Response to the editor and reviewers

We greatly appreciate the constructive comments and suggestions on the previous version of the manuscript from the editor and reviewers. We have attempted to address every point raised. The following is the point-by-point reply, with reference to the order of the comments made by the editor and reviewers.

The main changes we have made in the revised version are listed as below:

1. The referee suggested to add more information about our reconstruction in this study. We have provided the Table 1(on pages 42-45), Table S4 (on pages 5-8 in Supplementary Information), and Table S5 (on pages 8-13 in Supplementary Information) to show the detailed information of the pollen site, the biome scores of each record and the reconstructed result of each variable from IVM. We also give the boxplots of temperature and precipitation anomaly (MH-PI) in Figure 3 and Figure 4 to better illustrate the discrepancy between model-data of climate change over China during MH.
2. Following the referee comment, we did the cross-proxy validation of our reconstruction. In the revised version, we compared our reconstruction with previous studies over China based on multiple proxies (including pollen, lake core, palaeosol, ice core, peat and stalagmite). Compared to PI, most reconstructions reproduced a warmer and wetter annual condition during MH, same as our study. In other word, this discrepancy between model-data for climate change over China during MH is common and robust in reconstructions derived from different proxies. The results are shown in Fig. 7 on page 58 in the revised paper.
3. The referee raised an important issue on "One way to test the proposal of the authors would be prescribing the reconstructed vegetation in a climate model to see how the model results would be altered." Although we can't prescribe the MH vegetation with our reconstructed results in all PMIP3 models, we have succeeded to conduct such test in CESM version 1.0.5. The new-added Fig.9 (on page 60 in the revised paper) shows the climate anomalies between two simulations (6 ka_VEG minus 6 ka), for both annual and seasonal scale. For temperature, it's clear that the 6 ka_VEG

simulation reproduces the warmer annual (~0.3 K on average) and winter temperature (~0.6 K on average), especially the winter temperature. For precipitation, the reconstructed vegetation leads to higher annual and seasonal precipitation, which can also reconcile the discrepancy of increase amplitude for precipitation during MH between model-data (data reproduced larger amplitude than model, revealed by our study). So it's true that the mismatch between model-data in MH vegetation has significant influence on the discrepancy of climate, this is consistent with our proposal in this study.

4. Two referees indicated that the abstract need to provide more information from this work, we added sentences "Our results indicate that the main discrepancies between model and data for the MH climate are the annual and winter mean temperature. A warmer-than-present climate condition is derived from pollen data for both annual mean temperature (~0.7 K on average) and winter mean temperature (~1 K on average), while most of the models provide both colder-than-present annual and winter mean temperature and a relatively warmer summer, showing linear response driven by the seasonal forcing. By conducting simulations in BIOME4 and CESM, we show that the surface processes are the key factors drawing the uncertainties between models and data. These results pinpoint the crucial importance of including the non-linear responses of the surface water and energy balance to vegetation changes" on pages 1-2 lines 22-31 in the revised paper.
5. Following the referee's comment, we added the model-data comparison of Pjan in the revised paper on page 55 in the revised paper.
6. All the references mentioned in our paper are included in the reference list in the revised paper.

Other modifications for specific comments are indicated in each response and marked as underlined words in the marked-up manuscript below.

Response to the editor

1. Archiving data

Input data

Comments: Ideally, the pollen assemblages for each site, at least for the 6ka should be made available (e.g. in trusted archives). The biographic reference must be included for each of the sites. Many citations in Table 1 are not listed in the reference, list.

Response: The biographic reference for each site is included in Table 1 (on pages 42-45 in revised version), and the citations have been added in the reference list. About the pollen assemblages, we provide the biome scores at 6 ka for each pollen site in Table S4 (on pages 5-8 in revised version). The full dataset of pollen records used in our study are from Li et al. (2019), it is available upon the request.

Comments: All the original data must be archived in a vetted repository and a citation should be linked to them.

Response: For the 94 collected pollen records, we give the reference of each pollen record in Table 1, and we also give the Biome type at each site in Table S5, as well as the biome scores (Table S4). For the 65 pollen data from Chinese Quaternary Pollen Database, we need to obey the data usage rule, and the detailed information for these pollen records is not available since they are not public data yet.

Comments: Climate simulations: the citations in Table 3 are not listed in the reference list. This should be amended.

Response: The citations in Table 3 are added in reference list (line 888-890, 536-539, 803-808, 581-583, 632-636, 437-441, 740-753, 504-508, 515-525, 836-839, 540-548, 918-922 in revised version).

Output data

Comments: all reconstructed climate variables and the biomes for each site at 6ka should be archived (the values for the colored dots in Figs. 2-4).

Response: these values are provided in Table S5 (on pages 8-13 in revised version).

Comments: the simulated values for each of the climate variables (the colored bars in Figs. 3-4).

Response: The simulated values for climate variables from each model are provided in Table S6 and Table S7 on pages 13-14 in Supplementary Information.

Comments: basic metadata for each site (the information listed in Table 1)

Response: Provided in Table 1.

2. The "data availability" section

Comments: it should include the doi/url that links to the output data from this study and the reiterates the location of the input data (above). Alternatively, locations of the input data can be provided in the table.

Response: The data from Chinese Quaternary Pollen Dataset are not available yet, for other data used in our study, we prefer to provide them directly in a Table (like Table S4, Table S5) in the SI instead of putting them in a vetted repository.

3. Other reminders

Comments: Of course, the authors might also want to make the digital data for their maps available, or anything that they think might be useful for future studies.

Response: For now, we think all the information about our input and output data are enough, of course, we are open-minded to other possible requests.

Comments: A special attention to the reference list is required. The references marked as red in the attached file are missing in the reference list. The author should also check lines 483, 637 and 694 of their reference list. Is CQPD 2000 or 2001 or both? And also please note the supplement to this comment: http://www.clim-past-discuss.net/cp-2018-145-Ec1-supplement.pdf.

Response: It's CQPD 2000, and all these missing and errors in the reference list are modified in the revised version.

Reference

Li, Q., Wu, H., Yu, Y., Sun, A., and Luo, Y.: Quantifying regional vegetation changes in China during three contrasting temperature intervals since the last glacial maximum, Journal of Asian Earth Sciences, http://doi.org/10.1016/j.jseaes.2018.10.013.

Response to Reviewer #1

Comments from Reviewer #1:

The model-data comparison of climate change during mid-Holocene (MH) is an important issue to validate the results from Global Circulation Model (GCM) against the proxies gathered from dataset. Based on the new pollen dataset and Inverse Vegetation Model (IVM). This study provided a quantitative reconstruction of climate variables during MH over China was provided and compared to the simulation results from 13 models in PMIP3. A large discrepancy on the temperature anomaly between model-data at both annual and seasonal scale was depicted, mainly due to the failure of capturing vegetation change during MH by models, which is very helpful for better understanding the climatic changes during MH, and also pinpoints the possible way to reconcile model and data by accurately simulating the non-linear responses of vegetation and hydrology in GCMs. The manuscript can be accepted for publication after minor revision. A few basic comments and some issues to deal with as follow:

1. Since it's a quantitative model-data comparison based on pollen dataset, in which 91 records were digitized from published papers. More detailed information about the data should be provided, like the age control, pollen assemblages from around 6 ka at each site.

Response: the required information has been added in the Table 1 (page 45-48) and Table S5 (page 8-13 in Supplementary Information).

2. As mentioned in the manuscript, there is a difference in vegetation inputs for the MH period among models in PMIP3, a table for detail information should be given.

Response: we added a new Table S8 in the supplementary information (page 15 in Supplementary Information).

Table S5. Vegetation setting for the mid-Holocene among models in PMIP3

Model	*L A I*	*Stomatal Resistance Function Of*	*Vegetation Time Variation*
CCSM4	Prognostic	CO_2 | Light | Temperature | Water availability	Prescribed (varying from files)
MIROC-ESM	Prescribed	CO_2 | Light | Temperature | Water availability	Prescribed (varying from files)
BCC-CSM1.1	Prognostic	CO_2 | Light | Temperature | Water availability	Prescribed (varying from files)
CNRM-CM5	Prescribed	Light | Temperature | Water availability	Fixed (not varying)
CSIRO-MK3.6.0	Prescribed	Light | Temperature | Water availability	Prescribed (varying from files)
GISS-E2-R	Prescribed	CO_2 | Light | Temperature | Water availability	Fixed (not varying)
IPSL-CM5A-LR	Prognostic	CO_2 | Light | Temperature | Water availability	Prescribed (varying from files)
MPI-ESM-P	Prognostic	CO_2 | Water availability	Fixed (not varying)
MRI-CGCM3	Prescribed	CO_2 | Light | Water availability	Prescribed (varying from files)
HadGEM2-ES	Prognostic	CO_2 | Light | Temperature | Water availability	Dynamical (varying from simulation)
HadGEM2-CC	Prognostic	CO_2 | Light | Temperature | Water availability	Dynamical (varying from simulation)
FGOALS-g2	Prescribed	no data	Prescribed (varying from files)
FGOALS-s2	Prescribed	no data	Prescribed (varying from files)

3. The disparity of temperature anomaly during MH among models could be resulted from the difference in pre-industrial (PI) simulation. Authors should prove that there is no any clear relationship between PI temperature and temperature change (MH-PI).

Response: Fig.R1, as attached below, demonstrates that there is no any clear relationship between PI temperature and temperature change (MH-PI), for both annual and seasonal scale, which means the disparity of temperature anomaly during MH among models doesn’t come from the difference in PI simulation.

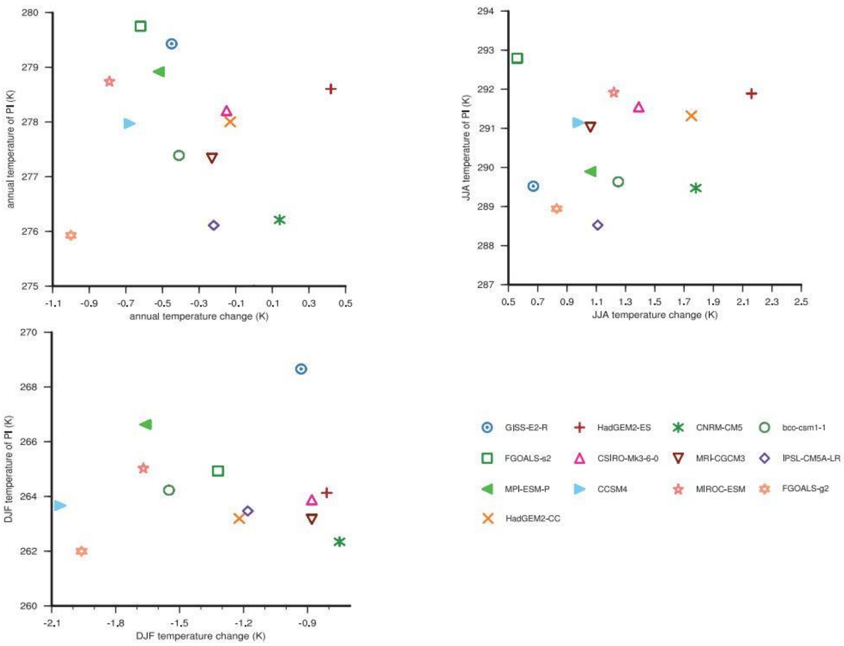

Fig.R1 The relationship between PI temperature and temperature change (MH-PI)

4. Some references are missing in the reference list. Such as the citations in Table 3.

Response: we have added the citations from Table 3 in the reference list (line 943-945, 582-585, 869-874, 629-631, 685-689, 476-480, 804-812, 543-547, 558-568, 896-899, 586-594, 973-977 in revised version) .

Response to Reviewer #2

General Comments: Data-model comparison is often problematic especially at regional scale, for which there are many reasons. This paper presents an interesting analysis to investigate the possible impact of poor representation of vegetation in climate models on the model-data discrepancy over China. The authors compare the PMIP3 results with their "reconstruction" and propose that lack of vegetation dynamics is the main reason of model-data discrepancy in seasonal climate over China. The results are clearly explained and the paper is well written. Especially, a large amount of data are presented and would be a remarkable contribution to the Holocene study. I would recommend its publication after the following comments are considered:

1. At least to my knowledge, regional diversity exists inside China regarding the timing of the mid-Holocene thermal maximum. However, the insolation of 6 ka BP is used in the PMIP3 simulations. In which degree might the model-data discrepancy be related to the forcing used in the climate models? Have the authors compared their reconstructions to simulations of other periods like 9 ka and 12 ka or to transient simulations to see whether the data-model comparison can be improved if different forcing is considered?

Response: Yes, there is a regional diversity exists over China regarding the timing of mid-Holocene thermal maximum (from ~8 ka to 4 ka). But our paper is focused on mid-Holocene time (defined as 6 ka in PMIP), not MH thermal maximum, and we also selected the pollen data at 6±0.5 ka. So for us, in term of the consistency in time, it's better to do a model-data comparison with the 6 ka isolation forcing used in PMIP3, rather than 9 ka or 12 ka.

For the transient simulation, Liu et al.(2014) analyzed the model results from 22 ka in three coupled ocean-atmosphere models: CCSM3, FAMOUS and LOVECLIM. It turns out that all three models reproduced a colder than present annual mean temperature during Holocene, no matter at 12 ka, 9 ka or 6 ka, which is consistent with our results. And we agree with the reviewer that 9 ka and 12 ka are also very important periods to understand the mechanism of climate change during MH, we plan to do this comparison in the future work.

2. One way to test the proposal of the authors would be prescribing the reconstructed vegetation in a climate model to see how the model results would be altered and whether the model would reproduce more realistic results when compare to other proxy data.

Response: We agree with the reviewer, it's a very efficient way to test our proposal if we can run the simulation with the reconstructed vegetation in GCMs. However, as far as we know, prescribing the vegetation in a coupled GCM is not easy. Moreover, the GCM models in PMIP3 have their own vegetation module, it definitely takes much time to do such test, that's why in this paper we choose BIOME4 to evaluate MH vegetation simulation against the reconstructed result.

Although we can't prescribe the MH vegetation with our reconstructed results in all PMIP3 models, we succeeded to conduct such test in CESM version 1.0.5. This version, developed at the National Center for Atmospheric Research, is a widely used coupled model with dynamic atmosphere (CAM4), land (CLM4), ocean (POP2), and sea-ice (CICE4) components (Gent et al., 2011). Here, we use ~2° resolution for the CAM4, configured by ~1.9° (latitude) × 2.5° (longitude) in the horizontal direction and 26 layers in the vertical direction. The POP2 adopts a finer grid, with a nominal 1° horizontal resolutions and 60 layers in the vertical direction. The land and sea-ice components have the same horizontal grids as the atmosphere and ocean components, respectively.

Two experiments were conducted, including a mid-Holocene (MH) experiment (6 ka) with original vegetation setting (prescribed as PI vegetation for MH) and a MH experiment with reconstructed vegetation (6 ka_VEG). In detail, experiment 6 ka used the MH orbital parameters (Eccentricity=0.018682; Obliquity=24.105°; Angular precession=0.87°) and modern vegetation (Salzmann et al., 2008). Compared to experiment 6 ka, experiment 6 ka_VEG used our reconstructed vegetation in China. Except for the changed vegetation, all other boundary conditions were kept unchanged in these two experiments, including the solar constant (1365 W m−2), modern topography and ice sheet, and pre-industrial greenhouse gases (CO_2 = 280 ppmv; CH_4 = 760 ppbv; N_2O = 270 ppbv). Experiment 6 ka was initiated from the default pre-industrial simulation and run for 500 model years. Experiment 6 ka_VEG was initiated from model year 301 of experiment 6 ka and run for another 200 model years. We analyzed the computed climatological means of the last 50 model years from each experiment here.

Fig. 9 in the revised paper (enclosed as below) shows the climate anomalies between two simulations (6 ka_VEG minus 6 ka), for both annual and seasonal scale. For temperature, it's clear that the 6 ka_VEG simulation reproduces the warmer annual (~0.3 K for grid mean) and winter temperature (~0.6 K for grid mean), especially the winter temperature. For precipitation, the reconstructed vegetation leads to higher annual and seasonal precipitation, which can also reconcile the discrepancy of increase amplitude for precipitation during MH between model-data (data reproduced larger amplitude than model, revealed by our study). So it's true that the mismatch between model-data in MH vegetation has significant influence on the discrepancy of climate, this is consistent with our proposal in this study.

Each model has different sensitivity to the boundary change, further work should be carried out in more models to test the influence of vegetation on climate, this is an ongoing work.

This response is on pages 17-18, lines 406-426 in the revised version.

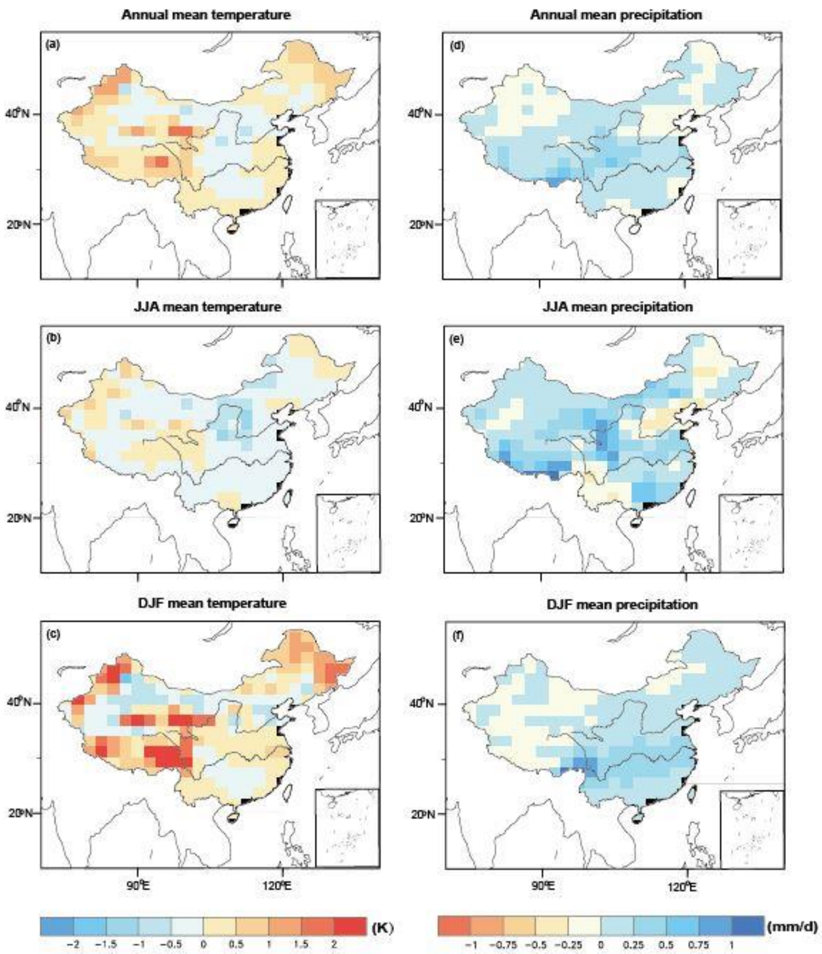

Figure 9. Climate anomalies between the two experiments (6 ka and 6 ka_VEG) conducted in CESM version 1.0.5. The anomalies (6 ka_VEG-6 ka) of temperature and precipitation at both annual and seasonal scale are presented, and all these climate variables are calculated as the last 50-year means from two simulations.

3. The spatial resolution of all the GCMS is very coarse when regional diversity within China is considered. The regional details of topography are not necessarily well represented. I wonder in which degree the model-data mismatch is related to rough topography used in the climate models.

Response: Thanks for the important comment, yes, we should consider the possible influence of rough topography on the model-data discrepancy, especially the Tibetan

Plateau (TP). Numerical simulations had been widely utilized to investigate the climate response of the uplift of TP, and it is also indicated by previous studies that most of the experiments use coarse resolution GCMs have deficiency in describing the small-scale topography and hence climate (Wang et al., 2005; Gao et al., 2008; Jiang et al., 2016).

In PMIP3, the topography for mid-Holocene is same as CMIP5 PI, and thus, each model has the same topography boundary for both MH and PI, the difference between them concerning the topography is the interpolation due to their different resolutions. Among the 13 models used in this paper, MRI-CGCM3 has the highest resolution (Atmosphere: 320*160*L48; Ocean: 364*368*L51), while IPSL-CM5A-LR has the lowest one (Atmosphere: 96*96*L39; Ocean: 182*149*L31). The possible influence of topography on the model-data mismatch captured in our study could be tested from two points:

Firstly, for the model with high resolution. In Fig. R2 (enclosed below), we give the actual modern orography and the interpolated orography used in MRI-CGCM3 and IPSL-CM5A-LR. For MRI-CGCM3, the topography is very close to the observation, so for this model, the model-data discrepancy during MH over China is not related to rough topography.

