Reply to detailed major comments

1. *Page 5, line 31: The model experiments are performed using the piControl standard scenario of the MPI-ESM (p. 5, line 31). Most of the observational or reanalysis products used to compute model biases cover more recent periods than pre-industrial (1850 or 1870). Which reference period is used to compare the model runs to?*

Reply:

Thanks for these comments. As introduced in section 2.4, the reference period is 1981~2010, the same time period of the reanalysis data. More information about the scenario setting has been added to the paper.

'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 ….'

2. *Page 6, line 1: "Model initialization is started from the climatology basic state recalculated with the AMIP run input data from 1981 to 2010." This suggests that the initial conditions in the atmosphere are based on a climatology calculated from AMIP simulations. Due to the chaotic nature of the atmospheric circulation, the choice of initial conditions of the atmosphere are not crucial for the performance of a coupled GCM. Hence we would strongly suggest to provide more information on the ocean initial conditions (see also our general comment above).*

Reply:

Thanks for these comments. As in the response to major concern No.1, the World Ocean Atlas (WOA) data has been used in the OGCM initialization. We have added some details in the ocean model initialization.

'The NEMO3.6 is initialized with temperature and salinity climatology from World Ocean Atlas (WOA) data, applying the geothermal heating at ocean bottom. The RGB formulation (Lengaigne et al., 2007) has been chosen to calculate the light penetration over the sea surface with observed time varying chlorophyll.'

3. *Figure 3c/d clearly shows the absence of a North Atlantic (NA) cold bias in a 2 ℃ ocean model coupled to a coarse resolution atmosphere (ECHAM5/6-NEMO3.6st configuration) which is a very striking result. The NA cold bias has been around for decades in coupled climate models at the given resolution, and numerous papers*

discuss it (e.g. Zhang and Zhao, 2015). None of this work is mentioned or compared to.

Reply:

Previous studies have been introduced in the introduction part, including Zhang and Zhao (2015) in the original manuscript. In the revised manuscript, more comparison has been added in section 5.1 about the AMOC inter-model comparison. The following picture is a snapshot of the original manuscript where Zhang and Zhao (2015) is mentioned.

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Geoscientific Model Development
Discussions
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amplify trade wind biases in general circulation models (GCMs) (Li and Xie, 2014), which is also responsible for excessive cold tongue simulation in equatorial Pacific. Besides traditional understanding of coupling processes that account for SST and precipitation biases, recent studies have revealed other factors in the air-sea interaction that significantly contribute to the model bias pattern. Burls et al. (2017) find a quadratic relationship between extra-tropical Pacific albedo and equatorial SST bias, and Pham et al. (2017) suggested that the deep cycle of cold tongue turbulence can be affected by cloud cover and rain. The air-sea kinetic energy budget is found to be linked with surface gravity waves, where wave age and friction velocity affect in the ratio between kinetic energy from the winds and underlying surface currents (Fan and Hwang, 2017).

The dynamic mechanisms that play a major role in the biases propagation in the CGCMs are also investigated from a wide range of perspectives. Double ITCZ precipitation problem is usually associated with biases in radiation budget and surface winds (Lin, 2007). There is a close relationship between clouds and SST variation (Klein & Hartmann, 1993; Norris & Leovy, 1994), and changes of low clouds and shortwave radiation flux react on the SST and sea level pressure (SLP) (Norris et al., 1998; Mochizuki & Awaji, 2008; Bond & Cronin, 2008). Wu and Kinter III (2010) suggested that high-frequency changes in atmospheric circulation affects largely on the surface shortwave radiation, and hence its correlation with SST variability in the mid-latitude North Pacific. The weak simulation of Atlantic meridional overturning circulation (AMOC) is found to be responsible for sea surface temperature (SST) cold biases in the northern hemisphere in 22 CMIP5 climate models (Wang et al., 2014), which poses a great impact on the North Pacific through Northern Hemisphere annular mode (NAM) and wind-evaporation-SST (WES) feedback, combining SST biases in extratropical North Atlantic (ENA) and tropical North Atlantic respectively (Zhang & Zhao, 2015). The temperature bias can also be attributed to underestimation of water vapor

