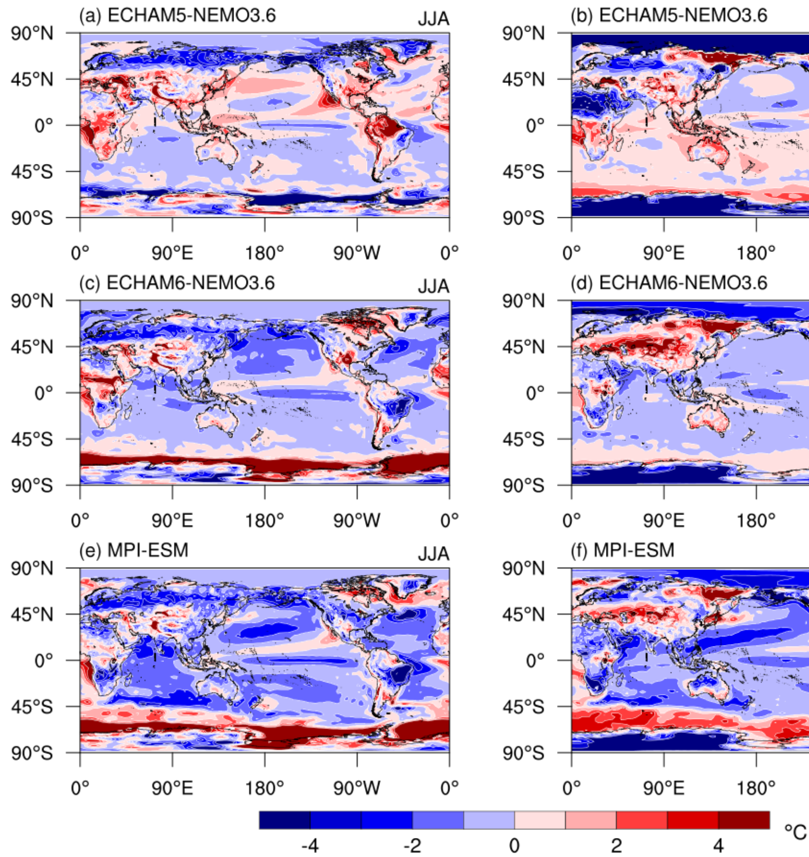
7. *Unfortunately, no information about the setup of the land component in the new coupled GCM is provided. We assume it is using JSBACH, the new land model component within ECHAM6. Is JSBACH running interactively? Why are the pattern correlations for albedo that weak? The interpretation of simulated precipitation is questionable, as differences in the extra tropics are not really visible (scale inappropriate). Additionally, the paper lacks also information about 2m temperatures (also referred to as SAT – surface air temperature) simulated over land.*

Reply:

Thank you for these comments. The land component of ECHAM6 is JSBACH, which is used with the default configuration as that of piControl run for both MPI-ESM and ECHAM6-NEMO3.6 experiments. Therefore, it should be running concurrently with the atmospheric core. The pattern correlations for albedo are calculated between the model differences of the SST and albedo, which includes the contribution of OGCMs with different model structures and parameterizations. Although low correlation values seem inconsistent with some studies, the model results are still within tolerance.

Precipitation biases are plotted with the same scales used in Huang et al. (2014), which basically emphasizes on tropical variations. In the paper, precipitation bias is just mentioned as one aspect of model evaluation. Extra-tropical biases are not closely associated with the qualitative reasoning part of the paper, which have thus been neglected.

The model SAT biases against the ERA-Interim reanalysis have been attached below. Large biases in polar areas may be attributed to model deficiencies and uncertainties in the reanalysis data.



Biases of the SAT simulation in summer (left column) and winter (right column) corresponding to each CGCM: (a, b) ECHAM6-NEMO3.6, (c, d) ECHAM5-NEMO3.6, (e, f) MPI-ESM.

8. *No information on sea ice in the different GCM configuration is provided. To be able to judge the SST differences between the different model configurations properly, some information such as sea ice extent and sea ice thickness should be added to the paper.*

Reply:

Thanks for these comments. We have added the sea-ice model description and configuration in section 2.1 and section 2.4 of the revised manuscript.

'…The Louvain-la-Neuve sea-ice model (LIM3), originally developed by Fichefet and Morales-Maqueda (1997), has been incorporated in NEMO3.6 to represent the sub-grid-scale dynamics and their impact on sea ice thickness and ice-ocean salt exchanges. Main differences between LIM3 and other ice models are related to the physical parameterization of open boundary conditions and sea-ice interactions, with the C-grid formulation of elastic-viscous-plastic rheology (Bouillon et al., 2013).

…The sea ice model (LIM3) in NEMO3.6 is configured to compute the ice-ocean fluxes under the influence of air-sea fluxes, ocean mass and salt exchanges, with light penetration of solar radiation. Ice freezing and melting also affects the albedo in the Arctic and Antarctic regions. Likewise, the sea ice thickness and density in the MPIOM respond to wind stress and ocean currents without consideration of turning angles. Surface heat balance and the internal ice stress also affect the variations of sea ice cover with zero-layer formulation of Semtner (1976).'

9. *Some of the presented model configurations (ECHAM5 coupled to NEMO) have been developed almost 10 years ago (Park et al., 2009), and have been used extensively during the last 10 years including work on the SST bias (Wahl et al., 2009, Harlass et al., 2015). Unfortunately, none of this work is mentioned in the introduction or in the discussion.*

Reply:

Thanks for these comments. We have implicitly mentioned the some of these previous studies in the OGCM introduction part in section 2.1.1.

'Designed to serve as a flexible tool for ocean and sea ice studies, NEMO manifests good usability interacting with other ACGMs (Gualdi et al., 2003; Luo et al., 2005; Park et al., 2009; Dunlap et al., 2014; Huang et al., 2014).'

These citations have been added to the introduction part as you suggest. However, no more discussion on these previous studies is supplemented because other similar studies have been introduced.

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