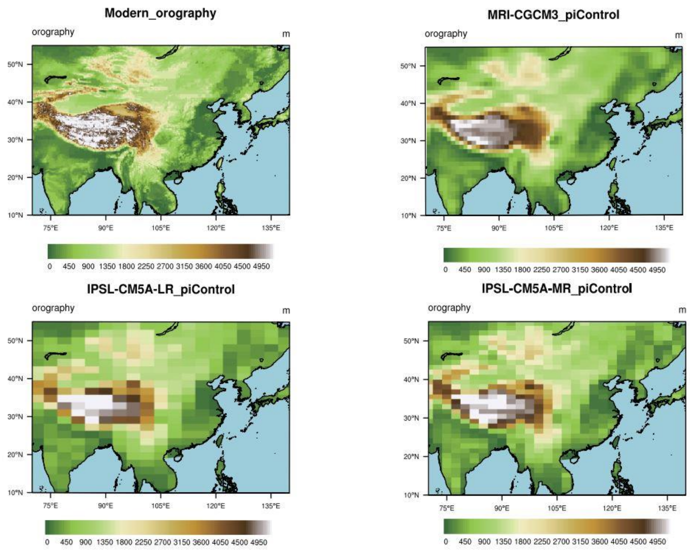

Figure R2. The topography comparison between models and observation

Secondly, for the model with course resolution. When we compare the topography of observation and that used in IPSL-CM5A-LR, it's true that the course version of model will lead to biases in topography when the regional diversity is discussed. To quantify such influence, we compare the results of IPSL-CM5A-LR and IPSL-CM5A-MR (Fig. R3). The difference in topography caused by model resolution has influence on some small regional climate, but no significant change for general pattern.

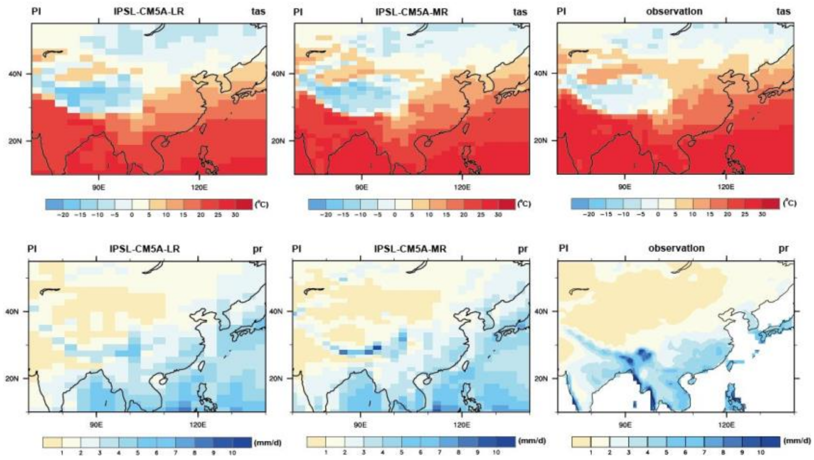

Figure R3. The preindustrial climate comparison between simulation and observation. Tas means temperature above 2m surface, pr means precipitation.

4. Line 372: the authors consider the poor capacity of vegetation modelling in climate models to be the major reason for model-data discrepancy. Before the author test for other reasons like those related to topography, soil types, selected climate forcing, I am not very convinced that vegetation is the major reason.

Response: For the selected climate forcing and topography, we have already gave the answer above (in question 1 and question 3). For soil type, to our knowledge, there is no relative research to quantify the soil type effect on climate over China during MH. But it's certainly true that soil type change could lead to climate anomaly through surface albedo variation and hydrology processes. For instance, if the bare soil transferred into vegetated soil, the regional climate could be warmer due to the decreased surface albedo. But for the further quantification of this contribution, it will be done in the future work.

In this paper, we only focus on the vegetation influence on the model-data discrepancy, and we do present and prove the mismatch between model-data in MH vegetation could partly account for the discrepancy of climate. We don't emphasis that the vegetation influence is the main reason. And according to your suggestion, we add the sentence: "Moreover, besides the vegetation influence, to which extent this model-data discrepancy is related to rough topography, soil type and other possible factors should be investigated in the future work." (on page 19, line 440-442).

5. Two models of 13 use dynamical vegetation model. According to your analyses, is there obvious advantage of using AOV instead of AO?

Response: As we mentioned in the manuscript, only 2 models (HadGEM2-ES and HadGEM2-CC) in PMIP3 has the dynamic vegetation simulation for mid-Holocene. However, the main vegetation changes during MH demonstrated by these two models are very different. HadGEM2-ES simulated increased tree coverage (~15%) and a decreased bare soil fraction (~6%), while HadGEM2-CC depicts a ~3% decrease in tree fraction and a ~1% increase in bare soil (Fig. S9 in supplementary information, on page 27 in the revised paper).

We made a rough calculation of albedo variance caused solely by vegetation change for both two models and for our reconstruction, based on the area fraction and albedo value of each vegetation type (Betts, 2000; Bonfils et al., 2001; Oguntunde et al., 2006; Bonan, 2008). Reconstruction showed vegetation changes during MH leading to a ~1.8% decrease in albedo when snow-free, with a much larger impact (~4.2% decrease) when snow-covered. The results from HadGEM2-ES are highly consistent with the albedo changes from the reconstruction, featuring a ~1.4% (~6.5%) decrease without (with) snow, while HadGEM2-CC produces an increased albedo value during MH (~0.22% for snow-free, ~1.9% with snow-cover), depending on its vegetation simulation.

The difference in simulating MH vegetation distribution between these two AOVGCM will influence their ability in capturing the climate change during MH. From Fig. 3 in the manuscript (on page 54), we can see that HadGEM2-ES succeeded to capture the increased annual temperature anomaly (~0.42 K), with relatively higher MTWA and MTCO among models, while HadGEM2-CC showed similar results with other models.

In conclusion, according to our analysis, there is an obvious advantage of using AOVGCM instead of AOGCM when we discussing about the MH climate, but the premise is that the AOVGCM can simulate accurate vegetation distribution.

6. Line 36: do you mean “an increase in the seasonal cycle of insolation”?

Response: Thanks for the correction, we mean “an increase in the amplitude of the seasonal cycle of insolation” in Line 36, and that has been modified in the new version of manuscript on page 2 line 40 in revised version.

7. I wonder how the pollen data of PI was collected. Were they collected from the surface? Is there any influence from human activities?

Response: Yes, the pollen data of PI are collected from the surface, but we only choose the sites without or with little influence of human activity. Moreover, when we collected the pollen data, we abandon the pollen records if the published paper mentions the influence of human activity (on page 5 line 113 in revised paper), so the key point here is that weather can we trust the climate reconstruction if the pollen records are influenced by human activities during PI. To clarify this issue, we have examined the statistical correlations between observed meteorological values and reconstructed climates by inverse vegetation model at the sample sites for PI (Table 6 in manuscript). The regression coefficients are very high (from 0.75 to 0.95), which means that IVM is able to reconstruct the PI climates over China based on the pollen data. In other words, the PI pollen data are reliable to obtain the climate parameters, and the human activity has no significant effect on it.

8. In Figure 3: is the anomaly relative to PI? How was the grid mean value calculated?

Response: Yes, it's the anomaly relative to PI. About the grid mean value, we firstly extract the simulated values at each pollen site, and then calculate the grid mean value in ncl.

9. Line 320: PMIP3

Response: Thanks, we have modified it.

Reference:

Wang, B., Ding, Q., Fu, X., Kang, I., Jin, K., Shukla, J., Francisco, D.: Fundamental challenge in simulation and prediction of summer monsoon rainfall, Geophysical Research Letters, 32, L15711, 2005.

Gao, X., Shi, Y., Song, R., Giorgi, F., Wang, Y., Zhang, D.: Reduction of future monsoon precipitation over China: comparison between a high resolution RCM simulation and the driving GCM. Meteorology and Atmospheric Physics, 100, 73–86, 2008.

Jiang, D., Tian, Z., Liang, X.: Reliability of climate models for China through the IPCC Third to Fifth Assessment Reports, International Journal of Climatology, 36, 1114–1133, 2016.

Betts, R. A.: Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, Nature, 408, doi: 10.1038/nature. 35041545, 2000.

Bonfils, C., de Noblet-Ducoudré, N, Braconnot, P., and Joussaume, S.: Hot Desert Albedo and Climate Change: Mid-Holocene Monsoon in North Africa, Journal of Climate, 14, 3724–3737, 2001.

Bonan, G. B.: Forests and Climate Change: Forcings, Feedbacks, and the Climate

Benefits of Forests, Science, 320, 1444-1449, 2008.

Oguntunde, P. G., Ajayi, A. E., and Giesen, N.: Tillage and surface moisture effects on bare-soil albedo of a tropical loamy sand, Soil and Tillage Research, 85, 107-114, 2006.

Response to Reviewer #3

General comments: The manuscript entitled "Mid-Holocene climate change over China: model-data discrepancy" by Lin et al. presented a study on model-data comparison by using the pollen data collection in China and PMIP3 mid-Holocene simulations. From the large discrepancy showed in model-data comparison, both in annual mean, warmest month and coldest month, they conclude that the major reason that PMIP3 simulations do not agree with data is because the vegetation distribution is not properly represented in climate models, where most models do not include dynamical vegetation and the prescribed MH vegetation map is the same as preindustrial. The MH vegetation issues have been recognized in recent years and many efforts are made to reconstruct a better MH land cover map, this includes the PAGES working group on Landcover6k. Therefore, a good vegetation map from China would be expected to contribute to an eventual global land-cover map during the mid-Holocene and benefit the paleoclimate community. However, the current work has a somewhat mislead focus and I have the following major concerns.

1. The reconstructed mid-Holocene climate in their study is largely depend on the pollen data collection. I am not an expert on pollen data, but I am wondering if all the published data use the same standard on data process. Can they be synthesized by Webb1-7 standard and put together for comparison? I hope a reviewer from pollen community may have some insights on the data process. There are no discussion on the potential uncertainties on collected data, at least one comparison with other proxy data can provide the cross-proxy verification. The authors emphasized three original data but no detailed information, which are important if

they are not published. When the significant differences are found in model-data comparisons, the uncertainties from the data should be discussed as well. One can not regard reconstruction is the truth. We need to know how reliable is the reconstructed climate from pollen data, given that the IVM method used to reconstruct the climate is a crude estimate. Otherwise it is dangerous if this paper is published and people take for granted that this is the climate (and vegetation map) in China during mid-Holocene.

Response: Thanks for this very important comment, we will answer it point by point:

Firstly, can the pollen records collected from papers be synthesized by Webb 1-7?

Yes, we need to do some data processing before we use the collected pollen records to reconstruct the climates. Firstly, the published papers only give the pollen diagram, not the pollen assemblages. So we need to digitize the pollen diagram for obtaining the pollen assemblages, and then use biomization to get the biome scores and biome types. Secondly, for age control, different dating methods are used in the collected pollen records, we use CalPal 2007 (Weninger et al., 2007) to correct ^{14}C age into calendar age so that they can be contrasted with each other. For lacustrine records, if the specific carbon pool age is mentioned in the literature, the calendar age is corrected after deducting the carbon pool. Otherwise, the influence of carbon pool is not considered. The age series of records were obtained by linear regression or linear interpolation of adjacent dating data. After these preprocessing, a unified chronological standard for all pollen records is built, and then the classification of age control followed the standard of Webb 1-7.

The description of these data processing are added in the revised manuscript from on pages 5-6 lines 115 to line 124 in the revised paper.

Secondly, what's the potential uncertainties on data reconstruction? How reliable are the pollen data used in this study? How about the cross-proxy verification?

For the reliability of pollen data, we have compared them with the BIOME6000 (Fig. 2, page 53), the match between collected data and the BIOME6000 is more than 90% for both MH and PI.

For the potential uncertainties on data reconstruction, IVM is relied on the BIOME4, a global vegetation model. Because of the particularity of vegetation types in the monsoon region of China, the BIOME4 needs further improvement of vegetation simulation accuracy in this area. This possible bias in simulating vegetation will lead to uncertainty in reconstruction. In this version, we added more information in Table S5 in supplementary information (on page 8-13 in the SI), we gave the climate variables reconstructed from IVM at each site. Moreover, we also showed the bias on data reconstruction by giving the median value (for instance, column named MTCO) and values indicating the 5% (MTCO1)-95% (MTCO2) uncertainty bands.

For the cross-proxy verification, we compared our reconstruction with previous studies over China based on multiple proxies (including pollen, lake core, palaeosol, ice core, peat and stalagmite). Compared to PI, most reconstructions reproduced a warmer and wetter annual condition during MH (Fig. 7 as below, on page 58 in revised paper), same as our study. In other word, this discrepancy between model-data for climate change over China during MH is common and robust in reconstructions derived from different proxies. Our study just reinforces the picture given by the discrepancies between PMIP simulation and pollen data derived from a synthesis of the literature.

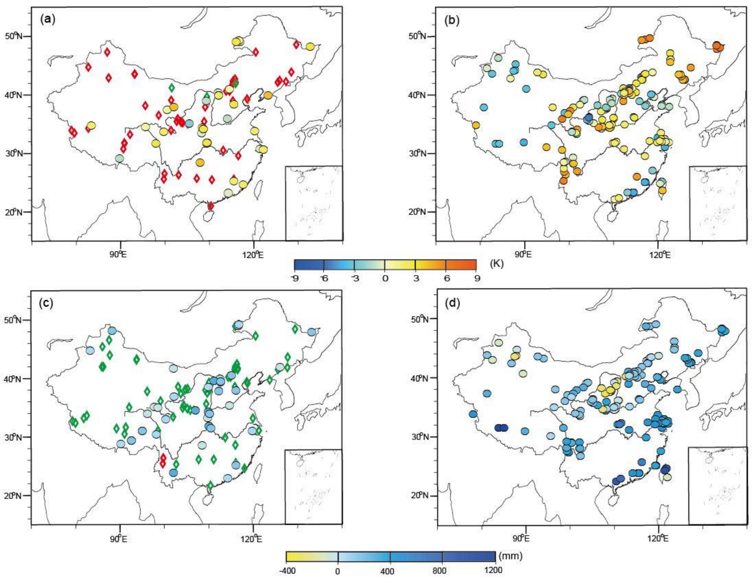

Figure 8. Comparison between our climate reconstruction and previous reconstruction. (a) Previous temperature results. Diamond is the qualitative reconstruction, red is the temperature increase and green is the temperature decrease; Circle is quantitative reconstruction; (b) Mean annual temperature reconstruction in this study; (c) Previous precipitation results, diamond is the qualitative reconstruction, red is the precipitation increase and green is the precipitation decrease; Circle is quantitative reconstruction; (d) Mean annual precipitation reconstruction in this study.

Thirdly, about the three original data, thanks for the reminder. They have been published, and we added the information in Table 1, as well as the reference list (lines 1011-1013, page 44 and lines 921-924, page 40).

2. The BIOME4 produced vegetation pattern in fig5 is determined by the input climate variables from the model, given the supplementary figures s1-s6 and previous studies by Jiang et al. (2012) have already show different climate patterns produced by different models, therefore the mismatch in vegetation pattern and reconstructed map in Fig5 is expected. I don't think this mismatch can be used to argue that the modelled MH climate is not good because they did not use a correct vegetation map and include the vegetation-climate interaction. Those vegetation patterns produced by BIMOE4 are not used in PMIP experiment setup, it would make more sense if authors compare the reconstruction and PMIP prescribed land cover map, or compare BIOME4 produced vegetation map with the ones produced by those climate models (for example HadGEM2-ES) that have dynamical vegetation to gain some understanding on vegetation-climate feedback.

Response: We totally agree with the reviewer, it's a very efficient way to test our proposal if we can run the simulation with the reconstructed vegetation in GCM. However, as far as we know, prescribing the vegetation in a coupled GCM is not easy. For instance, if we want to use the reconstructed vegetation in Orchidee (the vegetation module of IPSL), we need to modify numerous parameters to make sure that the experiment with new vegetation condition will not be killed by the model due to its mismatch in climate variables. Moreover, the GCM models in PMIP3 have their own vegetation module, it definitely takes much time to do such test, that's why in this paper we choose BIOME4 to evaluate MH vegetation simulation against the reconstructed result. Actually, we already plan to conduct this experiment in Orchidee to further test the proposal of this paper, it’s an ongoing work.

Although we can’t prescribe the MH vegetation with our reconstructed results in all PMIP3 models, we have succeeded to conduct such test in CESM version 1.0.5. The CESM version 1.0.5, developed at the National Center for Atmospheric Research, is a widely used coupled model with dynamic atmosphere (CAM4), land (CLM4), ocean (POP2), and sea-ice (CICE4) components (Gent et al., 2011). Here, we use ~2° resolution for the CAM4, configured by ~1.9° (latitude) × 2.5° (longitude) in the horizontal direction and 26 layers in the vertical direction. The POP2 adopts a finer grid, with a nominal 1° horizontal resolution and 60 layers in the vertical direction. The land and sea-ice components have the same horizontal grids as the atmosphere and ocean components, respectively.

Two experiments were conducted, including a mid-Holocene (MH) experiment (6 ka) with original vegetation setting (prescribed as PI vegetation for MH) and a MH experiment with reconstructed vegetation (6 ka_VEG). In detail, experiment 6 ka used the MH orbital parameters (Eccentricity=0.018682; Obliquity=24.105°; Angular precession=0.87°) and modern vegetation (Salzmann et al., 2008). Compared to experiment 6 ka, experiment 6 ka_VEG used our reconstructed vegetation in China. Except for the changed vegetation, all other boundary conditions were kept unchanged in these two experiments, including the solar constant (1365 W m^{-2}), modern topography and ice sheet, and pre-industrial greenhouse gases (CO_2 = 280 ppmv; CH_4 = 760 ppbv; N_2O = 270 ppbv). Experiment 6 ka was initiated from the default pre-industrial simulation and run for 500 model years. Experiment 6 ka_VEG was initiated from model year 301 of experiment 6 ka and run for another 200 model years. We analyzed the computed climatological means of the last 50 model years from each experiment here.

The new-added Fig.9 on page 60 in the revised paper (enclosed below) shows the climate anomalies between two simulations (6 ka_VEG minus 6 ka), for both annual and seasonal scale. For temperature, it's clear that the 6 ka_VEG simulation reproduces the warmer annual (~0.3 K on average) and winter temperature (~0.6 K on average), especially the winter temperature. For precipitation, the reconstructed vegetation leads to higher annual and seasonal precipitation, which can also reconcile the discrepancy of increase amplitude for precipitation during MH between model-data (data reproduced larger amplitude than model, revealed by our study). So it's true that the mismatch between model-data in MH vegetation has significant influence on the discrepancy of climate, this is consistent with our proposal in this study.

Each model has different sensitivity to the boundary change, further work should be carried out in more models to test the influence of vegetation on climate, this is an ongoing work.

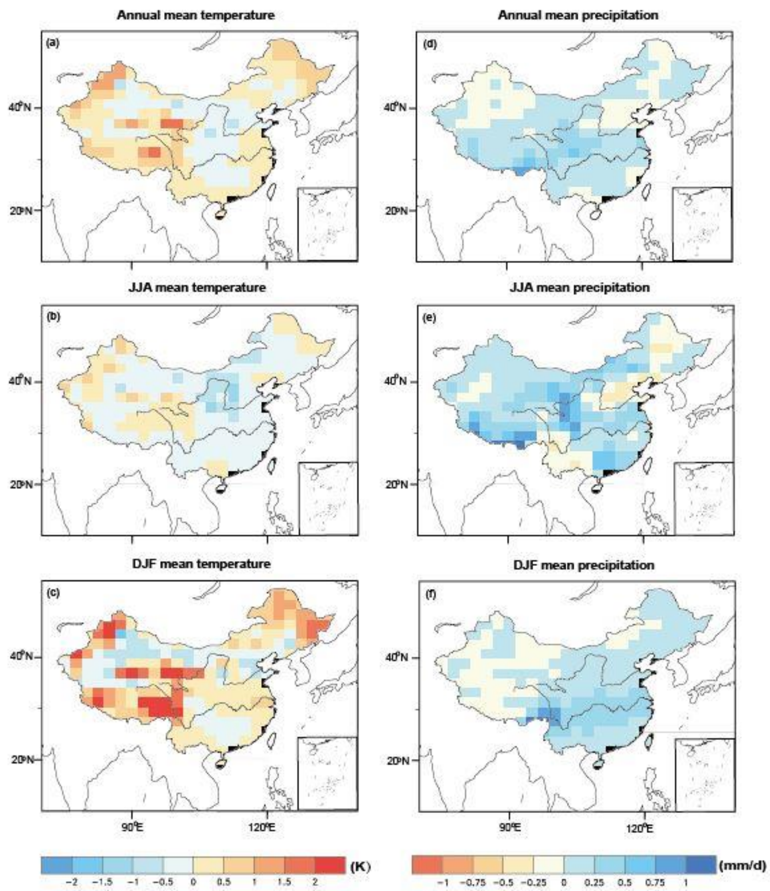

Figure 9. Climate anomalies between the two experiments (6 ka and 6 ka_VEG) conducted in

CESM version 1.0.5. The anomalies (6 ka_VEG-6 ka) of temperature and precipitation at both annual and seasonal scale are presented, and all these climate variables are calculated as the last 50-year means from two simulations.