No more comparison about the North Atlantic SST has been made in the original manuscript because the main purpose of this paper is to introduce the new CGCMs and the mechanisms behind their inter-model differences specifically in North Pacific. In the revised manuscript, the AMOC has also been analyzed in section 5.1. In section 6.1, the inter-model differences in North Atlantic SST also show that the AGCM replacement changes radiative forcing that affects surface heating. With more heat supply in subtropical and extra-tropical Atlantic, the MOC transports more heat to higher latitudes which ameliorates cold SST biases in North Atlantic in the ECHAM5-NEMO3.6 experiment. Roles of other teleconnections such as NAM through air-sea feedback is left for a future research. Relevant content 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.'

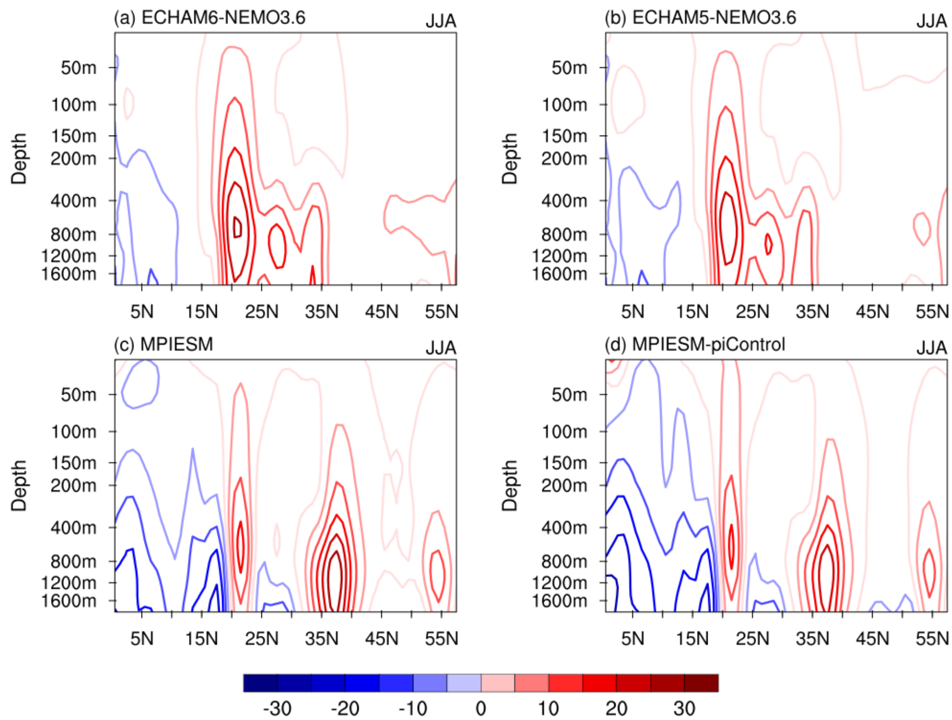

Figure 10: Model biases of the AMOC in summer, (a) ECHAM6-NEMO3.6, (b) ECHAM5-NEMO3.6, (c) MPI-ESM, (d) MPI-ESM piControl, Unit: Sv.

'…On the contrary, the AMOC enhancement is less significant. However, with increased surface heating in subtropical and extra-tropical North Atlantic, the MOC transports more heat to higher latitudes which ameliorates cold SST biases in North Atlantic. Roles of other teleconnections between North Pacific and North Atlantic suggested by Zhang & Zhao (2015), such as NAM through air-sea feedback, is left for a future research.'