Specific comments:

1. The abstract need to provide more information from this work, now only contains motivation and conclusion. And the conclusion in abstract actually is a speculation, did not come from the results of this work.

Response: We modified the abstract as following (on page 1-2 line 22-31 in the revised paper):

The mid-Holocene period (MH) has long been an ideal target for the validation of Global Circulation Model (GCM) results against reconstructions gathered in global datasets. These studies aimed to test the GCM sensitivity mainly to the seasonal changes induced by the orbital parameters (precession). Despite widespread agreement between model results and data on the MH climate, some important differences still exist. There is no consensus on the continental size of the MH thermal climate response, which makes regional quantitative reconstruction critical to obtain a comprehensive understanding of the MH climate patterns. Here, we compare the annual and seasonal outputs from the most recent Paleoclimate Modelling Intercomparison Projects Phase 3 (PMIP3) models with an updated synthesis of climate reconstruction over China, including, for the first time, a seasonal cycle of temperature and precipitation. Our results indicate that the main discrepancies between model-data for MH climates are the annual and winter mean temperature. A warmer-than-present climate condition are derived from pollen data for both annual mean temperature (~0.7 K on average) and winter mean temperature (~1 K on average), while most of the models provide a linear response driven by the seasonal forcing (a decreased annual mean temperature with a warmer summer and colder winter). By conducting simulations in BIOME4 and CESM, we show that to capture the seasonal pattern reconstructed by data, it is critical to assess surface processes. These results pinpoint the crucial importance of including the non-linear of the surface water and energy balance to vegetation changes.

2. Take line 49 as an example, 0.5K should be write as 0.5 K, follow SI standard, there is a space between number and unit. May correct throughout the manuscript.

Response: Corrected.

3. Line 116, "The new sites", if it is new, the data information should be described, otherwise they are unknown.

Response: Corrected by adding the description of new sites "91 digitized data and three original data" on page 6 line 128 in revised version.

4. Line 120, what is cloudiness, how are they measured? Because this is not a common variable, should be described.

Response: "Cloudiness" means the "Total Cloud Fraction", it is calculated for the whole atmospheric column, as seen from the surface or the top of atmosphere. Include both large-scale and convective cloud. The standard output name in PMIP is "clt". It's an inverse measure of sunshine (corrected in page 6 line 133 in revised version).

5. Line 129, how do you determine the anomalies for biome scores? What is the purpose of this paragraph L120-L139, to produce reconstruction in Fig5?

Response: To determine the anomalies for biome scores, we first use the biomization (Prentice et al., 1996) to get the biome score calculated from pollen taxa percentage for both MH and PI. And then we get the biome score anomaly (MH-PI). The purpose of line 120-139 is to demonstrate the scheme of artificial neural network (ANN) used in our study, and by using this interpolation method, we get the reconstructed spatial pattern of vegetation in Fig. 5 with red rectangle. The schematic diagram of ANN is provided as below (Fig. R3).

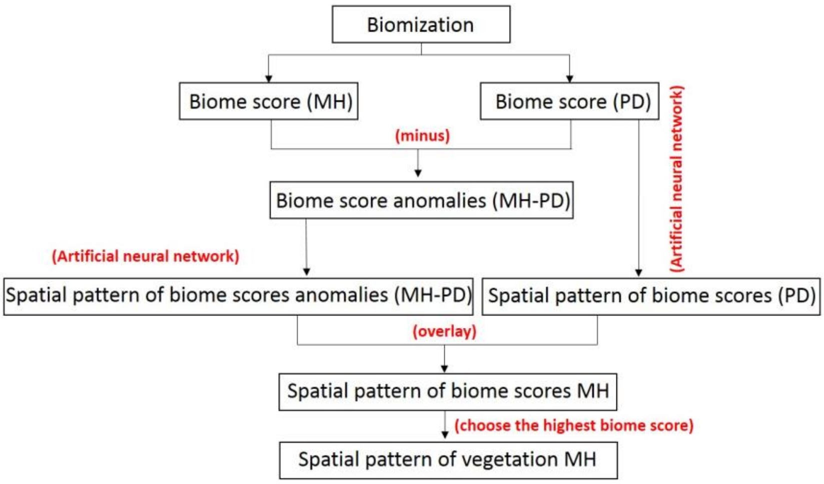

Figure R3. The schematic diagram of artificial neural network.

6. Line 143 to Line 147, on description of PMIP is a bit strange, what do you mean "in which the PI experiment was denied". "The main variability between MH and PI" should be "The main forcing between MH and PI".

Response: From Line 143 to Line 145, we previously wrote as "In its third phase (PMIP3), the models were identical to those used in the CMIP5 experiments, in which the PI experiment was defined", here we mean that the protocol of PI is defined in CMIP5, and the models of PMIP3 followed that from CMIP5. Now according to the suggestion from you and Patrick Bartlein, we deleted the words "in which the PI experiment was defined".

We corrected the "variability" into "forcing" (on page 7 line 161 in revised version).

7. Line 156, "interpolated to a common 2.5 grid", why do you think 2.5 is a common grid, given the pollen data are very local, 2.5 degree grid is too coarse.

Response: The "common" here means "uniform", we have corrected (on page 7 line 171 in revised paper). For the model resolution, yes, our study focus on China area, not globe, but for simulation, 2.5 degree is not very coarse even for local study. Moreover, some global models used in our study have lower than 2.5°*2.5° resolution, like IPSL-

CM5A-LR (96*96), it will not make more sense even if we interpolate it into higher resolution.

8. Line 161-162, How do you obtain the sunshine data from observation and model? Should be described more specific.

Response: The sunshine data could be calculated as an inverse measure of cloudiness. Cloudiness means the "total cloud fraction", it's an output of model which named as "clt". We first obtained the "clt" from each model, then calculate the sunshine based on "clt". In the new version of manuscript (on page 8 line 177 in revised version), we described more specific "sunshine percentage (an inverse measure of cloud area fraction)".

9. Line 184, "Weighting the attributes is subjective", will it cause uncertainties?

Response: As we mentioned in the manuscript, weighting the attributes is subjective because there is no obvious theoretical basis for relative significance. The attributes values listed in Table 4 and Table 5 are according to the previous studies (Skyes et al., 1999; Ni et al., 2000). It may cause some bias, however, it is not likely that different ecologists would assign greatly differing values (Skyes et al., 1999).

10. Line 191, from Zhang et al., 2010, the reference can not be found in reference list.

Response: Added in the reference list (on page 40 lines 933-935 in revised version).

11. I am wondering if the warmest month and coldest month changes between MH and PI (and between the models), or always July and January? Give there is a change in seasonality in MH, authors should mention this.

Response: For reconstruction, we obtained the biological climate based on pollen records, and the warmest month and coldest month are not always July and January for both MH and PI. And for models, we calculated the mean temperature for every month, and selected the warmest and coldest one to compare with the reconstruction. So the change in seasonality during MH doesn't influence our comparison for MTWA and

MTCO.

12. Line 261, “with a decrease in the northeastern regions”, also decrease in east monsoon region at Yangzi river valley.

Response: We have added the words “with a decrease in the northeastern regions and east monsoon region at Yangtze River valley” (on page 12 line 275 in revised version).

13. Line 310-312, “this failure to capture ..”, see above general comment 2.

Response: See the answers to comment 2.

14. Line 320, “triggered” is a weird word.

Response: We have deleted this word in revised version.

15. Fig 7 on feedback discussion, how do you determine the feedbacks from the cloud cover or surface cover? In Line 356 the authors mentioned the “surface albedo and cloud change are calculated . . .”, I don’t understand why the changes in forcing can be regarded as feedback, physically it is a climate response to forcing.

Response: The albedo feedback is not identical to the changes in forcing, and it doesn’t directly response to forcing. In fact, our philosophy to calculate the albedo feedback is: the forcing change during MH (mainly the seasonal solar radiation change) firstly leads to the seasonal climate change, and accordingly, the vegetation type at that period will be different from PI. Then, the changes in vegetation type have a feedback on climate through the albedo variation. This feedback can be calculated by measuring the changes in radiative fluxes at both Earth’s surface and at the top of atmosphere. For instance, if the land surface changes from bare soil to forest, the surface albedo will decrease and the net radiation at land surface increase, in this case, the surface albedo has a positive feedback on the net shortwave flux. The detailed information about how to quantify the feedback are shown in Taylor et al. (2007) and Braconnot and Kageyama (2015).

16. Line 733, “Importance” should be “Important”.

Response: Corrected.

17. Table 6, should give more information for meteorological data, how long, and give which month is the warmest coldest month, in line 742, should be "warmest month".

Response: We have added the data source in the description of Table 6 "data source: China Climate Bureau, China Ground Meteorological Record Monthly Report, 1951-2001" on page 51 lines 1052-1053 in revised paper. For the warmest month and coldest month, it depends on the mean temperature at each site, for instance, the warmest month could be June or July, so we can't give the exact month.

18. Line 744, "stand error" means "standard deviation"?

Response: Corrected.

19. Figure 1, should you mark your three original data in this map separately?

Response: The three original data are marked in the Fig. 1 in revised version of manuscript (on page 52) as green circles.

20. Figure 4, the huge annual precipitation anomaly in reconstruction, how reliable is it? I highly suspect it. The unit for precipitation is mm, does it mean annual 240 mm equal 20 mm/month? I suggest you use mm/month to avoid confusion.

Response: Yes, from our reconstruction, the annual precipitation anomaly (MH-PI) is huge. This increase in mean annual precipitation (MAP) is mainly due to the increased intensity of monsoon in eastern area over China, which brings much higher precipitation during summer, and results in an increased MAP. In Table 6, the regression coefficient (R) between the reconstructed modern MAP by inverse vegetation models (IVM) and observed meteorological values is 0.94, which means the MAP reproduced from the IVM is reliable during present day. But it's also true that there are some bias in MAP reconstruction, in Table S5, we give the median value (MAP) and values indicating the 5% (MAP1)-95% (MAP2) uncertainty bands to show the bias in IVM reconstruction.

21. Figure 6, Line 848 to 850, why do you give the abbreviation, they are not in the figure.

Response: Corrected (on page 57 in revised version).

Reference:

Weninger, B., Jöris, O., Danzeglocke, U., 2007. CalPal-2007. Cologne Radiocarbon Calibration and Palaeoclimate Research Package. http://www.calpal.de/.

Jiang, D., Lang, X., Tian, Z., and Wang, T.: Considerable Model–Data Mismatch in Temperature over China during the Mid-Holocene: Results of PMIP Simulations, Journal of Climate, 25, 4135-4153, 2012.

Gent, P.R., Danabasoglu, G., Donner, L.J., Holland, M.M., Hunke, E.C., Jayne, S.R., Lawrence, D.M., Neale, R.B., Rasch, P.J., Vertenstein, M., Worley, P.H., Yang, Z., and Zhang, M.: The community climate system model version 4, Journal of Climate, 24, 4973-4991, 2011.

Salzmann, U., Haywood, A.M., Lunt, D.J., Valdes, P.J., and Hill, D.J.: A new global biome reconstruction and data-model comparison for the middle Pliocene, Global Ecology and Biogeography, 17, 432-447, 2008.

Prentice, I. C., Guiot, J., Huntley, B., Jolly, D., and Cheddadi, R.: Reconstructing biomes from palaeoecological data: A general method and its application to European pollen data at 0 and 6 ka, Climate Dynamics, 12, 185-194, 1996.

Sykes, M.T., Prentice, I.C., and Laarif, F.: Quantifying the impact of global climate change on potential natural vegetation, Climatic Change, 41, 37–52, 1999.

Ni, J., Sykes, M. T., Prentice, I. C., and Cramer, W.: Modelling the vegetation of China using the process-based equilibrium terrestrial biosphere model BIOME3, Global Ecology and Biogeography, 9, 463-479, 2000.

Taylor, K.E., Crucifix, M., Braconnot, P., Hewitt, C. D., Doutriaux. C., Broccoli, A. J., Mitchell, J. F. B., Webb, M. J.: Estimating shortwave radiative forcing and response in climate models, Journal of Climate, 20, 2530-2543, 2007.

Braconnot, P., and Kageyama, M.: Shortwave forcing and feedbacks in Last Glacial Maximum and Mid-Holocene PMIP3 simulations, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 373, 2054-2060, 2015.

Response to Prof. Bartlein

General comments from the referee:

This paper presents an ambitious attempt at comparing simulations from the CMIP5/PMIP3 "midHolocene" archive with a new synthesis of fossil-pollen data for China. The pollen data are used in two ways: 1) to develop a set of quantitative reconstructions of several climate variables using an inverse-modeling approach (to compare with the climate-model output), and 2) to develop a map of "megabiomes" for present and 6 ka (for direct comparison with vegetation simulated by BIOME4 using climate-model output). The paper shows that there is a considerable mismatch between the reconstructed and simulated climates and vegetation. The authors attribute this mismatch to experimental-design issues, in which vegetation and land-cover data in the climate models were fixed at present-day values, thereby limiting the ability of the climate models to correctly represent the potential impact of vegetation (and surface water- and energy-balance) feedback in the paleo simulations.

I have two reservations about the results and conclusions:

First, there is insufficient information on the protocols adopted for generating the both present-day and paleo vegetation, as well as the paleo reconstructions. As for vegetation, Fig. 5 shows that there are large mismatches between the observed and simulated modern vegetation. These would naturally arise if the climate-model output were used directly to simulate the vegetation. We know that at their current resolutions, there is still considerable bias in present-day (or PI) climate simulations, and there is no reason to believe that those bias are the same in paleo simulations (or that they somehow go away). My impression of Fig. 5 and S7 is that those biases in simulated climate are indeed large, possibly swamping the real vegetation change, and so we're not really getting much insight into the nature of the mid-Holocene climate simulations, but instead learning about modern-day bias. As for reconstructed climate, despite the author's assertion otherwise, there is also considerable bias in the inverse-model reconstruction approach (Table 6). Only for Pjan does the regression between observed and fitted values not differ from one with a slope of 1.0 and an intercept of 0.0. It is not immediately clear how that bias might affect the reconstructed climate, but it reinforces the necessity of looking at the uncertainties in the reconstructions. Again, we may be learning more about the inverse approach than about model-data mismatches.

Second, the attribution of the mismatches to the experimental design of the CMIP5/PMIP3 simulations, while plausible, is not really supported by any direct hypothesis tests, or by the consideration and dismissal of alternative hypotheses. The correlation between the temperature responses and cloud-cover feedback (Figure 8) implicates at least one: inadequate simulation of atmospheric circulation as it may influence moisture flux or precipitation-generating mechanisms.

I think that if the questions related to the protocol for data-model comparisons are answered, and due consideration given to other possible mechanisms for the mismatch, then the paper will ultimately be publishable.

<u>Response to the major comments:</u>

Thanks for the very important comments, in conclusion, two main questions are proposed here:

1. **The insufficient information on protocol for model-data comparison of vegetation**.

Response: The referee is right when he pointed out that using climate for PD or 6 ka, there is a large mismatch between vegetation reconstructed by BIOME4 from model simulation and vegetation reconstructed from pollen data. Our aim here is to test whether the sensitivity of PMIP3 mid-Holocene simulations, mainly driven by insolation changes, may explain the vegetation changes observed from data. The trend depicted by all the models is cooler conditions during winter and warmer in summer which is consistent with a linear response to orbital forcing for 6 ka. On the contrary, the dataset shows for the seasonal response a warming during both seasons.

We agree with Prof. Bartlein that the attribution of those non linear responses to vegetation is not really explained in our original manuscript. This is due to the fact that each model has different ways to account for vegetation, therefore our explanation was plausible but too speculative. To be able to convince the referee with quantitative arguments, we have conducted a supplementary experiment to demonstrate that our mechanism was appropriate.

In this revised version, we succeeded to conduct such test in CESM version 1.0.5. The CESM version 1.0.5, developed at the National Center for Atmospheric Research, is a widely used coupled model with dynamic atmosphere (CAM4), land (CLM4), ocean (POP2), and sea-ice (CICE4) components (Gent et al., 2011). Here, we use ~2° resolution for the CAM4, configured by ~1.9° (latitude) × 2.5° (longitude) in the horizontal direction and 26 layers in the vertical direction. The POP2 adopts a finer grid, with a nominal 1° horizontal resolution and 60 layers in the vertical direction. The land and sea-ice components have the same horizontal grids as the atmosphere and ocean components, respectively.

Two experiments were conducted, including a mid-Holocene (MH) experiment (6 ka) with original vegetation setting (prescribed as PI vegetation for MH) and a MH experiment with reconstructed vegetation (6 ka_VEG). In detail, experiment 6 ka used the MH orbital parameters (Eccentricity=0.018682; Obliquity=24.105°; Angular precession=0.87°) and modern vegetation (Salzmann et al., 2008). Compared to experiment 6 ka, experiment 6 ka_VEG used our reconstructed vegetation in China. Except for the changed vegetation, all other boundary conditions were kept unchanged in these two experiments, including the solar constant (1365 W m−2), modern topography and ice sheet, and pre-industrial greenhouse gases (CO2 = 280 ppmv; CH4 = 760 ppbv; N2O = 270 ppbv). Experiment 6 ka was initiated from the default pre-industrial simulation and run for 500 model years. Experiment 6 ka_VEG was initiated from model year 301 of experiment 6 ka and run for another 200 model years. We analyzed the computed climatological means of the last 50 model years from each experiment here.

The new-added Fig.9 in manuscript (enclosed below) shows the climate anomalies between two simulations (6 ka_VEG minus 6 ka), for both annual and seasonal scale. For temperature, it's clear that the 6 ka_VEG simulation reproduces the warmer annual (~0.3 K on average) and winter temperature (~0.6 K on average), especially the winter temperature. For precipitation, the reconstructed vegetation leads to higher annual and seasonal precipitation, which can also reconcile the discrepancy of increase amplitude for precipitation during MH between model-data (data reproduced larger amplitude than model, revealed by our study). This new result strongly suggests vegetation changes may explain a part of the mismatch, which is consistent with our proposal in this study. Nevertheless, there are certainly other possibilities and indeed models that better captured the hydrologic cycle and enhance the precipitation/ evaporation pattern could also explain differences between model and data.

Each model has different sensitivity to the boundary change, further work will be carried out in more models to test the influence of vegetation on climate, this is an ongoing work.

This response is on pages 17-18, lines 410-430 in the revised paper.

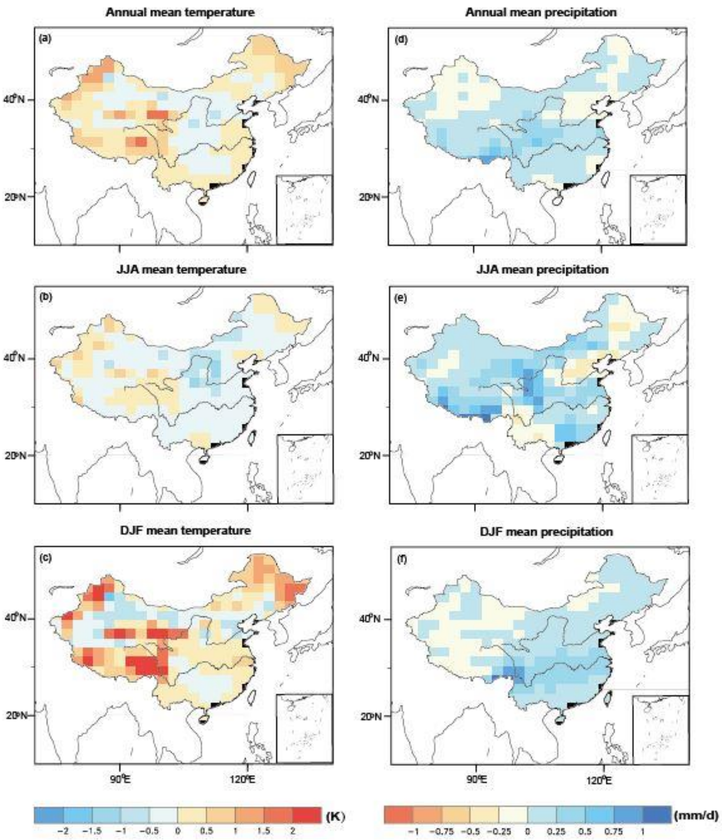

Figure 9. Climate anomalies between the two experiments (6 ka and 6 ka_VEG) conducted in CESM version 1.0.5. The anomalies (6 ka_VEG-6 ka) of temperature and precipitation at both annual and seasonal scale are presented, and all these climate variables are calculated as the last 50-year means from two simulations.