4. *Figure 3: The authors note that the SST bias is largest in the polar regions exceeding 4degC as shown on Figure 3. This large bias clearly coincides with sea-ice coverage. There, the HadISST data set, which is used as a reference here, provides temperatures near the freezing point of sea water (-1.9degC). While the authors are right that HadISST and other reanalysis products have deficiencies in high latitudes due to the lack of observations, it is quite astonishing how the model bias can exceed 4degC where the sea water should be at or near the freezing point. Large biases can be expected at the sea-ice edge, which position may quite differ among coupled models.*

Reply:

We have compared our model results with those of Huang et al. (2014), which yields the same large bias in polar areas. Their figure has been pasted below:

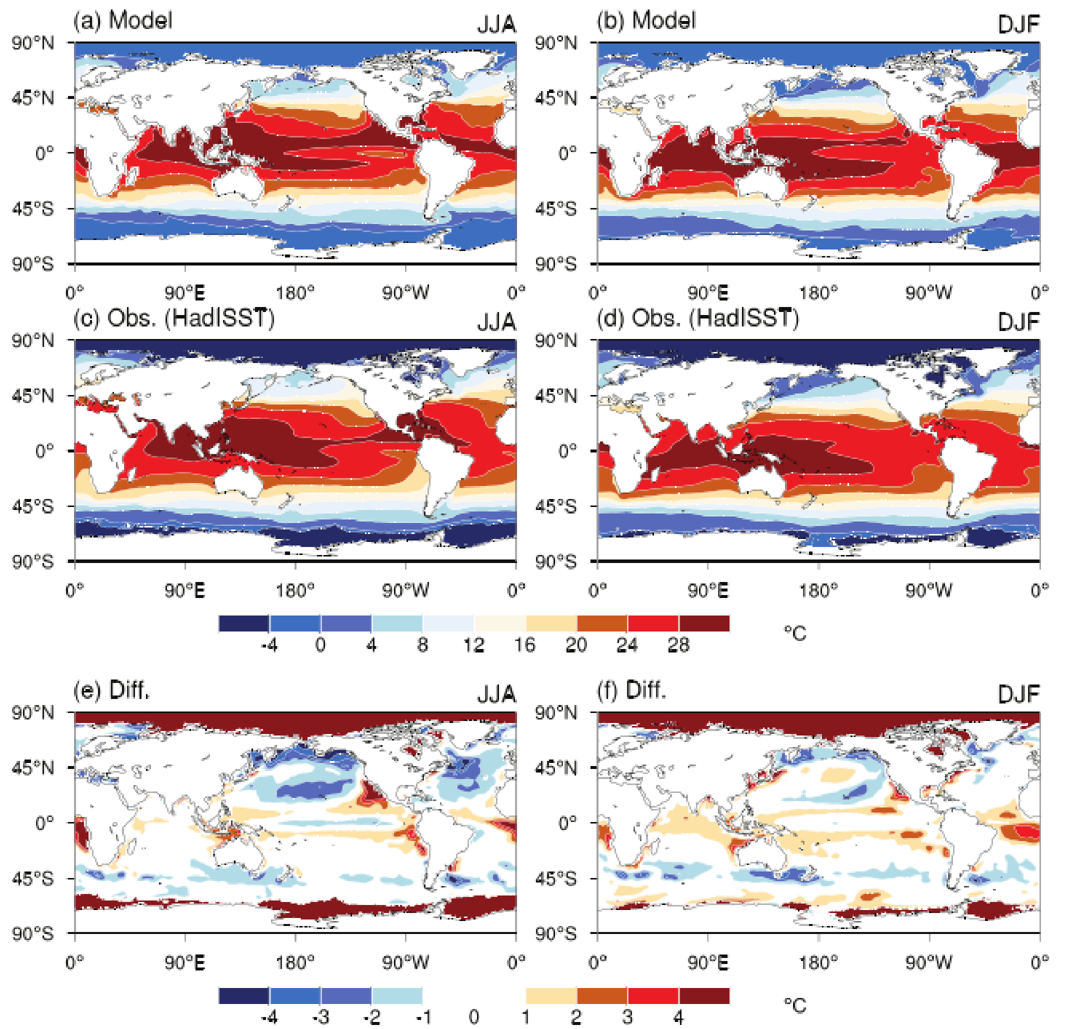

Fig. 3. Distribution of the (a, b) modeled and (c, d) observed SST (°C) in JJA and DJF for the periods as defined in section 2, and (e, f) their differences.

From the above figure, it can be seen that the HadISST possesses much lower SST in polar areas, far below -4°C, which is not the same as "-1.9 degC" in this major comment. It also proves that large biases in polar areas are not my fault.

5. *Page 9, section 4.4 on ocean currents: The section on ocean currents is confusing as the differences in ocean currents are not related to the underlying ocean currents. When discussing differences in ocean currents please term the ocean currents that are enhanced/weakened, for example "enhanced/weakened Kuroshio transport is present in Model A compared to observations."*

Reply:

Thank you for these comments. We have revised the manuscript as you suggest. Major modifications made in the section have been pasted below.

‘The ocean current biases are mainly located in tropical areas (Fig. 6), in predominantly zonal directions for ECHAM5-NEMO3.6 and ECHAM6-NEMO3.6, but meridionally distributed for MPI-ESM. South equatorial currents and equatorial counter currents are enhanced in ECHAM5-NEMO3.6, with more anomalous currents than those in ECHAM6-NEMO3.6 (Fig. 6a, c). Whereas the MPI-ESM features southward (northward) tilted biases south (north) of the equator to a larger degree than the other two CGCMs, which enhance the Kuroshio current, East Australian current, Brazil current and Mozambique current but weaken the Peru current, California current, Benguela current and West Australian current (Fig. 6e). The direction of ocean current biases generally agrees with that of wind stress biases, where poleward deflection can be attributed to Coriolis effects. Since the poleward motion is too strong in the MPI-ESM experiment, the ocean currents in subtropical North Pacific even turn to the east. The Kuroshio transport is enhanced for both MPI-ESM and ECHAM5-NEMO3.6, favouring more heat transport from subtropics to higher latitudes. Yet colder SST biases still exist over large maritime space in MPI-ESM experiment, which suggests an investigation on radiation budget and the meridional overturning currents that provide a full picture of most relevant oceanic processes. The SST biases are also attributed to different projection grids of NEMO3.6 and MPIOM, which however is beyond the scope of this paper. Biases in winter season are diminished to some degrees in tropical oceans, with little amplification of biases outside tropics in ECHAM5-NEMO3.6 and ECHAM6-NEMO3.6 experiments (Figs. 6b, d). But the MPI-ESM comes up with significantly enhanced Kuroshio transport in subtropical North Pacific (Fig. 6f), which may help to explain warm SST bias around Sea of Japan (Fig. 3f) and cold SST bias in the subtropical ocean.’

6. *Page 11, lines 11-15: In the first sentence you claim that the differences in NPMOC in the two MPI-ESM model simulations are not caused by the increased coupling frequency while in the second sentence you argue that “suggesting obvious improvements after decreasing coupling interval” are present. Please clarify. Additionally please provide more information on the MPI-ESM model data (e.g. MPI-ESM model version and a reference paper) cited as “The piControl experiment result (available in http://esgfnode. llnl.gov/)”. To our knowledge, the publicly available MPI-ESM output available at http://esgf-node.llnl.gov is based on the CMIP5 version of MPI-ESM which implements older versions of both ECHAM6 and MPIOM. It means that the two models differ by far more than just the coupling frequency.*

Reply:

I tried to say that more MOC biases in the MPI-ESM experiment than those in the ECHAM5-NEMO3.6 and ECHAM6-NEMO3.6 are not caused by increasing coupling frequency. In fact, it helps to improve the simulation quality, which can be seen from the comparison with piControl data. This sentence has been rewritten to avoid ambiguity.