2. **More information about the considerable bias in the inverse-model reconstruction approach.**

Response: In the climate reconstruction based on pollen data, the inverse-modeling approach considers the impact of CO_2, and provides sound logic to cope with the no-analogue problem. Moreover, the consequence of changing seasonality of climate forcing or climate response are also taken into account in the inverse-model reconstruction. The quantitative reconstructions derived from pollen data of Eurasia, Africa and Europe (Wu et al., 2007) at the LGM and the mid-Holocene, confirm the ability of the inverse vegetation model (IVM) method to provide spatially coherent patterns of palaeoclimate that are generally in agreement with previous reconstructions from climate proxies.

However, the IVM approach is not a panacea. First, it is highly dependent on the quality of the vegetation model BIOME4, because of the particularity of vegetation types in the monsoon region of China, the BIOME4 needs further improvement of vegetation simulation accuracy in this area. This possible bias in simulating vegetation will lead to uncertainty in reconstruction. Second, the output of the model is not directly compared to the pollen data, the conversion of BIOME4 biomes to pollen biomes by the transfer matrix may add the source of uncertainty in reconstruction. These possible bias in climate reconstruction derived from IVM are described in the new version of manuscript (on page 15 lines 343-353 in revised version).

For the potential uncertainties on data reconstruction, besides the Table 6, we added more information in Table S5 in supplementary information, we gave the climate variables reconstructed from IVM at each site. We also showed the bias on data reconstruction by giving the median value (for instance, column named MTCO) and values indicating the 5% (MTCO1)-95% (MTCO2) uncertainty bands. Moreover, to validate our reconstruction, we compared the results with numerical previous studies concerning MH climate change over China based on multiple proxies (including pollen, lake core, palaeosol, ice core, peat and stalagmite), the relative references and detailed information are listed in Supplementary Information (Table S9 and Table S10). As shown in Figure 7 on page 59 in the revised paper (enclosed below). Compared to PI, most reconstructions reproduced a warmer and wetter annual condition during MH, same as our study. In other words, this discrepancy between model-data for climate change over China during MH is common and robust in reconstructions derived from different proxies. Our study just reinforces the picture given by the discrepancies between PMIP simulation and pollen data derived from a synthesis of the literature. And thus, our reconstruction is reliable even with the potential uncertainties mentioned above.

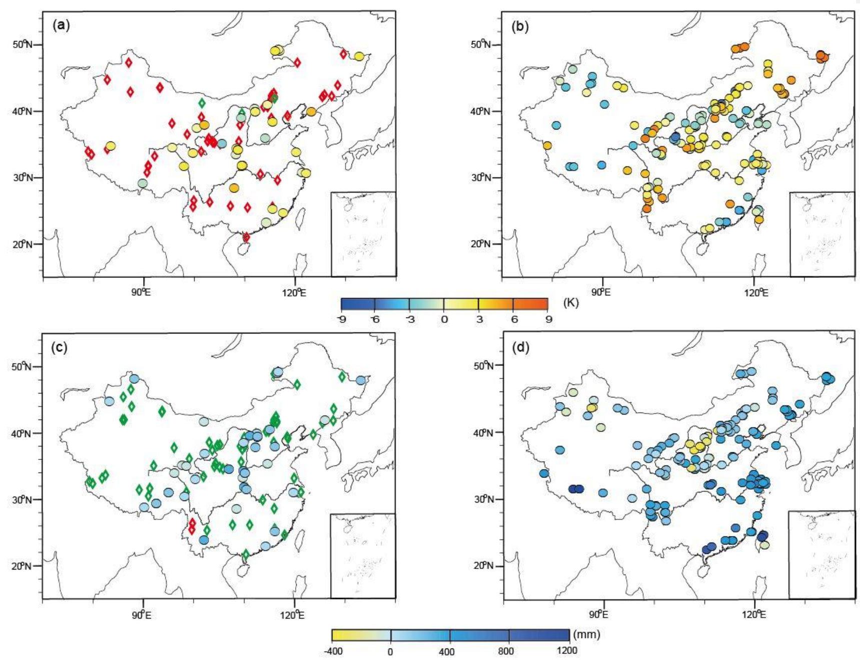

Figure 7. Comparison between our climate reconstruction and previous reconstruction. (a) Previous temperature results. Diamond is the qualitative reconstruction, red is the temperature increase and green is the temperature decrease; Circle is quantitative reconstruction; (b) Mean annual temperature reconstruction in this study; (c) Previous precipitation results, diamond is the qualitative reconstruction, red is the precipitation increase and green is the precipitation decrease; Circle is quantitative reconstruction; (d) Mean annual precipitation reconstruction in this study.

Specific comments from the referee:

Abstract: The abstract fails to disclose conclusions of paper.

Response: We modified the abstract as following (on pages 1-2 Line 12-31 in the revised paper):

The mid-Holocene period (MH) has long been an ideal target for the validation of Global Circulation Model (GCM) results against reconstructions gathered in global datasets. These studies aimed to test the GCM sensitivity mainly to the seasonal changes induced by the orbital parameters (precession). Despite widespread agreement between model results and data on the MH climate, some important differences still exist. There is no consensus on the continental size of the MH thermal climate response, which makes regional quantitative reconstruction critical to obtain a comprehensive understanding of the MH climate patterns. Here, we compare the annual and seasonal outputs from the most recent Paleoclimate Modelling Intercomparison Projects Phase 3 (PMIP3) models with an updated synthesis of climate reconstruction over China, including, for the first time, a seasonal cycle of temperature and precipitation. Our results indicate that the main discrepancies between model-data for MH climates are the annual and winter mean temperature. A warmer-than-present climate condition are derived from pollen data for both annual mean temperature (~0.7 K on average) and winter mean temperature (~1 K on average), while most of the models provide a linear response driven by the seasonal forcing (a decreased annual mean temperature with a warmer summer and colder winter). By conducting simulations in BIOME4 and CESM version 1.0.5, we show that to capture the seasonal pattern reconstructed by data, it is critical to assess surface processes. These results pinpoint the crucial importance of including the non-linear of the surface water and energy balance to vegetation changes.

Line 14: “proxy reconstructions” Aren’t the reconstructions used here “real” reconstructions? I understand the notion of paleoclimatic evidence that can be used as a “proxy” for climate or other phenomena (like land cover). But the reconstructions here are actual reconstructions, not a stand-in or substitute for reconstructions.

Response: We have deleted the word “proxy” in Line 14 in revised version.

Line 18: “continental size” Are you referring to the area of the temperature anomaly or to terrestrial as opposed to marine responses?

Response: We are referring to the area of the temperature anomaly.

Line 20: New definition for PMIP?

Response: Corrected as “Paleoclimate Modelling Intercomparison Projects Phase 3” (on page 1 line 21 in revised version).

Line 22: “a seasonal cycle. . .”

Response: Corrected as “a seasonal cycle of temperature and precipitation” (on page 1 line 22 in revised version).

Line 25: “access surface processes” I don’t know what this means.

Response: Sorry for the wrong spelling, it should be “assess”.

Line 27: “non-linear process associated with vegetation changes in hydrology and radiative forcing” Does this mean “non-linear responses in hydrology and radiative forcing to vegetation changes”? “Radiative forcing” in the context of the midHolocene experiment is usually reserved for describing the insolation forcing, so an alternative expression might be “non-linear response of the surface water and energy balance to vegetation changes” (which is what I think the paper is arguing for).

Response: Thanks for the suggested expression, we have corrected it (on page 2 lines 30-31 in revised version).

Line 34: This definition of the age of the mid-Holocene is inconsistent with what is actually used in the paper (line 101). It might be good to distinguish between the midHolocene time slice, and the “midHolocene” CMIP5/PMIP3 experiment, throughout the paper.

Response: According to IntCal13 (Reimer et al., 2013), the mid-Holocene time slice 6000±500 ^{14}C yr BP is about 6800 Cal BP (the average value), which is not totally consistent with the “mid-Holocene” used in CMIP5/PMIP3 experiment (6000 Cal BP). We agree with the reviewer that this is a problem in model-data comparison for paleoclimate, but for a better comparison with BIOME6000 (which defined as 6000±500 ^{14}C yr BP), we decided to choose the pollen data at 6000±500 ^{14}C yr BP in our study.

Thanks to the comment, we will take care of this inconsistency and make better comparison of time slice in the future work.

Line 36: “an increase in insolation in the seasonal cycle” Replace with “an increase in the amplitude of the seasonal cycle of insolation. . .”

Response: Corrected. On page 2 line 40 in revised version.

Line 38: “climate response to changes in the seasonal distribution” It’s not the response to the seasonal variations of insolation that you’re looking at here, but instead the response to changes in the distribution.

Response: Corrected. On page 2 line 43 in revised version.

Line 42: “consistency of the dataset incorporating different proxies” I don’t know what that means.

Response: We have changed it into “much work has been done to reconstruct the paleoclimate change based on different proxies” (on page 2 line 46 in revised version).

Line 45: Again, the data are real, not proxy.

Response: Corrected (on page 3 line 49 in revised version).

Line 47: “the source of discrepancies. . .”

Response: Corrected it as “the source of discrepancies between model and data …” (on page 3 line 52 in revised version).

Lines 50-51: But see Marsicek et al. (2018, Nature) the “Holocene conundrum” apparently arose from comparing apples and oranges. A different example might be more convincing.

Response: Yes, the reconstruction used in Marcott et al. (2013) is mainly from the marine records (~80%) and the cooling trend is largely associated with North Atlantic. And in Marsicek et al. (2018), they show a better consistency of temperature between model-data for Europe and North America continents during Holocene based on 642 sub-fossil pollen data. The different trends of pollen- and marine-based reconstruction indicate the spatial variability of annual temperature change during MH over the globe, which has already been investigated by Bartlein et al. (2010). Here, we use Liu et al. (2014) to pinpoint the decreased annual temperature in MH simulated by model, compared to PI.

Line 62: The sheer expanse of the country. . . Why should the synthesis of paleoclimatic data or simulations necessarily be restricted to political subdivisions? Extending the area of the comparison deeper into the interior of Eurasia would generate a bit more “leverage” in comparing the data and models, but I understand the logic of restricting the analysis to China.

Response: For this study, we only focus on China, but we agree that extending the area into Eurasia or globe is more comprehensive, which is carrying out by other colleges in our group now.

Line 64 (and elsewhere). The article “the” is required before “MH” in this context (i.e. when “MH” is being used as a noun). Elsewhere, as in line 55, where “MH” is used as a modifier of another word (“precipitation” in this context), the article is not used.

Response: Corrected.

Line 66: “warmer and wetter than present. . .”

Response: Corrected it as “warmer and wetter than present conditions” (on page 3 line 71 in revised version).

Line 73: “colder than the baseline” What baseline? Present-day or preindustrial?

Response: The baseline period of 36 models are different. 10 of 36 models refer to present-day, while others refer to preindustrial.

Line 75: “This study” Which study? Reword as “That study. . .” or more explicitly “Jiang et al. (2013) were the first to point out the model-data discrepancy over China during the MH, but the lack of seasonal reconstructions in their study limits comparisons with simulations.”?

Response: Corrected as “Jiang et al. (2012) were the first to point out the model-data discrepancy over China during the MH, but the lack of seasonal reconstructions in their study limits comparisons with simulations.”(on page 4 lines 80-82 in revised version).

Line 83: Bartlein et al. didn’t synthesize land-cover changes.

Response: Corrected.

Lines 86-91: The terminology here needs to be sorted out. The “process-based biogeographic model” alluded to here is BIOME4, and it is employed in making inferences about past climates using an “inverse modeling through iterative forward modeling” (IMIFM) approach (Guiot et al. 2000; Wu et al., 2007, 2009). (See Izumi and Bartlein, 2016, GRL for further discussion.) So BIOME4 is the vegetation model, while the overall approach (which employs that model) is “IMIFM” (or after that is all explained, simply “the inverse approach”).

Response: Thanks for the professional and detailed explanation. We have modified this description into “we firstly used the quantitative method of biomization to reconstruct vegetation types during the MH based on a new synthesis of pollen datasets, and then used the Inverse Vegetation Model (Guiot et al., 2000; Wu et al., 2007) to obtain the annual, the mean temperature of the warmest month (MTWA) and the mean temperature of the coldest month (MTCO) climate features over China for the MH.” (on page 4 lines 92-94 in revised version).

Line 91: “In the case of models. . .” Which models? Is it the case that you’re evaluating the PMIP3 simulations made with state-of-the-art climate models using reconstructions of temperature and precipitation?

Response: Yes, we mean the PMIP3 models. And we changed this sentence into “In the case of PMIP3 models, we present a comprehensive evaluation of the PMIP3 simulations made with state-of-art climate models using reconstructions of temperature and precipitation.” (on page 4, lines 94-96 in revised paper).

Line 94: “thanks to the seasonal reconstruction” But in all previous applications of the inverse modeling approach using BIOME4 or related models, some sort of reconstruction or estimation of the seasonal variations in climate must have been involved, because BIOME4 requires monthly temperature, precipitation and cloudiness (or sunshine) data as input.

Response: Yes, the monthly climate variables are required in BIOME4 or related models, here we only emphasis that our study is to reconstruct the seasonal cycle of MH climate change over China with a synthesis of pollen datasets. We have deleted the words “thanks to the seasonal reconstruction”.

Lines 95-96: “the forcing factor we used for MH is essential the seasonal change.” I think that what’s going on here is that the midHolocene CMIP5/PMIP3 experiment is essentially one that looks at the response of the models to changes in the seasonality of insolation, and that you are attempting to derive reconstructions of both summer and winter temperature and precipitation to compare with the simulations.

Response: Corrected, according to your suggestion (on page 5 lines 98-102 in revised version).

Line 101: If you’re referring to radiocarbon ages, this should be written as 6000 ± 500 14C yr BP)

Response: Corrected (on page 5 line 106 in revised version).

Line 102: Spell out “three”.

Response: Corrected (on page 5 line 107 in revised version).

Line 105: I don’t understand the notion of “distinct” pollen records. Distinct in the sense of “unique” or distinct in the sense of “clearly readable”?

Response: We have corrected it into “clearly readable” (on page 5 line 110 in revised version).

Line 107: Criterion 2 seems to be combining two things: sampling resolution and data present within the age range. Please reword.

Response: Corrected as "including the pollen taxa during 6000±500 14C yr BP period with a minimum sampling resolution of 1000 years per sample" (on page 5 lines 111-113 in revised version).

Line 108: How far?

Response: We abandon the pollen records in our dataset if the published paper mentions the influence of human activity on the pollen. (replaced the "far away" by "abandon the pollen records if the published paper mentions the influence of human activity" on page 5 lines 113-114 in revised version.

Line 109: "or by regression"

Response: Corrected (on page 5 line 121 in revised version).

Line 113: Fix the Webb (1985) citation. (Webb, T. III, etc.)

Response: Corrected (on page 6 line 124 in revised version).

Lines 110-113: Reorganize sentence to describe the ranking scheme first, and the results second.

Response: Corrected (on pages 5-6 lines 114-124 in revised version).

Line 114: Add a citation for the concept of "biomization" (which will be a mystery to modelers).

Response: Corrected, we have added Prentice et al., 1996 (on page 6 line 125 in revised version).

Line 116: CQPD. Not in references. Also "sedimentary" what?

Response: The CQPD reference was added, and it should be "sediment" (on page 6 line 128 in revised version).

Lines 117-119: Add region names to Fig. 1?

Response: Corrected, we added the “Tibetan Plateau” and “Loess Plateau”.

Lines 120-135: There seem to be two tasks described in the paragraph: 1) interpolation of modern climate data (from some unspecified source, and by some by some unspecified approach) to the locations of the pollen data, and 2) interpolation of biome scores onto a regular grid using ANN. I suggest breaking this paragraph up, while providing more information on the first task.

Response: The modern climate data are based on the datasets (1951-2001) from 657 meteorological observation stations over China, we also added the data source in the manuscript.

Line 129: If the ANN is calibrated using present-day biomes, then I don’t see how it can be used to interpolate anomalies. Or was it the case that present-day and paleo biomes were independently interpolated onto the grid, after which anomalies were calculated.

Response: The high spatial coverage of present-day pollen records and the application of ANN in interpolating the biome scores makes it possible to reconstruct the past spatial variability with a few pollen sites. In our study, at each pollen site, we firstly used the biomization to get the biome scores for both present-day (PD) and mid-Holocene (MH). Then we calculated the biome score anomalies between two periods (MH-PD). Based on the artificial neural network (ANN), we got the interpolated spatial pattern of biome scores for both PD and anomalies (MH-PD). The spatial pattern of MH biome scores was obtained by overlay the PD pattern with anomalies pattern (MH-PD). Finally, the biome with the highest index is attributed to each grid point, and thus, the spatial pattern of MH vegetation was obtained. The detailed scheme is provided in the enclosed Fig. R2 as below.

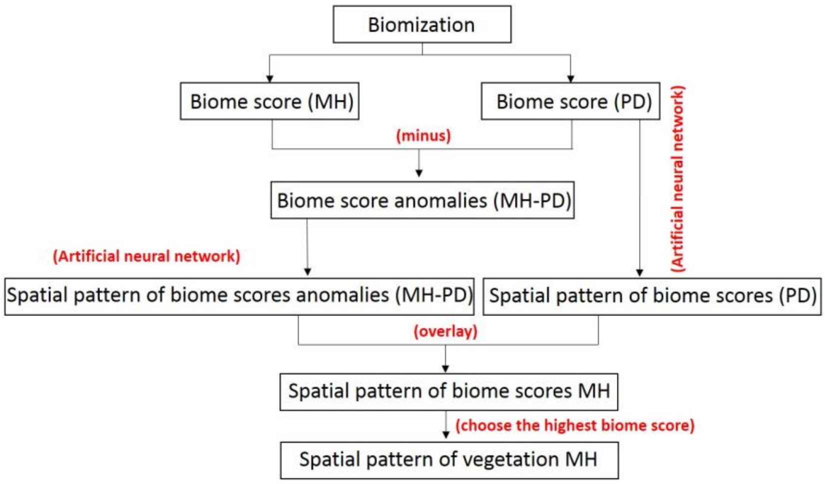

Figure R2. The schematic diagram of artificial neural network.

Lines 142-143: What are “climate anomalies in the present day”?

Response: Corrected it into “climate anomalies in the past periods” (on page 7 line 157 in revised version).

Line 145: Delete “in which the PI experiment was defined.”

Response: Corrected.

Line 146: Here it would be good to refer explicitly to the “midHolocene” experiment.

Response: Corrected.

Line 153: Spell out eight and five.

Response: Corrected (on page 7 line 167 in revised version).

Line 156: “in order to calculate” These variables could also be calculated on the models’ native grids. The motivation for interpolation onto a common grid is simply to get the data onto a common grid.

Response: Corrected as “in order to get the bioclimatic variables (e.g. MAT, MAP, MTWM, MTCO, July precipitation) onto a common grid for comparison with the reconstruction results" (on pager 7 lines 171-172 in revised version).

Line 160: Either delete the hyphens here, or put them into other instances of "biogeography" or biogeochemistry".

Response: Corrected (on page 8 line 174 in revised version).

Line 162: "sunshine percentage (relative to cloud cover)" I don't know what this means.

Response: The sunshine percentage is related to cloud cover (not "relative"). We have corrected it as "an inverse measure of cloud area fraction (on page 8 line 176 in revised version).

Line 171: Bigelow: not in references.

Response: Corrected (on pages 21 lines 490-496 in revised version).

Line 173: Were the climate variables downscaled in any way (as in the apply-the anomalies approach, Harrison et al., 1998, J. Climate, Harrison et al., 2014, Climate Dynamics). If not, then the climate fields will not contain the spatial variability of modern climate that in topographically complex areas can have a major impact on vegetation. Fig. S7 attests to the existence of bias in the PI simulations. If the simulated climate values are used directly, then a quantitative estimate of the bias (as in Table 6 for the present-day reconstructions) should be provided.

Response: We directly used the climate fields from models without downscaling. We agree with the reviewer that there is bias between simulation and observation, especially the topographically complex areas. According to the Taylor diagrams (Figure 1 and Figure 7, the models used in our study are represented as NO. 33, 37, 45, 47, 49, 50, 58, 62, 63, 65, 70, 74 and 75 in blue color) from Jiang et al. (2016, Int. J. Climatol, https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/joc.4406), the GCMs from PMIP3 is reliable to simulate the geographical distribution of surface air temperature and precipitation over China for present day even without downscaling. But there are considerable bias between GCMs and observation for precipitation. Concerning this issue, we added the following sentences on page 17 lines 406-411 in the revised paper:

“However, the vegetation patterns produced by BIOME4 in Fig. 5 are not used in PMIP3 experiment setup, it’s actually determined by the input variables from models. Previous study shows the GCMs from PMIP3 is reliable to simulate the geographical distribution of temperature and precipitation over China for present day without downscaling, but there is considerable bias between simulation and observation for precipitation (Jiang et al., 2016). Therefore, the disagreements of MH vegetation pattern possibly are inherited from the PI.”

And thanks for the very important reminder, in the future work, we will try to downscale the climate variables before applying them into regional study.

Line 174: “more than 30 years” How much more? Why not use the same number of years for each model?

Response: Corrected (on page 8 line 188 in revised version).

Line 176: Replace “model-data discrepancies” with “differences between simulated (by the climate-model output) and reconstructed (from pollen). . .”

Response: Corrected (on page 8 lines 190-191 in revised version).

Line 183: Replace “estimate” with “describe”.

Response: Corrected（on page 9 line 198 in revised version）.

Line 192-194: I’m not sure why you’re describing the interpolation of biome data again.

Response: We have deleted this sentence.

Line 197: “Inverse Vegetation Model” See earlier comments.

Response: Corrected (on page 9 line 210 in revised version).

Line 208: I’m not sure why CO_2 concentrations and soil characteristics are being perturbed (i.e. estimated by the inverse approach). We know CO2, and earlier you argued that soils were assumed not to differ. Also, Table 3 implies that anomalies (or better put, long-term mean differences between present and past) were iteratively generated, which implies that, as is standard procedure, they were applied to present-day climate values and passed to the biome model. If so, what were those present-day values?

Response: Sorry for the inaccurate expression here, the CO_2 concentration and soil are being perturbed by model. For the soil properties, because of a lack of paleosol data, soil characteristics were assumed to have been the same during the MH. While the atmospheric CO_2 concentration for the MH was taken from ice core records (EPICA community members 2004), and set at 270 ppmv; the modern CO_2 concentration was set at 340 ppmv, because most of the modern pollen samples were collected during 1970s and 1980s. We have added these descriptions on page 6 lines 136-139 in revised paper:

"The MH soil properties and characteristics used in inverse vegetation model were kept the same with PI conditions, which are derived from the digital world soil map produced by the Food and Agricultural organization (FAO) (FAO, 1995). Atmospheric CO2 concentration for the MH was taken from ice core records (EPICA community members 2004), and was set at 270 ppmv."

Lines 216-218: I don't know if I'm reading Table 6 correctly, but if I am, the slopes and intercepts are anything but close to 1.0 and 0.0. Only for the case of Pjan is the slope within two standard errors of 1.0, and only for MAP and Pjan is the intercept within two standard errors of 0.0. It would be useful to see scatter diagrams of the observed and estimated values for each variable.

Response: According to your suggestion, we added the reconstruction result of Pjan in Fig. 4 (on page 56 in revised paper), and we also replace the bars with boxplots in Figure 3 and Figure 4 to show the variability of each model and reconstruction. We agree with the referee that there are some bias in IVM, but based on the comparison with numerical previous studies in China (Figure 7 on page 59 in the revised paper), this discrepancy between model-data for climate change over China during MH is common and robust in reconstructions derived from different proxies. Our study reinforces the picture given by the discrepancies between PMIP simulation and pollen data derived from a synthesis of the literature.

Line 224: The "collected data" is your data set, right? How was the comparison statistic calculated?

Response: Yes, the collected data is the dataset used in this study. The comparison statistic calculated by the match number of pollen sites. We categorized our pollen records into megabiomes, and 145 of 159 (more than 90%) pollen data match well with the BIOME 6000 during MH, while the match number is 149 for PI. We have added the words "145 out of 159 sites" on page 10 line 238 in revised paper.

Lines 226-239: How are the changes or differences in the reconstructions calculated? As differences between the mid-Holocene reconstructions and present-day observations, or present-day inverse-approach estimates? There is considerable bias in the estimates for the present day (Table 6). How would that contribute to the mismatch between simulations and observations? Section 3.1 (throughout): No information on the uncertainties of the reconstructions is given. These are customarily obtained from the variability of the "feasible" climate vectors generated in the optimization step in the inverse approach (e.g. Izumi and Bartlein, 2016, Fig. 3). For that matter, there is no information on the spatial variability of the simulations. Uncertainties for both could be displayed by plotting boxplots in Fig. 3, as opposed to bar graphs.

Response: The changes or differences in the paleoclimate reconstructions are calculated as the differences of biome scores between mid-Holocene and present-day times by inverse approach. And the considerable bias listed in Table 6 between observation and estimation for present-day will add the uncertainty in IVM climate reconstruction. We agree with the reviewer and added the boxplots in Figure 3 and Figure 4 on page 55 and page 56 in revised paper. Considering the main purpose here is to show the climate discrepancy between each model and data, we choose to give the boxplots of 13 models instead of showing MME result with different region. We also give the columns for every variable (derived from IVM at each site) indicating 5-95% uncertainty bands. More detailed information about the uncertainties from reconstruction can be found in Table S5 (on pages 8-13 in SI).

Line 249: “a decreasing trend” Conventionally, trends are described in the sense of a change from one time to another, or the change over a fixed period of time, so here, if the mid-Holocene MTWA values are lower than present, the trend would be positive or increasing over time (i.e. from the mid-Holocene to present). Check the discussion of precipitation trends too. It would be best to simply drop the notion of “trends” and concentrate on the change between midHolocene and PI.

Response: Corrected.

Line 265: “more detailed information about the geographic distribution of simulated temperature. . .” Section 3.1 (overall): It would be interesting to see a comparison for Pjan, the single variable with an intercept of 0.0 and a slope of 1.0.

Response: Corrected (on page 12 line 280-281). For Pjan, we have added the plot of Pjan in Figure 4. And we also added the description of model-data comparison for Pjan as:

“For January precipitation, the reconstruction shows an overall increase in most region (~15 mm), except for the northwestern region, while MME indicates a slight decrease (~3 mm on average).” on page 12 lines 278-280 in revised paper.

Line 273: “which would introduce a bias. . .” That’s certainly plausible, but right now it’s simply a conjecture.

Response: Yes, it’s true that we haven’t quantified the impact of different MH vegetation setting on the role of vegetation-atmosphere interaction in the MH climates among all PMIP3 models. But by giving Fig.5, Fig. 8 and Fig.9, we think that the failure to capture MH vegetation change has influence on model-data discrepancy for climate change.

Line 309: “However, none of the models succeed in capturing these features,. . .” I agree. However, the differences between the simulated and reconstructed biomes for the midHolocene simulations strike me as apparently similar in magnitude to those for the PI, and casual comparison of Figs. 5 and S7 suggests to me that some of the patterns of disagreement in the midHolocene case are inherited from the PI. This makes me wonder again about the protocol followed for generating the midHolocene simulations (see comment on line 173).

Response: According to the Taylor diagrams (Figure 1 and Figure 7, the models used in our study are represented as NO. 33, 37, 45, 47, 49, 50, 58, 62, 63, 65, 70, 74 and 75 in blue color) from Jiang et al. (2016, Int. J. Climatol, https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/joc.4406), the GCMs from PMIP3 is reliable to simulate the geographical distribution of surface air temperature and precipitation over China for present day even without downscaling. But there are considerable bias between GCMs and observation for precipitation. This possible bias in simulating vegetation will lead to the mismatch of MH vegetation pattern between model and observation. We agree with the reviewer that the downscaling is very important in applying global model into regional study, which will be taken into account in our future studies. In this study, to be able to convince the referee with quantitative arguments, we decided to conduct a supplementary experiment to demonstrate that our mechanism was appropriate. This new modeling strongly suggests vegetation changes may explain a large part of the mismatch (as shown in Fig. 9), which is very consistent with our proposal in this study. Nevertheless, there are certainly other possibilities and indeed models that better captured the hydrologic cycle and enhance the precipitation/ evaporation pattern could also explain differences between model and data.

Line 310: What are “enhanced vegetation conditions”?

Response: The “enhanced vegetation conditions” refers to the transition from grassland to forest in the northeast during MH. We have modified it as “transition from grassland into forest”.

Line 311: “. . .a cumulating inconsistency in the model-data comparisons . . . because of the vegetation-climate feedbacks.” Except for the two AOV models, vegetation-climate feedback is only present in the real, as opposed to simulated, climate, i.e. in the reconstructions.

Response: Yes, all models except for the two AOV models present the real vegetation-climate feedback in PI, but they failed to present the real feedback in MH. The vegetation during MH is prescribed as PI in these 11 models, which means no change of such vegetation-climate feedback for PI and MH among them. This will lead to a cumulating inconsistency.

Line 315-316: “wetter and warmer in MTWA, colder in MTCO” This makes no sense. You might say “higher temperatures in the warmest month of the year,” but did you indeed look at precipitation in the warmest month? I think what you want to say is “higher (than present) July precipitation and MTWA, lower than present MTCO” or something like that.

Response: Corrected (on page 18 lines 432-433 in revised version).

Line 318: Trend again. Data show higher-than-present MTCO during the mid-Holocene while models simulate lower-than-present MTCO.

Response: Corrected.

Line 319: My reading of Fig. 3 shows that CNRM-CM5 and HadGEM2-ES are consistent with all of the other models in simulating lower-than-present MTCO.

Response: We have corrected the expression of this sentence. On page 18 line 436 in revised paper.

Line 322: “among models”

Response: We have deleted the sentence in the revised paper.

Line 323-324: Replace “shed light” with “raises” (the question). (“Shedding light” implies that the variability referred to would answer the question.)

Response: We have deleted the sentence in the revised paper.

Line 326: Replace “amplitude” with “amplitude and pattern”. (You emphasize pattern as much as area.) Also, it’s not the failure of the models to simulate vegetation change that’s important, it’s the fact that (apart from HadGEM2-ES and HadGEM2-CC) they can’t, because the vegetation is not interactive. However, can’t albedo still vary, through variations in soil color and snow cover?

Response: The “amplitude” has been replaced by “amplitude and pattern”. To the second comment, yes, the albedo could vary through the variation in soil and snow cover, so we checked the monthly surface albedo change (MH-PI) of all models with prescribed vegetation. The Table enclosed below indicates that the surface albedo change caused by snow cover between two periods is very small (no more than 0.005), which could be neglected in this study. About the soil color, to our knowledge, it is prescribed as PI during MH in PMIP3, so this impact on albedo change is also negligible for our study.

Table. The monthly albedo change caused by soil color and snow cover among models.

	Model	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
PI	bcc-csm1-1	0.149	0.156	0.156	0.154	0.142	0.127	0.136	0.143	0.147	0.153	0.152	0.145
MH	bcc-csm1-1	0.149	0.156	0.157	0.155	0.142	0.126	0.134	0.140	0.142	0.148	0.147	0.143
MH-PI	anomaly	-0.001	0.000	0.001	0.001	0.000	-0.001	-0.001	-0.003	-0.004	-0.004	-0.006	-0.002
PI	CCSM4	0.170	0.172	0.173	0.174	0.164	0.145	0.143	0.153	0.159	0.168	0.168	0.164
MH	CCSM4	0.170	0.174	0.175	0.176	0.166	0.146	0.142	0.150	0.156	0.167	0.166	0.160
MH-PI	anomaly	0.001	0.001	0.003	0.002	0.002	0.001	-0.001	-0.003	-0.002	-0.001	-0.003	-0.003
PI	CNRM-CM5	0.151	0.164	0.164	0.161	0.146	0.128	0.130	0.140	0.143	0.152	0.152	0.141
MH	CNRM-CM5	0.149	0.161	0.161	0.159	0.144	0.124	0.130	0.137	0.138	0.145	0.147	0.140
MH-PI	anomaly	-0.002	-0.003	-0.003	-0.002	-0.002	-0.003	-0.001	-0.003	-0.005	-0.007	-0.004	-0.001
PI	CSIRO-Mk3-6-0	0.169	0.181	0.178	0.171	0.156	0.140	0.147	0.161	0.167	0.171	0.169	0.162
MH	CSIRO-Mk3-6-0	0.170	0.180	0.179	0.172	0.157	0.139	0.145	0.161	0.164	0.168	0.164	0.162
MH-PI	anomaly	0.001	0.000	0.001	0.001	0.000	-0.001	-0.001	0.000	-0.003	-0.004	-0.005	-0.001
PI	FGOALS-g2	0.170	0.172	0.170	0.168	0.154	0.137	0.141	0.155	0.156	0.164	0.168	0.161
MH	FGOALS-g2	0.172	0.175	0.173	0.173	0.159	0.141	0.142	0.156	0.158	0.167	0.168	0.163
MH-PI	anomaly	0.002	0.003	0.004	0.005	0.005	0.004	0.001	0.002	0.002	0.003	0.000	0.002
PI	FGOALS-s2	0.165	0.173	0.171	0.170	0.161	0.148	0.153	0.164	0.165	0.168	0.166	0.161
MH	FGOALS-s2	0.164	0.174	0.173	0.172	0.162	0.142	0.150	0.159	0.160	0.165	0.160	0.156
MH-PI	anomaly	0.000	0.001	0.002	0.002	0.001	-0.006	-0.003	-0.005	-0.005	-0.004	-0.005	-0.005
PI	GISS-E2-R	0.144	0.153	0.154	0.150	0.131	0.114	0.119	0.126	0.132	0.138	0.138	0.134
MH	GISS-E2-R	0.144	0.153	0.153	0.149	0.131	0.114	0.111	0.122	0.124	0.129	0.132	0.130
MH-PI	anomaly	0.000	-0.001	-0.001	0.000	0.000	0.000	-0.007	-0.004	-0.008	-0.009	-0.006	-0.003
PI	IPSL-CM5A-LR	0.149	0.158	0.161	0.159	0.148	0.133	0.140	0.149	0.152	0.155	0.148	0.142
MH	IPSL-CM5A-LR	0.149	0.158	0.162	0.160	0.149	0.133	0.140	0.147	0.150	0.152	0.144	0.139
MH-PI	anomaly	0.000	0.000	0.001	0.001	0.001	0.000	0.000	-0.001	-0.002	-0.003	-0.004	-0.002
PI	MIROC-ESM	0.162	0.171	0.173	0.167	0.146	0.123	0.129	0.136	0.143	0.153	0.155	0.151
MH	MIROC-ESM	0.164	0.174	0.176	0.172	0.150	0.124	0.131	0.137	0.144	0.154	0.153	0.152
MH-PI	anomaly	0.002	0.002	0.003	0.005	0.004	0.001	0.002	0.000	0.000	0.001	-0.002	0.001
PI	MPI-ESM-P	0.170	0.164	0.160	0.155	0.153	0.155	0.151	0.145	0.145	0.151	0.161	0.173
MH	MPI-ESM-P	0.169	0.163	0.160	0.157	0.154	0.154	0.148	0.141	0.141	0.147	0.160	0.171
MH-PI	anomaly	-0.001	-0.001	0.000	0.001	0.001	-0.001	-0.003	-0.004	-0.004	-0.004	-0.001	-0.002
PI	MRI-CGCM3	0.183	0.194	0.194	0.190	0.173	0.156	0.158	0.172	0.176	0.187	0.189	0.180
MH	MRI-CGCM3	0.183	0.195	0.196	0.191	0.174	0.154	0.156	0.168	0.172	0.183	0.183	0.175
MH-PI	anomaly	0.000	0.001	0.001	0.002	0.001	-0.001	-0.002	-0.003	-0.005	-0.004	-0.005	-0.005

Line 337: “Reconstruction showed. . .” I thought you were talking about the two AOV models. This sentence implies that you estimated the overall albedo change from the vegetation reconstruction, and compared with the two models with interactive vegetation. Is that right? If not, please explain a bit more.

Response: Yes, it’s right. We modified the sentence into “The overall albedo change from the vegetation reconstruction during the MH shows a ~1.8% decrease when snow-free, with a much larger impact (~4.2% decrease) when snow-covered” on page 16 lines 373-374 in revised paper.

Line 348-349: “should act” or “most likely would act” (We don’t really know if it would.)

Response: Corrected.

Line 351-353: It may well be the case that cloud radiative feedback (or rather, inadequate simulation of that) could play a role in the data-model mismatch, but if so, that points to a completely different kind of model inadequacy, involving atmospheric circulation, moisture flux, and cloud-producing or cloud-suppressing mechanisms. Those mechanisms have been implicated in explaining the mismatch between simulations and reconstructions in the Eurasian midcontinent (Bartlein et al., 2017, GRL).

Response: It’s a very important comment. We agree with your proposal that cloud radiative feedback may play a role in model-data mismatch, which indicates another kind of inadequacy. For this study, we simply focuses on the surface land change, we are not able to quantify the possible influence of mechanisms related to cloud on this model-data discrepancy for now, but we can do more in the future.

Line 354: Taylor (and fix reference too).

Response: Corrected.

Technical comments: I concur with the Editor and other referees that some work needs to be Corrected on the references and data-availability aspects of the paper. References: Format varies from reference to reference. Tables 4, 5 & 6: Replace commas with periods (decimal points). Fig. 7: Define dotted horizontal and vertical lines. Maps (throughout): Why does the "nine-dash line" inset vary in size and shape? I realize that the inset has to be there for geopolitical reasons, but why does it change from map to map? Fig. S7: What is the white horizontal line? SI, p. 1: Dallmeyer et al. (2017), not in references. SI, p. 3: Material at the bottom of the table is hard to read. Please reformat into a table-like arrangement. SI, p. 5: Add citations to original data sources.

Response: The references format is uniform in the revised paper. We added the sentence on page 60 line 1195 to define the dotted horizontal and vertical lines in Fig. 8. For the nine-dash line inset, it's only a schematic diagram, the size and shape could be different from figures as long as we show the nine-dash line in the right location. The Dallmeyer et al. (2017) is included in the references, and we reformatted the material at the bottom of the table in the revised paper. For the citations in the SI, p. 5, we give the information in Table. 1 in the manuscript, and the main aim of able S4 is to show the reconstruction results from IVM at each site.

The marked-up manuscript version

Mid-Holocene climate change over China: model-data discrepancy

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Abstract:

The mid-Holocene period (MH) has long been an ideal target for the validation of Global Circulation Model (GCM) results against ~~proxy~~ reconstructions gathered in global datasets. These studies aim~~ed~~ to test the GCM sensitivity mainly to the seasonal changes induced by the orbital parameters (precession). Despite widespread agreement between model results and data on the MH climate, some important differences still exist. There is no consensus on the continental size of the MH thermal climate response, which makes regional quantitative reconstruction critical to obtain a comprehensive understanding of the MH climate patterns. Here, we compare the annual and seasonal outputs from the most recent Paleoclimate Modelling ~~and Coupled Modelling~~ Intercomparison Projects Phase 3 (PMIP3) models with an updated synthesis of climatetemperature reconstruction over China, including, for the first time, a seasonal cycle of temperature and precipitation. Our results indicate that the main discrepancies between model-data for MH climates are the annual and winter mean temperature. A warmer-than-present climate condition are derived from pollen data for both annual mean temperature (~0.7 K on average) and winter mean temperature (~1 K on average), while mMost of the models provide a linear response driven by the seasonal forcing (warmer in summer, cooler in wintera decreased annual mean temperature with a warmer summer and colder winter), which disagrees with the new seasonal data reconstruction over China. By conducting simulations in BIOME4 and CESM, wWe show that to capture the seasonal pattern reconstructed by data, it is critical to assess access surface processes. These results pinpoint the crucial importance of including the non-linear– of the surface water and energy balance to vegetation changesprocess associated with vegetation changes in hydrology and radiative forcing.