'The piControl experiment result (available in http://esgf-node.llnl.gov/) is attached (Fig. 9d) to demonstrate that the prominent biases in MPI-ESM than those in the NEMO3.6 coupled experiments are not caused by increasing coupling frequency from one day to 4 hours. The piControl run data used in this study has the same time span as that of the reanalysis data from the year 1981 to 2010, which should be able to represent the model abilities in reproducing the climatology of the same period.'

There are indeed many differences between the MPI-ESM AGCM and the counterpart in CMIP5 piControl, due to model updates of all kinds. By using the piControl data for comparison, I just try to prove that the model simulation is not degraded by changing coupling frequency, which can be used for inter-model comparison with other CGCMs. I have revised the manuscript to convey this idea more clearly.

'More contour lines appear in NPMOC biases of piControl than the MPI-ESM experiment conducted in this paper (Fig. 9c, d). Although the MPI-ESM in the CMIP5 piControl experiment is an older version, it can at least demonstrate that increasing coupling frequency from one day to 4 hours does not degrade the MPI-ESM simulation. Previous studies also suggest that model simulation can be improved by decreasing coupling interval (Bernie et al., 2008; Ge et al., 2017). Hence, the MPI-ESM experiment result and the inter-model comparison with other CGCMs are trustworthy.'

7. *page 12, line 15: "The analysis on oceanic and atmospheric circulation has made it clear that the SST bias is consistent with meridional overturning circulation in North Pacific, driven by surface wind stress anomalies that are maintained by anomalous Walker circulation over the tropical Pacific. Cumulus convection process is found to be a major contributor to inter-model differences". The authors should explain in more detail why they assume that cumulus convection is the key in the chain of arguments provided.*

Reply:

Thanks for these comments. We have added a more detailed explanation.

'Since cumulus convection modulates changes in temperature, specific humidity and atmospheric circulation, it is most likely to be the predominant factor that shapes the inter-model differences.'

8. *page 13, line 11: This sentence is confusing. Your statement that enhanced northerly winds (which we cannot find on Figure 10b as you indicate in the text) in ECHAM6-NEMO3.6 compared to ECHAM5-NEMO3.6 in a region dominated by easterly trade winds are responsible for stronger evaporative cooling of SSTs in ECHAM6-NEMO3.6 compared to ECHAM5-NEMO3.6 is unclear. Please clarify.*

Reply:

Thank you for pointing out the problem. The “northerly winds” in the text should be changed into “southerly winds”. We are sorry for the mistake. In our opinion, the easterly winds superimposed by southerly anomalies result in a bigger wind speed that helps to increase surface evaporation. Evaporative cooling in the region decreases the SST. We have revised the statement to avoid ambiguity.

‘Deviations of 10m wind exhibit southerly anomalies around the central tropical Pacific in southern hemisphere (Fig. 12b), where easterly winds prevail for summer climatology (Fig. 10a). The easterly winds superimposed by southerly anomalies result in a bigger wind speed that helps to increase surface evaporation. Hence the latent heat absorption over the sea surface are enhanced that makes SST deviation colder than 1℃ (Fig. 12d).’

9. *page 13, line 18: "Since the latent heat and surface wind differences are caused by replacing the AGCM,..." The statement is challenging, as for example the latent heat flux between ocean and atmosphere is a coupled process (see also 12. below).*

Reply:

Thank you for giving us the advice. We have corrected the statement.

‘Since the latent heat and surface wind differences are caused by replacing the AGCM and the associated air-sea feedback, it is advisable to compare deviations in vertical circulation that may shed some light on corresponding physical processes.’

10. *Page 13, line 27: “It turns out that deviations in shortwave flux and latent heat are more significant than those in longwave and sensible heat fluxes.” Additional information on the physics behind this statement would be helpful. In its current form it completely ignores the fact that there are large differences in the regional importance of the different fluxes.*

Reply:

Thank you for pointing out the problem. We have modified the statement as follows:

‘From the general view of ocean surface energy balance, the amount of incoming and outgoing energy should be equal. Variations of shortwave flux and latent heat are more significant than those of longwave and sensible heat fluxes after replacing the AGCM.’