Keywords: PMIP3 Pollen data Inverse Vegetation Model Seasonal climate change

1. Introduction

Much attention of paleoclimate study has been focused on the current interglacial (the Holocene), especially the mid-Holocene (MH, 6±0.5 ka). The major difference in the experimental configuration between the MH and pre-Industrial (PI) arises from the orbital parameters which brings about an increase in the amplitude of the seasonal cycle of insolation of the Northern Hemisphere and a decrease in the Southern Hemisphere (Berger, 1978). Thus, the MH provides an excellent case study on which to base an evaluation of the climate response to seasonal changes in the distributions of insolation. Great efforts are devoted by the modeling community to the design of the MH common experiments using similar boundary conditions (Joussaume and Taylor, 1995; Harrison et al., 2002; Braconnot et al., 2007a, b). In addition, much work has been done to reconstruct the paleoclimate changes based on constrain the consistency of the dataset incorporating different proxies at global and continental scale (Guiot et al., 1993; Kohfeld and Harrison, 2000; Prentice et al., 2000; Bartlein et al., 2011). The greatest progress in understanding the MH climate change and variability has consistently been made by comparing large-scale analyses of proxy data with simulations from global climate models (Joussaume et al., 1999; Liu et al., 2004; Harrison et al., 2014).

However, the source of discrepancies between model and data is still an open and stimulating question. Two types of inconsistencies have been identified: 1) where the model and data show opposite signs, for instance, paleoclimate evidence from data-records indicates an increase of about 0.5 K in global annual mean temperature during the MH compared with PI (Shakun et al. 2012; Marcott et al. 2013), while there is a cooling trend in model simulations (Liu et al., 2014). 2) where the same trend is displayed by both model and data but with different magnitudes. Previous studies have shown that while climate models can successfully reproduce the direction and large-scale patterns of past climate changes, they tend to consistently underestimate the magnitude of change in the monsoons of the Northern Hemisphere as well as the amount of the MH precipitation over northern Africa (Braconnot et al., 2012; Harrison et al., 2015). Moreover, significant spatial variability has been noted in both observations and simulations (Peyron et al. 2000; Davis et al. 2003; Braconnot et al., 2007a; Wu et al. 2007; Bartlein et al. 2011), which makes regional quantitative reconstruction (Davis et al., 2003; Mauri et al., 2015) essential to obtain a comprehensive understanding of the MH climate patterns, and to act as a benchmark to evaluate climate models (Fischer and Jungclaus, 2011; Harrison et al., 2014;).

China offers two advantages in respect to these issues. The sheer expanse of the country means that the continental response to insolation changes over a large region can be investigated. Moreover, the quantitative reconstruction of seasonal climate changes during the MH, based on the new pollen dataset, provides a unique opportunity to compare the seasonal cycles for models and data. Previous studies indicate that warmer and wetter than present conditions prevailed over China during the MH and that the magnitude of the annual temperature increases varied from 2.4-5.8 K spatially, with an annual precipitation increase in the range of 34-267 mm (e.g., Sun et al., 1996; Jiang et al., 2010; Lu et al., 2012; Chen et al., 2015). However, Jiang et al. (2012) clearly show a mismatch between multi-proxy reconstructions and model simulations. In terms of climate anomalies (MH-PI), besides the ~1 K increase in summer temperature, 35 out of 36 Paleoclimate Modelling ~~and Coupled Modelling~~ Intercomparison Projects (PMIP) models reproduce annual (~0.4 K) and winter temperatures (~1.4 K) that are colder than the baseline, and a drier-than-baseline climate in some western and middle regions over China is depicted in models (Jiang et al. 2013). Jiang et al. (2012) the first to point out the model-data discrepancy over China during the MH, but the lack of seasonal reconstructions in their study limits comparisons with simulations. This study firstly pinpoints the model-data discrepancy over China during MH, but the lack of statistical seasonal reconstruction hampers the quantitative comparison of data with simulations for seasonal climate.

An important issue raised by Liu et al. (2014) is that the discrepancy at the annual level could be due to incorrect reconstructions of the seasonal cycle, a key objective in our paper. Moreover, it has been suggested that the vegetation change can strengthen the temperature response in high latitudes (O'Ishi et al., 2009; Otto et al., 2009), as well as alter the hydrological conditions in the tropics (Liu et al., 2007). However, compared to the substantial land cover changes in the MH derived from pollen datasets (Ni et al., 2010; Yu et al., 2000; Bartlein et al., 2011), the changes in vegetation have not yet been fully quantified and discussed in PMIP3 (Taylor et al., 2012).

In this study, for the reconstruction, we firstly used the quantitative method of biomization to reconstruct vegetation types during the MH based on a new synthesis of pollen datasets, and then used the process-based biogeographic model – the Inverse Vegetation Model (Guiot et al. 2000; Wu et al. 2007, 2016) to obtain the annual, the mean temperature of the warmest month (MTWA) and the mean temperature of the coldest month (MTCO) climate features over China for the MH. In the case of PMIP3 models, we present a comprehensive evaluation of the state-of-the-art models based on the MH climate variables (vegetation, temperature and precipitation), using the simulations from the PMIP3. This is the first time that such progress towards a quantitative seasonal climate comparison for the MH over China has been made, thanks to the seasonal reconstruction and the PMIP3 results. This point is crucial because ~~of the fact that~~ the MH PMIP3 experiment is essentially one that looks at the response of the models to changes in the seasonality of insolation, and the attempt to derive reconstructions of both summer and winter climate to compare with the simulations ~~the forcing factor we used for MH is essential the seasonal change. We~~ will thus be able to answer the question posed by Liu et al. (2014) on the importance of seasonal reconstruction.

2. Data and Methodology

2.1 Data

In this study, we collected 159 pollen records, covering most of China, for the MH period (6000±~~0.5ka ^{14}C timescale~~500 ^{14}C yr BP) (Fig. 1). Of these, 65 were from the Chinese Quaternary Pollen Database (CQPD, 2000), three~~3~~ were original datasets obtained in our study, and the others were digitized from pollen diagrams in published papers with a recalculation of pollen percentages based on the total number of terrestrial pollen types. These digitized 91 pollen records were selected according to three criteria: (1) ~~distinct~~ clearly readable pollen diagrams with a reliable chronology with the minimum of three independent age control points since the LGM; (2) including the pollen taxa during 6000±500 ^{14}C yr BP period with a minimum sampling resolution of

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1000 years per sample~~ and only extracted the pollen taxa during the 6±0.5ka period~~; (3) ~~located far from archeological sites to avoid the influence of human activity~~ abandon the pollen records if the published paper mentions the influence of human activity. Based on the digitized pollen assemblages, we use biomization to get the biome scores and biome types~~ at 6 ka~~. For age control, different dating methods are utilized in the collected pollen records, we applied the CalPal 2007 (Weninger et al., 2007) to correct ^{14}C age into calendar age so that they can be contrasted with each other. For lacustrine records, if the specific carbon pool age is mentioned in the literature, the calendar age is corrected after deducting the carbon pool. Otherwise, the influence of carbon pool is not considered. The age-depth model for the pollen records was estimated by linear interpolation between adjacent available dates or by regression. Using ranking schemes from the Cooperative Holocene Mapping Project, t~~T~~he quality of dating control for the mid-Holocene was assessed by assigning a rank from 1 to 7~~, using ranking schemes from the Cooperative Holocene Mapping Project,~~. And 70% of the records fell into the first and second classes (see Table 1 for detailed information) according to the Webb 1-7 standards (Webb~~,~~ III T.~~ III,~~ 1985). Vegetation type was quantitatively reconstructed using biomization (Prentice et al., 1996), following the classification of plant functional types (PFTs) and biome assignment in China by the Members of China Quaternary Pollen Data (CQPD, 2000), which has been widely tested in surface sediment~~ary~~. The new sites (91 digitized data and three original data) added to our database improved the spatial coverage of pollen records, especially in the northwest, the Tibetan Plateau, the Loess Plateau and southern regions, where the data in the previous databases are very

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limited.

Modern monthly mean climate variables, including temperature, precipitation and cloudiness, have been spatially interpolatedcollected for each modern pollen site based on the datasets (1951-2001) from 657 meteorological observation stations over China (data source: China Climate Bureau, China Ground Meteorological Record Monthly Report, 1951-2001). Soil properties were derived from the digital world soil map produced by the Food and Agricultural organization (FAO) (FAO, 1995), and, because of a lack of paleosol data, soil characteristics were assumed to have been the same during the MH. Atmospheric CO_2 concentration for the MH was taken from ice core records (EPICA community members 2004), and set at 270 ppmv.

A 3-layer back-propagation (BP) artificial neural network technique (ANN) was used for interpolation on each pollen site (Caudill and Butler, 1992). Five input variables (latitude, longitude, elevation, annual precipitation, annual temperature) and one output variable (biome scores) have been chosen in ANN for the modern vegetation. The ANN has been calibrated on the training set, and its performance has been evaluated on the verification set (20%, randomly extracted from the total sets). After a series of training run, the lowest verification error is obtained with 5 neurons in the hidden layer after 10000 iterations. The anomalies between past (6ka) and modern vegetation indices (biome scores) was then interpolated to the 0.2×0.2° grid resolution by applying the ANN. After that, the modern grid values are added to the values of the grid of palaeo-anomalies to provide gridded paleo-biome indices. Finally, the biome with the highest index is attributed to each grid point. This ANN method is more efficient than many other techniques on condition that the results are validated by independent data sets, and therefore, it has been widely applied in paleoclimatology (Guiot et al., 1996; Peyron et al., 1998). Soil properties were derived from the digital world soil map produced by the Food and Agricultural organization (FAO) (FAO, 1995), and, because of a lack of paleosol data, soil characteristics were assumed to have been the same during MH. Atmospheric CO_2 concentration for the MH was taken from ice core records (EPICA community members 2004), and set at 270 ppmv.

2.2 Climate models

PMIP, a long-standing initiative, is a climate-model evaluation project which provides an efficient mechanism for using global climate models to simulate climate anomalies in the present past periodsday and to understand the role of climate feedback. In its third phase (PMIP3), the models were identical to those used in the Climate Modelling Intercomparison Project 5 (CMIP5) experiments, in which the PI experiment was defined. The experimental set-up for PMIP3 the mid-HoloceneMH simulations in PMIP3 followed the PMIP protocol (Braconnot et al. 2007a, b, 2012). The main variability forcing between the MH and PI in PMIP3 are the orbital configuration and CH_4 concentration. More precisely, the orbital configuration in the MH climate has an increased summer insolation and a decreased winter insolation in the Northern Hemisphere compared to the PI climate (Berger, 1978). Meantime, the CH_4 concentration is prescribed at 650 ppbv in the MH, while it is set at 760 ppbv in PI (Table 2).

All 13 models (Table 3) from PMIP3 that have the MH simulation have been included in our study, including eight~~8~~ ocean-atmosphere (OA) models and ~~5~~ five ocean-atmosphere-vegetation (OAV) models. Means for the last 30 years were calculated from the archived time-series data on individual model grids for climate variables: near surface temperature and precipitation flux, which were bi-linearly interpolated to a ~~common~~ uniform 2.5° grid, in order to ~~calculate~~ get the bioclimatic variables (e.g. MAT, MAP, MTWM, MTCO, July precipitation) onto a common grid for comparison with the reconstruction results.

2.3 Vegetation model

The vegetation model, BIOME4 is a coupled bio-geography and bio-geochemistry model developed by Kaplan et al. (2003). Monthly mean temperature, precipitation, sunshine percentage (~~relative~~ an inverse measure of cloud area fraction~~to cloud cover~~), absolute minimum temperature, atmospheric CO_2 concentration and subsidiary information about the soil's physical properties like water retention capacity and percolation rates are the main input variables for the models. It incorporates 13 plant functional types (PFTs), which have different bioclimatic limits. The PFTs are based on physiological attributes and bioclimatic tolerance limits such as heat, moisture and chilling requirements and resistance of plants to cold. These limits determine the areas where the PFTs could grow in a given climate. A viable combination of these PFTs defines a particular biome among 28 potential options. These 28 biomes can be further classified into 8 megabiomes (Table S1). BIOME4 has been widely utilized to analyze the past, present and potential future vegetation patterns (e.g. Bigelow et al., 2003; Diffenbaugh et al., 2003; Song et al., 2005). In this study, we conducted 13 PI and the

MH biome simulations using PIMP3/CMIP5 climate fields (temperature, precipitation and sunshine) as inputs. The climate fields, obtained from PMIP3/CMIP5, are the monthly mean data of ~~more than~~the last 30 model years.

2.4 Statistics and interpolation for vegetation distribution

To quantify the ~~model-data disparities~~differences between simulated (by the climate-model output) and reconstructed (from pollen) between megabiomes, a map-based statistic (point-to-point comparison with observations) called ΔV（Sykes et al., 1999; Ni et al., 2000）was applied to our study. ΔV is based on the relative abundance of different plant life forms (e.g. trees, grass, bare ground) and a series of attributes (e.g. evergreen, needle-leaf, tropical, boreal) for each vegetation class. The definitions and attributes of each plant form follow naturally from the BIOME4 structure and the vegetation attribute values in the ΔV computation were defined for BIOME4 in the same way as for BIOME1（Sykes et al., 1999). The abundance and attribute values are given in Table 4 and Table 5, which ~~estimate~~ describe the typical floristic composition of the biomes. Weighting the attributes is subjective because there is no obvious theoretical basis for assigning relative significance. Transitions between highly dissimilar megabiomes have a weighting of close to 1, whereas transitions between less dissimilar megabiomes are assigned smaller values. The overall dissimilarity between model and data megabiome maps was calculated by averaging the ΔV for the grids with pollen data, while the value was set at 0 for any grid without data. ΔV values < 0.15 can be considered to point to very good agreement between simulated and actual distributions, 0.15-0.30 is good, 0.30-0.45 fair, 0.45-0.60 poor, and > 0.80 very poor (adjusted from Zhang et al., 2010). For spatial pattern comparison, we used the back-propagation (BP) artificial neural network technique again for interpolation, as described above for climate variables (see data section), to obtain the spatial pattern of megabiomes from pollen records. Secondly, we compared the simulated vegetation distribution from BIOME4 from each model with the interpolated pattern.

2.5 Inverse vegetation model

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A process-based biogeography model, named Inverse Vegetation Model (Guiot et al., 2000; Wu et al. 2007), which is highly dependent on the BIOME4 model, is applied to our reconstruction. The key concept of this model can be summarized in two points: firstly, a set of transfer functions able to transform the model output into values directly comparable with pollen data is defined. There is not full compatibility between the biome typology of BIOME4 and the biome typology of pollen data. A transfer matrix (Table S2) was defined in our study where each BIOME4 vegetation type is assigned a vector of values, one of each pollen vegetation type, ranging from 0 (representing an incompatibility between BIOME4 type and pollen biome type) to 15 (corresponding to a maximum compatibility). Secondly, using an iterative approach, a representative set of climate scenarios compatible with the vegetation records is identified among the climate space, constructed by systematically perturbing the input variables (e.g. atmospheric CO_2 concentration, soil, ΔT, ΔP) of the model (Table S3).

Inverse Vegetation Model (IVM) provides a possibility, for the first time, to reconstruct both annual and seasonal climates for the MH over China. Moreover, it offers a way to consider the impact of CO_2 concentration on competition between PFTs as well as on the relative abundance of taxa, and thus make reconstruction from pollen records more reliable. More detailed information about IVM can be found in Wu et al. (2007).

We applied the inverse model to modern pollen samples to validate the approach by reconstructing the modern climate at each site and comparing it with the observed values. The high correlation coefficients (R=0.75–0.95), intercepts close to 0 (except for the mean temperature of the warmest month), and slopes close to 1 (except for the July precipitation) demonstrated that the inversion method worked well for most variables in China (see Table 6).

3. Results

3.1 Comparison of annual and seasonal climate changes at the MH

In this study, we collected 159 pollen records, broadly covering the whole of China (Fig. 1). To check the reliability of the collected data, we first categorized our pollen records into megabiomes in line with the standard tables developed for the BIOME6000 (Table S1), and compared them with the BIOME6000 dataset (Fig.2). The match between collected data and the BIOME6000 is more than 90% for both the MH and PI.

Based on pollen records, the spatial pattern of climate changes over China during the MH, deduced from IVM, are presented in Fig. 3 (left panel, points), alongside the results from PMIP3 models (shaded in Fig. 3). For temperature, a warmer-than-present annual climate condition (~0.7 K on average) is derived from pollen data (the points in Fig. 3a), with the largest increase occurring in the northeast (3-5 K) and a decrease in the northwest and on Tibetan Plateau. On the other hand, the results from a multi-model ensemble (MME) indicate a colder annual temperature generally (~-0.4 K on average), with significant cooling in the south and slight warming in the northeast (shaded in Fig. 3a). Of the 13 models, 11 simulate a cooler annual temperature compared with PI as MME. However, two models (HadeGEM2-ES and CNRM-CM5) present the same warmer ~~trend~~ condition as was found in the reconstruction (Fig. 3d). Compared to the reconstruction, the annual mean temperature during the MH is largely underestimated by most PMIP3 models, which depict an anomaly ranging from ~-1 to ~0.5 K. ~~Detailed information of reconstructed climate change derived from IVM at each pollen site can be found in Table S4.~~

Concerning seasonal change, during the MH, MTWA from the data is ~0.5 K higher than PI, with the largest increase in the northeast and a decrease in the northwest. From model outputs, an average increase of ~1.2 K is reproduced by MME, with a more pronounced warming at high latitudes which is consistent with the insolation change (Berger, 1978). Fig. 3e shows that all 13 models reproduce the same warmer summer temperatures as the data, and that HadGEM2-ES and CNRM-CM5, reproduce the largest increases among the models. Although the warmer MTWA is consistent between the models and data, there is a discrepancy between them on MTCO. In Fig. 3c, the data show an overall increase of ~1 K, with the largest increase occurring in the northeast and a decrease of opposite magnitude on the Tibetan Plateau. Inversely, MME reproduces a decreas~~ing trend~~ed MTCO with an average amplitude of ~-1.3 K, the coolest areas being the southeast, the Loess Plateau and the northwest. Similarly to the

MME, all 13 models simulate a colder-than-present climate with amplitudes ranging from ~-2.0 K (CCSM4 and FGOALS-g2) to ~-0.7 K (HadGEM2-ES and CNRM-CM5).

Concerning annual change in precipitation, the reconstruction shows wetter conditions during the MH across almost the whole of China with the exception of part of the northwest. The southeast presents the largest increase in annual precipitation. All but 2 models (MIROC-ESM and FGOALS-g2) depict wetter conditions with an amplitude of ~10 mm to ~50 mm. The reconstruction and MME results also indicate an increasing trended annual precipitation during MH (Fig.4a), with a much larger magnitude visible in the reconstruction (~30 mm, ~230 mm respectively). The main discrepancy in annual precipitation between simulations and reconstruction occurs in the northeast, which is depicted as drier by the models and wetter by the data. With regard to seasonal change, the reconstruction shows an overall increase in July rainfall (~50 mm on average), with a decrease in the northwestern regions and EEast MMonsoon region at Yangtze River valley. In line with the reconstruction, the MME also shows an overall increase in rainfall (~7 mm on average), with a decrease in the northwest for July (Fig.4b). Notably, a much larger increase is simulated for the south and the Tibetan Plateau by the models, while the opposite pattern emerges along the eastern margin from both models and data. For January precipitation, the reconstruction shows an overall increase in most region (~15 mm), except northwestern, and MME indicates a slight decrease (~3 mm on average). More detailed information about the geographic distribution of simulated temperature and precipitation for each model can be found in Fig. S1-S6.

Table S4 provides the biome score from IVM for pollen data collected from published papers. The reconstructed climate change derived from IVM at each pollen site can be found in Table S5, in which the columns show the median and the 90% interval (5th to 95th percentage) for feasible climate values produced with the IVM approach. The simulated values for each of the climate variables as shown in the boxplots (Figure 3 and Figure 4) are given in the Table S6 and Table S7.

3.2 Comparison of vegetation change at the MH

The use of the PMIP3 database is clearly limited by the different vegetation inputs among the models for the MH period (Table S8). Only HadGEM2-ES and HadGEM2-CC use a dynamic vegetation for the MH, and the other 11 models are prescribed to PI with or without interactive LAI, which would introduce a bias to the role of vegetation-atmosphere interaction in the MH climates. To evaluate the model results against the reconstruction for the MH vegetation, we conducted 13 biome simulations in BIOME4 using PIMP3 climate fields, and the megabiome distribution for each model during the MH is displayed in Fig. 5 (see Fig. S7 for PI vegetation comparison). To quantify the model-data dissimilarity between megabiomes, a map-based statistic called ΔV (Sykes et al., 1999; Ni et al., 2000) was applied here (detailed information is in the methodology section).