11. *Page 14 first lines: "...can be confirmed that the AGCM replacement first alters cumulus convection that modulates temperature, specific humidity and atmospheric circulation, which in turn accommodates cloud radiation feedback to a consistent change and affects the radiation budget". Some references that underpin the postulated process chain should be added.*

Reply:

Thank you for your suggestion. We have added citations of related publications at the end of the sentence.

‘…which in turn accommodates cloud radiation feedback and changes the radiation budget (Xu and Randall, 1995; Stephens et al., 2008; Ghate et al., 2015).’

12. *Page 16, line 8: “Through analysis on circulation and radiation terms, it has been clear that latent heat of evaporation plays a predominant role in the SST differences after changing the OGCM.” This statement does not take into account that LH flux is a coupled process. LH heat flux may impact SSTs in the tropics where atmospheric temperature is high and hence strong evaporation is possible, but is mainly dominated by stability of the atmospheric stratification, windspeed, moisture and temperature in the lowest atmospheric level. It’s not as simple as the sentence suggests.*

Reply:

Thank you for pointing out the problem. We have addressed the problem in the response to one anonymous referee. Since the OGCM replacement changes the ocean dynamics simulation, which changes the ocean surface properties and the air-sea feedback. The atmospheric model responds to this perturbation during coupling with the OGCM. The atmosphere and ocean systems finally reach a quasi-equilibrium that exhibit variations in the SST. Although the latent heat flux holds the biggest correlation coefficient and the most obvious deviation pattern among the four radiation terms, it is more likely a manifestation of the large-scale ocean dynamical effect on the inter-model differences as suggest by Ying and Huang (2016). Major changes regarding this issue are pasted below:

‘Since the top 3 variables that are most relevant to SST deviations (Tab. 1) suggest changes in the surface heat budget, involving the momentum and temperature exchanges between ocean and atmosphere, it implies that the joint effects of atmosphere and ocean models lead to the model deviation patterns (Fig. 15). Simulation of ocean dynamics is different after replacing the OGCM. With changes in ocean advection, the SST and surface currents are altered which modulates the surface evaporation, convection and heat conduction. Subsequently the latent heat and sensible heat fluxes vary over the sea surface. The thermal and moisture perturbations from the ocean are passed to the atmosphere during coupling processes (Fig. 15c, d). Variations of low-level atmospheric circulation and humidity take effects on cloud formation and cloud liquid water path that changes precipitation and cloud radiative forcing. The net shortwave and longwave radiations are influenced and make a difference to the atmospheric circulation (Fig. 12c) and the heat budget over the sea surface (Fig. 15 a, b). Then, the perturbation signal is transferred back to the ocean that changes the SST and surface currents. This air-sea feedback finally reaches a quasi-equilibrium with marked SST warming over vast maritime spaces over the globe. The associated physical processes represented by each radiation term in Figure 15 are in accordance with their signs of pattern correlation (Tab. 1). It seems to suggest that surface evaporation plays a predominant role in the SST differences, because the latent heat flux holds the biggest correlation coefficient and the most obvious deviations among the four radiation terms. However, it is more likely a manifestation of the large-scale ocean dynamical effect on the inter-model differences as suggest by Ying and Huang (2016).'

13. *Page 16, line 10: What are "conduction processes" and how do they affect sensible heat flux? Additionally, this sentence indicates that the authors don't take into account that e.g. sensible heat flux is a coupled ocean-atmosphere process that mainly depends on the ocean atmosphere temperature difference. The importance of sensible heat flux for SST depends on the region. The authors should also provide a reference if and to what extend the surface flux parameterizations have changed in ECHAM6 with respect to ECHAM5.*

Reply:

Thanks for these comments. "Conduction processes" refer to heat conduction over the sea surface. Sensible heat flux can be affected by heat conduction and convection near the sea surface, which indeed depends on the air-sea temperature differences. We have modified the sentence as you suggest. This statement is for the OGCM replacement case, in which the AGCM is only ECHAM6. Therefore, the citations of surface flux parameterizations are provided, but changes in surface flux parameterizations are not mentioned.