Fig. S8 shows the dissimilarity between simulations and observations for megabiomes during the MH, with the overall values for ΔV ranging from 0.43 (HadGEM2-ES) to 0.55 (IPSL-CM5A-LR). According to the classification of ΔV (see in the methodology section) for the 13 models, 12 (all except HadGEM2-ES) showed poor agreement with the observed vegetation distribution. Most models poorly simulate the desert, grassland and tropical forest areas for both periods, but perform better for warm mixed forest, tundra and temperate forest. However, this statistic is based on a point-to-point comparison and so the ΔV calculated here cannot represent an estimation of full vegetation simulation due to the uneven distribution of pollen data and the potentially huge difference in area of each megabiome. For instance, tundra in our data for PI is represented by only 4 points, which counts for a small contribution to the ΔV since we averaged it over a total of 159 points, but this calculation could induce a significant bias if these 4 points cover a large area of China.

So, we used the biome scores based on the artificial neural network technique as described by Guiot et al. (1996) for interpolation (the plots in red rectangle in Fig. 5), and compared the simulated vegetation distribution from BIOME4 for each model with the interpolated pattern. During the MH, most models are able to capture the tundra on the Tibetan Plateau as well as the combination of warm mixed forest and temperate forest in the southeast. However, all models fail to simulate or underestimate the desert area in the northwest compared to reconstructed data. The main model-data inconsistency in the MH vegetation distribution occurs in the northeast, where data show a mix of grassland and temperate forest, and the models show a mix of grassland and boreal forest.

The area statistic carried out for simulated vegetation changes (Fig. 6) reveals that the main difference during the MH, compared with PI, is that grassland replaced boreal forest in large tracts of the northeast (Fig. 5, Fig. S7). No other significant difference in vegetation distribution between the two periods was derived from models. Unlike in models, three main changes in megabiomes during the MH are depicted by the data. Firstly, the megabiomes converted from grassland to temperate forest in the northeast. Secondly, a large area of temperate forest was replaced in the southeast by a northward expansion of warm mixed forest. Thirdly, in the northwest and at the northern margin of the Tibetan Plateau, part of the desert area changed into grassland. However, none of the models succeed in capturing these features, especially the enhanced vegetation conditionstransition from grassland into forest in the northeast during the MH. Therefore, this failure to capture vegetation changes between the two periods will lead to a cumulating inconsistency in the model-data comparison for climate anomalies because of the vegetation-climate feedbacks.

4. Conclusion and Discussion

In response to the seasonal insolation change prescribed in PMIP3 for the MH, all models produce similar large-scale patterns for seasonal temperature and precipitation (wetter and warmer in MTWA, colder in MTCOhigher than present July precipitation and MTWA, lower than present MTCO), with either an over- or underestimate of the climate changes when compared to the data. The main discrepancy emerging from the model-data comparison occurs in the annual and MTCO temperature, where data show an increased trend value and most models (except CNRM-CM5 and HadGEM2-ES) simulate the opposite except CNRM-CM5 and HadGEM2-ES reproduced the higher-than-present annual temperature during MH as data showed. The bias raised from both reconstruction and simulation should be considered in this discord between model-data for MH climate change over China.

4.1 Validation and uncertainties for reconstruction

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To investigate the discrepancy between model-data for the MH climate change over China, the reliability of our reconstruction should be firstly considered. For the cross-proxy validation, we compared our reconstruction with numerous previous studies concerning the MH climate change over China based on multiple proxies (including pollen, lake core, palaeosol, ice core, peat and stalagmite), the related references and detailed information are listed in Supplementary Information (Table S9 and Table S10). In comparison with PI condition, most reconstructions reproduced warmer and wetter annual condition during the MH (Fig. 7), same as our study. In other words, this discrepancy between model-data for climate change over China during the MH is common and robust in reconstructions derived from different proxies. Our study just reinforces the picture given by the discrepancies between PMIP simulation and pollen data derived from a synthesis of the literature.

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However, there are still some bias in the reconstruction. Estimated climates for the present day from IVM were compared with observed climates (Table 6), the slopes and intercepts show slightly bias for annual and January precipitation, while there is considerable bias between IVM reconstruction and observation for temperature and July precipitation. For the uncertainties on data reconstruction, IVM relies heavily on BIOME4, and since BIOME4 is a global vegetation model, it is possible that the spatial robustness of regional reconstruction could be less than that of global reconstruction due to the failure in simulating local features (Bartlein et al., 2011). Moreover, the output of the model is not directly compared to the pollen data, the conversion of BIOME4 biomes to pollen biomes by the transfer matrix may add the source of uncertainty in reconstruction. All these bias in reconstruction should be considered in the discrepancy between model-data for climate change during the MH over China.

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4.2 Potential uncertainties for simulation

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Besides the qualitative consistency among models, ~~triggered~~ caused by the protocol of –PMIP3 experiments (Table 2), a variability in the magnitude of anomalies between models is clearly illustrated by the ~~column bars~~boxplots (Fig.3 and Fig.4). These disparities in value or even pattern ~~between~~ among models reflect the obvious differences in the response by the climate models to the MH forcing which ~~shed light~~raises on the question of the magnitude of feedbacks among models.

As positive feedbacks between climate and vegetation are important to explain regional climate changes, the failure to capture or the underestimation of the amplitude and pattern of the observed vegetation differences among models (see Section 3.2) could amplify and partly account for the model-data disparities in climate change, mainly due to variations in the albedo. Because the HadGEM2-ES and HadGEM2-CC are the only two models in PMIP3 with dynamic vegetation simulation for the MH, we thus focused on them to examine the variations in vegetation fraction in the simulations. The main vegetation changes during the MH demonstrated by HadGEM2-ES are increased tree coverage (~15%) and a decreased bare soil fraction (~6%), while HadGEM2-CC depicts a ~3% decrease in tree fraction and a ~1% increase in bare soil (Fig. S9). We made a rough calculation of albedo variance caused solely by vegetation change for both two models and for our reconstruction, based on the area fraction and albedo value of each vegetation type (Betts, 2000; Bonfils et al., 2001; Oguntunde et al., 2006; Bonan, 2008).

Reconstruction showed vegetation changes during the MH leading to a ~1.8% decrease in albedo when snow-free, with a much larger impact (~4.2% decrease) when snow-covered. The results from HadGEM2-ES are highly consistent with the albedo changes from the reconstruction, featuring a ~1.4% (~6.5%) decrease without (with) snow, while HadGEM2-CC produces an increased albedo value during the MH (~0.22% for snow-free, ~1.9% with snow-cover), depending on its vegetation simulation. Two ideas could be inferred from this calculation, 1) HadGEM2-ES is much better in simulating the MH vegetation changes than HadGEM2-CC. 2) the failure by models to capture these vegetation changes will result in a much larger impact on winter albedo (with snow) than summer albedo (without snow).

These surface albedo changes due to vegetation changes could have a cumulative effect on the regional climate by modifying the radiative fluxes. For instance, the spread of trees into the grassland biome in the northeast during the MH, revealed by the reconstruction in our study, ~~will~~ should act as a positive feedback to climate warming by increasing the surface net shortwave radiation associated with reductions in albedo due to taller and darker canopies (Chapin et al., 2005). Previous studies show that cloud and surface albedo feedbacks on radiation are major drivers of differences between model outputs for past climates. Moreover, the land surface feedback shows large disparities among models (Braconnot and Kageyama, 2015).

We used a simplified approach (Taylor et al., 2007) to quantify the feedbacks and to compare model behavior for the MH, thus justifying the focus on surface albedo and atmospheric scattering (mainly accounting for cloud change). Surface albedo and cloud change are calculated using the simulated incoming and outgoing radiative fluxes at the Earth's surface and at the top of atmosphere (TOA), based on data for the last 30 years averaged from all models. Using this framework, we quantified the effect of changes in albedo on the net shortwave flux at TOA (Braconnot and Kageyama, 2015), and further investigated the relationship between these changes and temperature change. Fig.7 shows that most models produced a negative cloud cover and surface albedo feedback on the annual mean shortwave radiative forcing. Concerning seasonal change, the shortwave cloud and surface feedback in most models tend to counteract the insolation forcing during the boreal summer, while they enhance the solar forcing during winter. A strong positive correlation between albedo feedback and temperature change is depicted, with a large spread in the models owing to the difference in albedo in the 13 models. In particular, CNRM-CM5 and HadGEM2-ES capture higher values of cloud and surface albedo feedback, which could be the reason for the reversal of the decreased annual temperature~~cooling trend~~ seen in other models (Fig. 3d).

However, the vegetation patterns produced by BIOME4 in Figure 5 are not used in PMIP3 experiment setup, it's actually determined by the input variables from models.

Previous study shows the GCMs from PMIP3 are reliable to simulate the geographical distribution of temperature and precipitation over China for present day without downscaling, but there is considerable bias between simulation and observation for precipitation (Jiang et al., 2016). Therefore, the disagreements of MH vegetation pattern possibly are inherited from the PI. To better quantify the vegetation-climate feedback, two experiments were conducted in CESM version 1.0.5, including a mid-Holocene (MH) experiment (6 ka) with original vegetation setting (prescribed as PI vegetation for the MH) and a MH experiment with reconstructed vegetation (6 ka_VEG). Figure 9 shows the climate anomalies (6 ka_VEG minus 6 ka) between two simulations, for both annual and seasonal scale. For temperature, it's clear that the 6 ka_VEG simulation reproduces a warmer annual mean climate (~0.3 K on average) as well as an obviously warmer winter (~0.6 K on average). For precipitation, the reconstructed vegetation leads to more annual and seasonal precipitation, which can also reconcile the discrepancy of increase amplitude for precipitation during the MH between model-data (data reproduced larger amplitude than model, revealed by our study). So the mismatch between model-data in MH vegetation could partly account for the discrepancy of climate due to the interaction between vegetation and climate through radiative and hydrological forcing with albedo. These results pinpoint the value of building a new generation of models able to capture not only the atmosphere and ocean response, but also the non-linear responses of vegetation and hydrology to the climate change.

Although the MH remains an ideal target for model-data comparison, the PMIP exercise only allows the atmosphere and ocean response to be computed for seasonal forcing. In this study, we show that the model-data inconsistency for temperature is mainly because we are not able to simulate the MH vegetation and its interaction with climate through radiative and hydrological forcing with albedo. These results pinpoint the value of building a new generation of models able to capture not only the atmosphere and ocean response, but also the non-linear responses of vegetation and hydrology.

Besides the uncertainties in the models, IVM, from the data perspective, relies heavily on BIOME4, and since BIOME4 is a global vegetation model, it is possible that the spatial robustness of regional reconstruction could be less than that of global reconstruction due to the failure to simulate local features (Bartlein et al., 2011). China, located in the Asian monsoon area, has some specialized vegetation types which call for an improved ability to simulate regional vegetation in BIOME4. Of course, more reconstruction studies using multiple proxies and reliable methods are also required to narrow the discrepancies between data and model results.

5. Conclusion

In this study, we compare the annual and seasonal outputs from the PMIP3 models with an updated synthesis of climate reconstruction over China, including, for the first time, a seasonal cycle of temperature and precipitation. In response to the seasonal insolation change prescribed in PMIP3 for the MH, all models produce similar large-scale patterns for seasonal temperature and precipitation (higher than present July precipitation and MTWA, lower than present MTCO), with either an over- or underestimate of the climate changes when compared to the data. The main discrepancy emerging from the model-data comparison occurs in the annual and MTCO, where data show an increased value and most models simulate the opposite except CNRM-CM5 and HadGEM2-ES reproduced the higher-than-present annual temperature during MH as data showed. By conducting simulations in BIOME4 and CESM, we show that the surface processes are the key factors drawing the uncertainties between models and data. These results pinpoint the crucial importance of including the non-linear responses of the surface water and energy balance to vegetation changes. Moreover, besides the vegetation influence, to which extent this model-data discrepancy is related to rough topography, soil type and other possible factors should be investigated in the future work.

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Data availability

The PMIP3 output is publicly available at website (http://pmip3.lsce.ipsl.fr/) by the climate modelling groups, the 65 pollen biomization results are provided by Members of China Quaternary Pollen Data Base, Table 1 shows the information (including references) of the 91 collected pollen records and 3 original ones in our study. All the reconstructed climate values at each pollen site from IVM are provided in Table S5. The biome scoresfull datasets of our collected pollen records from published papers are availableprovided in Table S4.

upon the request to the corresponding author.

Author contribution

Yating Lin carried out the model-data analysis and prepared for the first manuscript, Gilles Ramstein contributed a lot to the paper's structure and content, Haibin Wu provided the reconstruction results from IVM and contributed the paper's structure and content. Raj Rani-Singh conducted the BIOME4 simulations. Ran Zhang carried out the simulation in CESM. Pascale Braconnot, Masa Kegeyama and Zhengtang Guo contributed great ideas on model-data comparison work. Qin Li and Yunli Luo provided pollen data. All co-authors helped to improve the paper.

Competing interest

The authors declare no competing interests.

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Table 1. Basic information of the pollen dataset used in this study

Site	Lat	Lon	Alt	Webb 1-7	Source
Sujiawan	35.54	104.52	1700	2	original data (Zou et al., 2009)
Xiaogou	36.10	104.90	1750	2	original data (Wu et al., 2009)
Dadiwan	35.01	105.91	1400	1	original data (Zou et al., 2009)
Sanjiaocheng	39.01	103.34	1320	1	Chen et al., 2006
Chadianpo	36.10	114.40	65	2	Zhang et al., 2007
Qindeli	48.08	133.25	60	2	Yang and Wang, 2003
Fuyuanchuangye	47.35	133.03	56	3	Xia, 1988
Jingbo Lake	43.83	128.50	350	2	Li et al., 2011
Hani Lake	42.22	126.52	900	1	Cui et al., 2006
Jinchuan	42.37	126.43	662	5	Jiang et al., 2008
Maar Lake	42.30	126.37	724	1	Liu et al., 2009
Maar Lake	42.30	126.37	724	1	Liu et al., 2008
Xie Lake SO4	37.38	122.52	0	1	Zhou et al., 2008
Nanhuiheming Core	31.05	121.58	7	2	Jia and Zhang, 2006
Toushe	23.82	120.88	650	1	Liu et al., 2006
Dongyuan Lake	22.17	120.83	415	2	Lee et al., 2010
Yonglong CY	31.78	120.44	5	3	Zhang et al., 2004
Hangzhou HZ3	30.30	120.33	6	4	Liu et al., 2007
Xinhua XH1	32.93	119.83	2	3	Shu et al., 2008
ZK01	31.77	119.80	6	2	Shu et al., 2007
Chifeng	43.97	119.37	503	2	Xu et al., 2002
SZK1	26.08	119.31	9	1	Zheng et al., 2002
Gucheng	31.28	118.90	6	4	Yang et al., 1996
Lulong	39.87	118.87	23	2	Kong et al., 2000
Hulun Lake	48.92	117.42	545	1	Wen et al., 2010
CH-1	31.56	117.39	5	2	Wang et al., 2008
Sanyi profile	43.62	117.38	1598	4	Wang et al., 2005
Xiaoniuchang	42.62	116.82	1411	1	Liu et al., 2002
Haoluku	42.87	116.76	1333	2	Liu et al., 2002
Liuzhouwan	42.71	116.68	1410	7	Liu et al., 2002
Poyang Lake 103B	28.87	116.25	16	4	Jiang and Piperno, 1999
Baiyangdian	38.92	115.84	8	2	Xu et al., 1988
Bayanchagan	42.08	115.35	1355	1	Jiang et al., 2006
Huangjiapu	40.57	115.15	614	7	Sun et al., 2001

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Dingnan	24.68	115.00	250	2	Xiao et al., 2007
Guang1	36.02	114.53	56	1	Zhang et al., 2007
Angulinao	41.33	114.35	1315	1	Wang et al., 2010
Yangyuanxipu	40.12	114.22	921	6	Wang et al., 2003
Shenzhen Sx07	22.75	113.78	2	2	Zhang and Yu, 1999
GZ-2	22.71	113.51	1	7	Wang et al., 2010
Daihai99a	40.55	112.66	1221	2	Xiao et al., 2004
Daihai	40.55	112.66	1221	2	Sun et al., 2006
Sihenan profile	34.80	112.40	251	1	Sun and Xia, 2005
Diaojiaohaizi	41.30	112.35	2015	1	Yang et al., 2001
Ganhaizi	39.00	112.30	1854	3	Meng et al., 2007
Jiangling profile	30.35	112.18	37	1	Xie et al., 2006
Helingeer	40.38	111.82	1162	3	Li et al., 2011
Shennongjia2	31.75	110.67	1700	1	Liu et al., 2001
Huguangyan Maar Lake B	21.15	110.28	59	2	Wang et al., 2007
Yaoxian	35.93	110.17	1556	2	Li et al., 2003
Jixian	36.00	110.06	1005	6	Xia et al., 2002
Shennongjia Dajiu Lake	31.49	110.00	1760	2	Zhu et al., 2006
Qigai nuur	39.50	109.85	1300	1	Sun and Feng, 2013
Beizhuangcun	34.35	109.53	519	1	Xue et al., 2010
Lantian	34.15	109.33	523	1	Li and Sun, 2005
Bahanniao	39.32	109.27	1278	1	Guo et al., 2007
Midiwan	37.65	108.62	1400	1	Li et al., 2003
Jinbian	37.50	108.33	1688	2	Cheng, 2011
Xindian	34.38	107.80	608	1	Xue et al., 2010
Nanguanzhuang	34.43	107.75	702	1	Zhao et al., 2003
Xifeng	35.65	107.68	1400	3	Xu, 2006
Jiyuan	37.13	107.40	1765	3	Li et al., 2011
Jiacunyuan	34.27	106.97	1497	2	Gong, 2006
Dadiwan	35.01	105.91	1400	1	Zou et al., 2009
Maying	35.34	104.99	1800	1	Tang and An, 2007
Huiningxiaogou	36.10	104.90	1750	2	Wu et al., 2009
Sujiawan	35.54	104.52	1700	2	Zou et al., 2009
QTH02	39.07	103.61	1302	1	Yu et al., 2009
Laotanfang	26.10	103.20	3579	2	Zhang et al., 2007
Hongshui River2	38.17	102.76	1511	1	Ma et al., 2003,
Ruoergai	33.77	102.55	3480	1	Cai, 2008
Hongyuan	32.78	102.52	3500	2	Wang et al., 2006
Dahaizi	27.50	102.33	3660	1	Li et al., 1988
Shayema Lake	28.58	102.22	2453	1	Tang and Shen, 1996
Luanhaizi	37.59	101.35	3200	5	Herzschuh et al., 2006

Lugu Lake	27.68	100.80	2692	1	Zheng et al., 2014
Qinghai Lake	36.93	100.73	3200	2	Shen et al., 2004
Dalianhai	36.25	100.41	2850	3	Cheng et al., 2010
Erhai ES Core	25.78	100.19	1974	1	Shen et al., 2006
Xianmachi profile	25.97	99.87	3820	7	Yang et al., 2004
TCK1	26.63	99.72	3898	1	Xiao et al., 2014
Yidun Lake	30.30	99.55	4470	4	Shen et al., 2006
Kuhai lake	35.30	99.20	4150	1	Wischnewski et al., 2011
Koucha lake	34.00	97.20	4540	2	Herzschuh et al., 2009
Hurleg	37.28	96.90	2817	2	Zhao et al., 2007
Basu	30.72	96.67	4450	3	Tang et al., 1998
Tuolekule	43.34	94.21	1890	1	An et al., 2011
Balikun	43.62	92.77	1575	1	Tao et al., 2010
Cuona	31.47	91.51	4515	3	Tang et al., 2009
Dongdaohaizi2	44.64	87.58	402	1	Li et al., 2001
Bositeng Lake	41.96	87.21	1050	1	Xu, 1998
Cuoqin	31.00	85.00	4648	4	Luo, 2008
Yili	43.86	81.97	928	2	Li et al., 2011
Bangong Lake	33.75	78.67	4241	1	Huang et al., 1996
Shengli	47.53	133.87	52	2	CQPD, 2000
Qingdeli	48.05	133.17	52	1	CQPD, 2000
Changbaishan	42.22	126.00	500	2	CQPD, 2000
Liuhe	42.90	125.75	910	7	CQPD, 2000
Shuangyang	43.27	125.75	215	1	CQPD, 2000
Xiaonan	43.33	125.33	209	1	CQPD, 2000
Tailai	46.40	123.43	146	5	CQPD, 2000
Sheli	45.23	123.31	150	4	CQPD, 2000
Tongtu	45.23	123.30	150	7	CQPD, 2000
Yueyawan	37.98	120.71	5	1	CQPD, 2000
Beiwangxu	37.75	120.61	6	1	CQPD, 2000
East Tai Lake1	31.30	120.60	3	1	CQPD, 2000
Suzhou	31.30	120.60	2	7	CQPD, 2000
Sun-Moon Lake	23.51	120.54	726	2	CQPD, 2000
West Tai Lake	31.30	119.80	1	1	CQPD, 2000
Changzhou	31.43	119.41	5	1	CQPD, 2000
Dazeyin	39.50	119.17	50	7	CQPD, 2000
Hailaer	49.17	119.00	760	2	CQPD, 2000
Cangumiao	39.97	118.60	70	1	CQPD, 2000
Qianhuzhuang	40.00	118.58	80	6	CQPD, 2000
Reshuitang	43.75	117.65	1200	1	CQPD, 2000
Yangerzhuang	38.20	117.30	5	7	CQPD, 2000
Mengcun	38.00	117.06	7	5	CQPD, 2000