‘For the OGCM replacement, the top 3 variables are latent heat flux, sensible heat flux and net longwave flux. Through analysis on circulation and radiation terms, it has been clear that the ocean dynamical effect plays a predominant role in the SST differences after changing the OGCM. The ocean advection initiates the perturbations of SST and surface evaporation that modulate the atmospheric humidity and low-level circulation. Consequently, the cloud masking effect on radiative fluxes are altered which influences the atmospheric circulation and surface heat budget. The resulting equilibrium of the air-sea feedback manifest itself as the inter-model differences in the related meteorological fields. With the same surface flux parameterizations in the AGCM (Stevens et al., 2013), latent heat flux holds the largest correlation coefficient and exhibits the most prominent variations at the global scale. Since the latent heat differences are resulted from the OGCM replacement, it changes the SST and surface evaporation that also contribute to differences in the near-surface atmospheric humidity. Cao et al. (2015) point out that diversity of simulated SST and near-surface atmospheric specific humidity lead to the most diverse variability of latent heat flux over Pacific in CMIP5 models, which coincides with our research finding.’

14. *page 16: line 11: "Attributing simulation deviations to latent heat in the OGCM case is consistent with Cao et al. (2015), which points out that amplitude and meridional variability of latent heat flux over Pacific are the most diverse in CMIP5 models." From our understanding, Cao et al. summarize that LH flux is very diverse amongst coupled models due to the large differences in simulated SST but not that the LH flux differences between the models can explain the bias (From the abstract of Cao et al., 2015: "Regression analysis indicates that the inter-model diversity [in LH flux] may come from the diversity of simulated SST and near-surface atmospheric specific humidity").*

Reply:

Thank for your comments. As we have explained in the previous question, the latent heat differences are resulted from the OGCM replacement, which changes the SST and surface evaporation. It also contributes to differences in the near-surface atmospheric specific humidity. We have modified the statement to avoid ambiguity.

‘With the same surface flux parameterizations in the AGCM (Stevens et al., 2013), latent heat flux holds the largest correlation coefficient and exhibits the most prominent variations at the global scale. Since the latent heat differences are resulted from the OGCM replacement, it changes the SST and surface evaporation that also contribute to differences in the near-surface atmospheric humidity. Cao et al. (2015) point out that diversity of simulated SST and near-surface atmospheric specific humidity lead to the most diverse variability of latent heat flux over Pacific in CMIP5 models, which coincides with our research finding.'

15. *Page 16, line 14: Please explain what the term "reverse transformation of model bias" means.*

Reply:

We would like to say the inverse variations of model SST by replacing the AGCM and OGCM. The sentence has been rewritten.

'…suggesting that inverse variations of model SST bias can be realized through ….'

16. *Page 16, line 25: More details on the "coupling processes" (line 26) that you claim to be responsible for the differences in the wind field in the different GCMs should be added.*

Reply:

Thank you for your advice. We have briefly included the physical processes that are responsible for less wind biases in zonal direction.

'… which suggests that OGCM replacement can also diminish this bias through coupling processes involving evaporative cooling and cloud radiative feedback. The associated thermal forcing drives the atmospheric circulation and changes the ocean surface wind biases. It is easy to see that an anomalous Walker circulation rotating clockwise appears over the tropical Pacific, when the surface heating is colder in the east and warmer in the west (Fig. 13b and Fig. 15).'

17. *Page 16, line 28: Please explain what you mean by "net surface radiation is warmer in the east and colder in the west."*

Reply:

We would like to say that the surface heating is enhanced over the tropical eastern Pacific but is weakened in the tropical western Pacific. We have revised the statement with proper expressions.

'It is easy to see that an anomalous Walker circulation rotating clockwise appears over the tropical Pacific, when the surface heating is weakened in the tropical eastern Pacific and is enhanced in the tropical western Pacific'

References

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