Hanjiang-CH2	23.48	116.80	5	2	CQPD, 2000
Hanjiang-SH6	23.42	116.68	3	7	CQPD, 2000
Hanjiang-SH5	23.45	116.67	8	2	CQPD, 2000
Hulun Lake	48.90	116.50	650	1	CQPD, 2000
Heitutang	40.38	113.74	1060	1	CQPD, 2000
Zhujiang delta PK16	22.73	113.72	15	7	CQPD, 2000
Angulitun	41.30	113.70	1400	7	CQPD, 2000
Bataigou	40.92	113.63	1357	1	CQPD, 2000
Dahewan	40.87	113.57	1298	2	CQPD, 2000
Yutubao	40.75	112.67	1254	7	CQPD, 2000
Zhujiang delta K5	22.78	112.63	12	1	CQPD, 2000
Da-7	40.52	112.62	1200	3	CQPD, 2000
Hahai-1	40.17	112.50	1200	5	CQPD, 2000
Wajianggou	40.50	112.50	1476	4	CQPD, 2000
Shuidong Core A1	21.75	111.07	-8	2	CQPD, 2000
Dajahu	31.50	110.33	1700	2	CQPD, 2000
Tianshuigou	34.87	109.73	360	7	CQPD, 2000
Mengjiawan	38.60	109.67	1190	7	CQPD, 2000
Fuping BK13	34.70	109.25	422	7	CQPD, 2000
Yaocun	34.70	109.22	405	2	CQPD, 2000
Jinbian	37.80	108.60	1400	4	CQPD, 2000
Dishaogou	37.83	108.45	1200	2	CQPD, 2000
Shuidonggou	38.20	106.57	1200	5	CQPD, 2000
Jiuzhoutai	35.90	104.80	2136	7	CQPD, 2000
Luojishan	27.50	102.40	3800	1	CQPD, 2000
RM-F	33.08	102.35	3400	2	CQPD, 2000
Hongyuan	33.25	101.57	3492	1	CQPD, 2000
Wasong	33.20	101.52	3490	1	CQPD, 2000
Guhu Core 28	27.67	100.83	2780	7	CQPD, 2000
Napahai Core 34	27.80	99.60	3260	2	CQPD, 2000
Lop Nur	40.50	90.25	780	7	CQPD, 2000
Chaiwobao1	43.55	87.78	1100	2	CQPD, 2000
Chaiwobao2	43.33	87.47	1114	1	CQPD, 2000
Manasi	45.97	84.83	257	2	CQPD, 2000
Wuqia	43.20	83.50	1000	7	CQPD, 2000
Madagou	37.00	80.70	1370	2	CQPD, 2000
Tongyu	44.83	123.10	148	5	CQPD, 2000
Nanjing	32.15	119.05	10	2	CQPD, 2000
Banpo	34.27	109.03	395	1	CQPD, 2000
QL-1	34.00	107.58	2200	7	CQPD, 2000
Dalainu	43.20	116.60	1290	7	CQPD, 2000
Qinghai	36.55	99.60	3196	2	CQPD, 2000

Table 2. Earth's orbital parameters and trace gases as recommended by the PMIP3 project

Simulation	Orbital parameters			Trace gases		
	Eccentricity	Obliquity(°)	Angular precession(°)	CO_2(ppmv)	CH_4(ppbv)	N_2O(ppbv)
PI	0,0167724	23,446	102,04	280	760	270
MH	0,018682	24,105	0,87	280	650	270

Table 3. PMIP3 model characteristics and references

Model Name	***Modelling centre***	***Type***	***Grid***	***Reference***
BCC-CSM-1-1	BCC-CMA (China)	AOVGCM	Atm: 128×64×L26; Ocean: 360×232×L40	Xin et al. (2013)
CCSM4	NCAR (USA)	AOGCM	Atm: 288 × 192×L26; Ocean: 320×384×L60	Gent et al. (2011)
CNRM-CM5	CNRM&CERFACS (France)	AOGCM	Atm: 256 × 128×L31; Ocean: 362×292×L42	Voldoire et al. (2012)
CSIRO-Mk3-6-0	QCCCE, Australia	AOGCM	Atm: 192 × 96×L18; Ocean: 192×192×L31	Jeffrey et al. (2013)
FGOALS-g2	LASG-IAP (China)	AOVGCM	Atm: 128 × 60×L26; Ocean: 360×180×L30	Li et al. (2013)
FGOALS-s2	LASG-IAP (China)	AOVGCM	Atm: 128 × 108×L26; Ocean: 360×180×L30	Bao et al. (2013)
GISS-E2-R	GISS (USA)	AOGCM	Atm: 144 × 90×L40; Ocean: 288×180×L32	Schmidt et al. (2014a,b)
HadGEM2-CC	Hadley Centre (UK)	AOVGCM	Atm: 192 × 145×L60; Ocean: 360×216×L40	Collins et al. (2011)
HadGEM2-ES	Hadley Centre (UK)	AOVGCM	Atm: 192 × 145×L38; Ocean: 360×216×L40	Collins et al. (2011)
IPSL-CM5A-LR	IPSL (France)	AOVGCM	Atm: 96 × 96×L39; Ocean: 182×149×L31	Dufresne et al. (2013)
MIROC-ESM	Utokyo&NIES (Japan)	AOVGCM	Atm: 128×64×L80; Ocean: 256×192×L44	Watanabe et al. (2011)
MPI-ESM-P	MPI (Germany)	AOGCM	Atm: 196×98×L47; Ocean: 256×220×L40	Giorgetta et al. (2013)
MRI-CGCM3	MRI (Japan)	AOGCM	Atm: 320 × 160×L48; Ocean: 364×368×L51	Yukimoto et al. (2012)

Table 4. Important values for each plant life form used in the ΔV statistical calculation as assigned to the megabiomes

Megabiomes	*Life form*		
	Trees	**Grass/grass**	**Bare ground**
Tropical forest	1		
Warm mixed forest	1		
Temperate forest	1		
Boreal forest	1		
Grassland and dry shrubland	0.25	0.75	
Savanna and dry woodland	0.5	0.5	
Desert		0.25	0.75
Tundra		0.75	0.25

Table 5. Attribute values and the weights for plant life forms used by the ΔV statistic

Life form	*Attribute*			
Trees	Evergreen	Needle-leaf	Tropical	Boreal
Tropical forest	1	0	1	0
Warm mixed forest	0.75	0.25	0	0
Temperate forest	0.5	0.5	0	0.5
Boreal forest	0.25	0.75	0	1
Grassland and dry shrubland	0.75	0.25	0.75	0
Savanna and dry woodland	0.25	0.75	0	0.5
weights	0.2	0.2	0.3	0.3
Grass/Shrub	Warm	Arctic/alpine		
Grassland and dry shrubland	1	0		
Savanna and dry woodland	0.75	0		
Desert	1	0		
Tundra	0	1		
weights	0.5	0.5		
Bare Ground	Arctic/alpine			
Desert	0			
Tundra	1			
weight	1			

Table 6. Regression coefficients between the reconstructed climates by inverse vegetation models and observed meteorological values

Climate parameter	Slope	Intercept	R	ME	RMSE
MAT	0.82±0.02	0.92±0.18	0.89	0.16	3.25
MTCO	0.81±0.01	-1.79±0.18	0.95	-0.17	3.19

MTWA ~~(jul)~~	0.75±0.03	4.57±0.60	0.75	-0.19	4.02
MAP	1.15±0.02	32.90±18.41	0.94	138.01	263.88
Pjan	1.01±0.02	0.32±0.47	0.94	0.52	8.89
Pjul	1.30±0.03	-21.67±4.52	0.89	16.45	52.9

The climatic parameters used for regression are the actual values. MAT annual mean temperature, MTCO mean temperature of the coldest month, MTWA mean temperature of the ~~coldest~~ warmest month, MAP annual precipitation, RMSE the root-mean-square error of the residuals, ME mean error of the residuals, Pjan: precipitation of January, Pjul: precipitation of July, R is the correlation coefficient, ± stand error

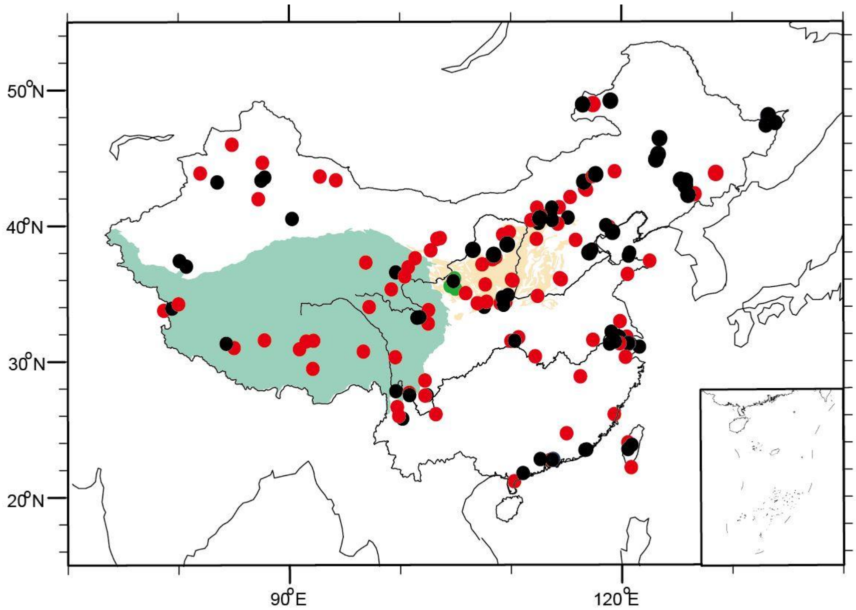

Figure 1. Distribution of pollen sites during mid-Holocene period in China. Black circle is the original China Quaternary Pollen Database, ~~and the~~ red circles are ~~new-added~~digitized ones from published papers, green circles represent the three original pollen data used in this study.

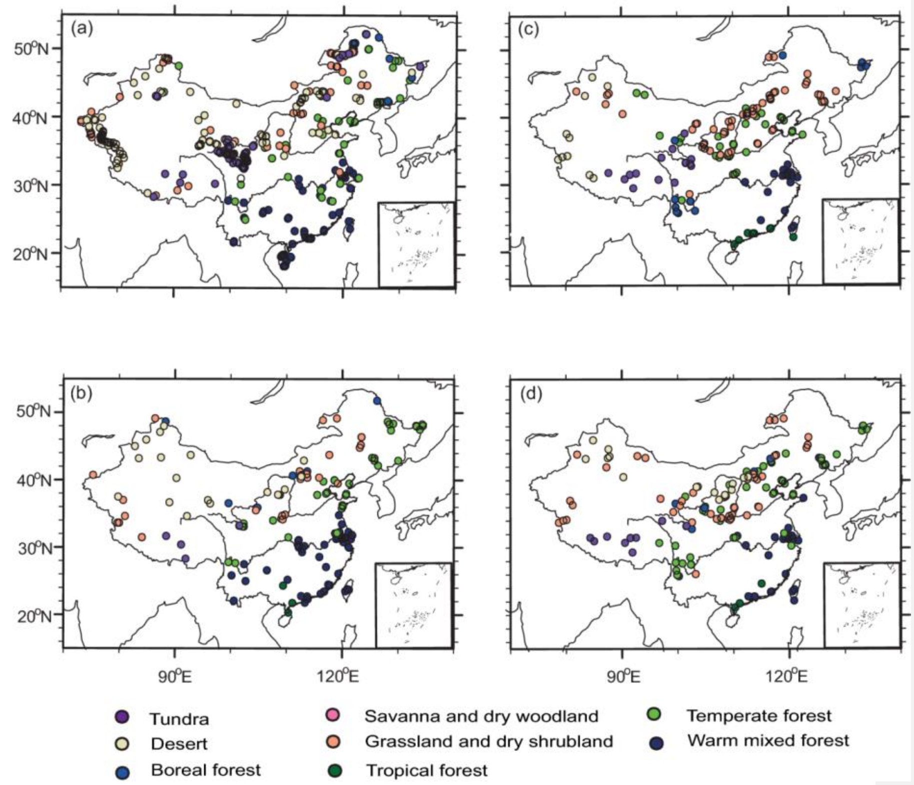

Figure 2. Comparison of megabiomes for PI (first row) and the MH (second row): (a,b) BIOME6000, (c,d) pollen data collected in this study.

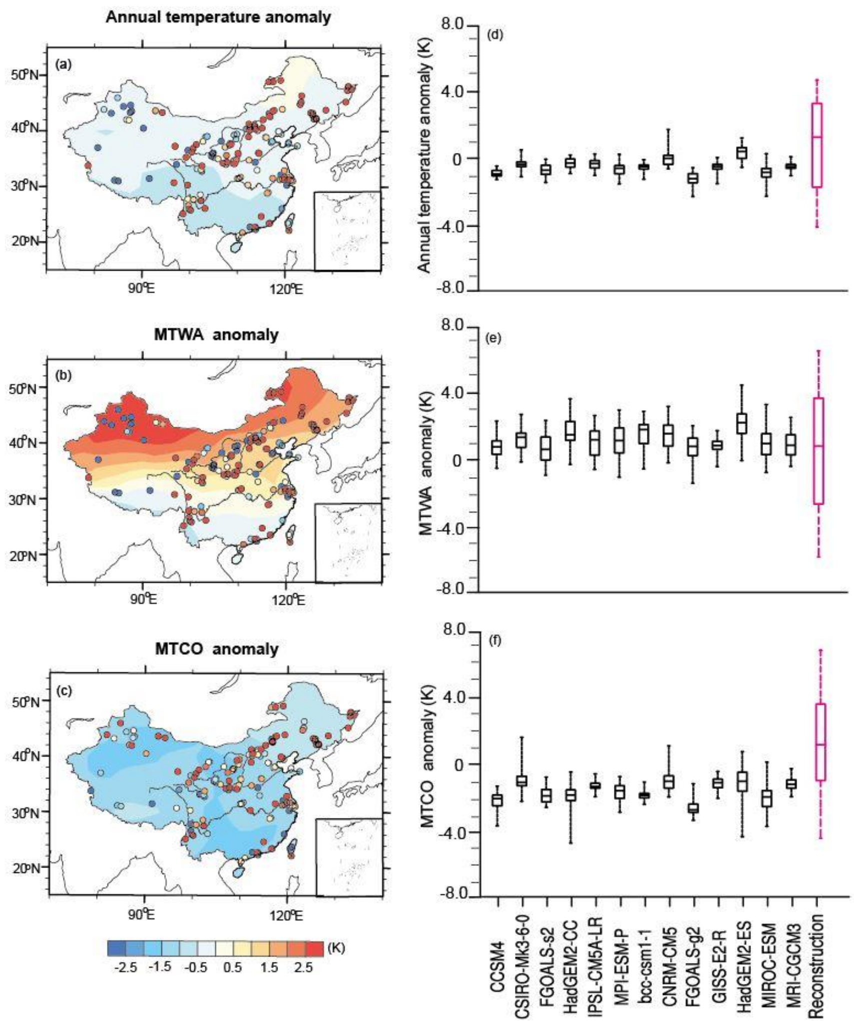

Figure 3. Model-data comparison for annual and seasonal (MTWA and MTCO) temperature (K). For the left panel (a-c), points represent the reconstruction from IVM, shades show the last 30-year means simulation results of multi-model ensemble (MME) for 13 PMIP3 models. The box-and-whisker plots (d-f) show the changes as shown by each PMIP3 model and the reconstruction. (d) considers changes in annual temperature, (e) indicates changes in MTWA, and (f) shows changes in MTCO. The lines in each box shows the median value from each set of measurements, the box shows the 25%-75% range, and the whiskers show the 90% interval (5th to 95th percentile). ~~The grid mean value of temperature for each model, MME and reconstruction are also displayed at the right panel (d-f).~~

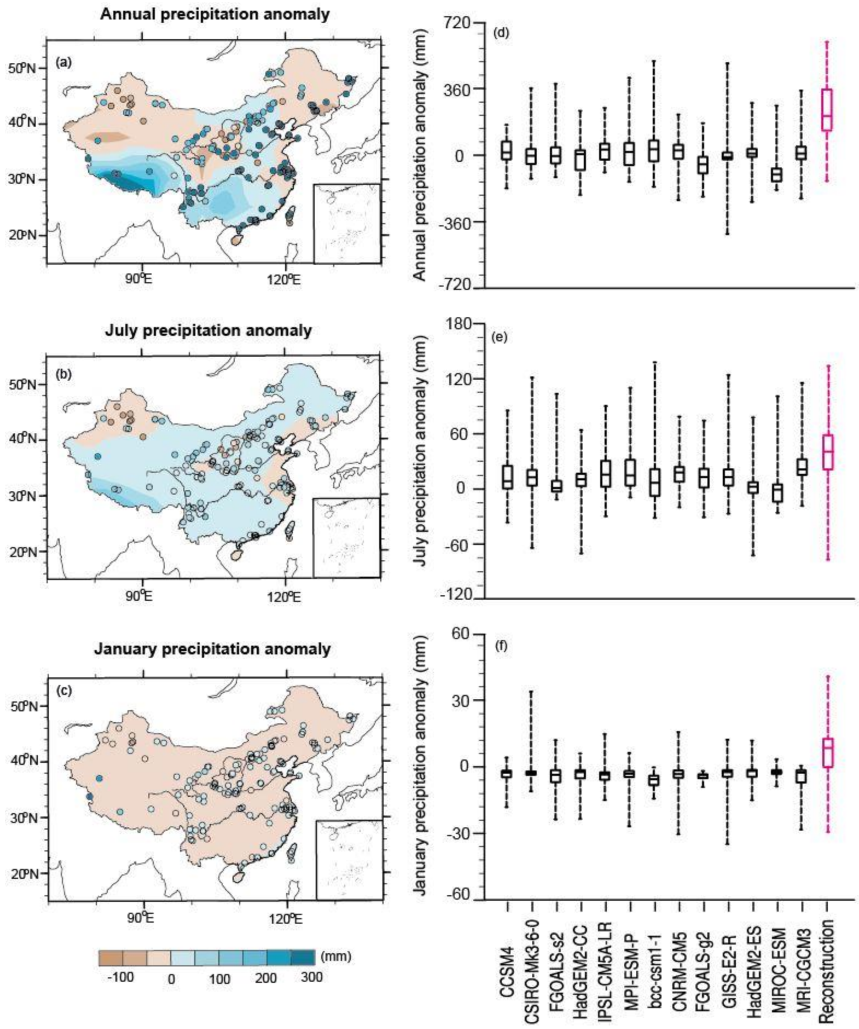

Figure 4. Model-data comparison for annual~~, and~~ July and January precipitation (mm). For the left panel (a,b), points represent the reconstruction from IVM, shades show the last 30-year means simulation results of multi-model ensemble (MME) for 13 PMIP3 models. The box-and-whisker plots (d-f) show the changes as shown by each PMIP3 model and the reconstruction. (d) considers changes in annual precipitation, (e) indicates changes in July precipitation, and (f) shows changes in January precipitation. The lines in each box shows the median value from each set of measurements, the box shows the 25%-75% range, and the whiskers show the 90% interval (5th to 95th percentile). ~~The grid mean value of precipitation for each model, MME and reconstruction are also displayed at the right panel (c,d).~~

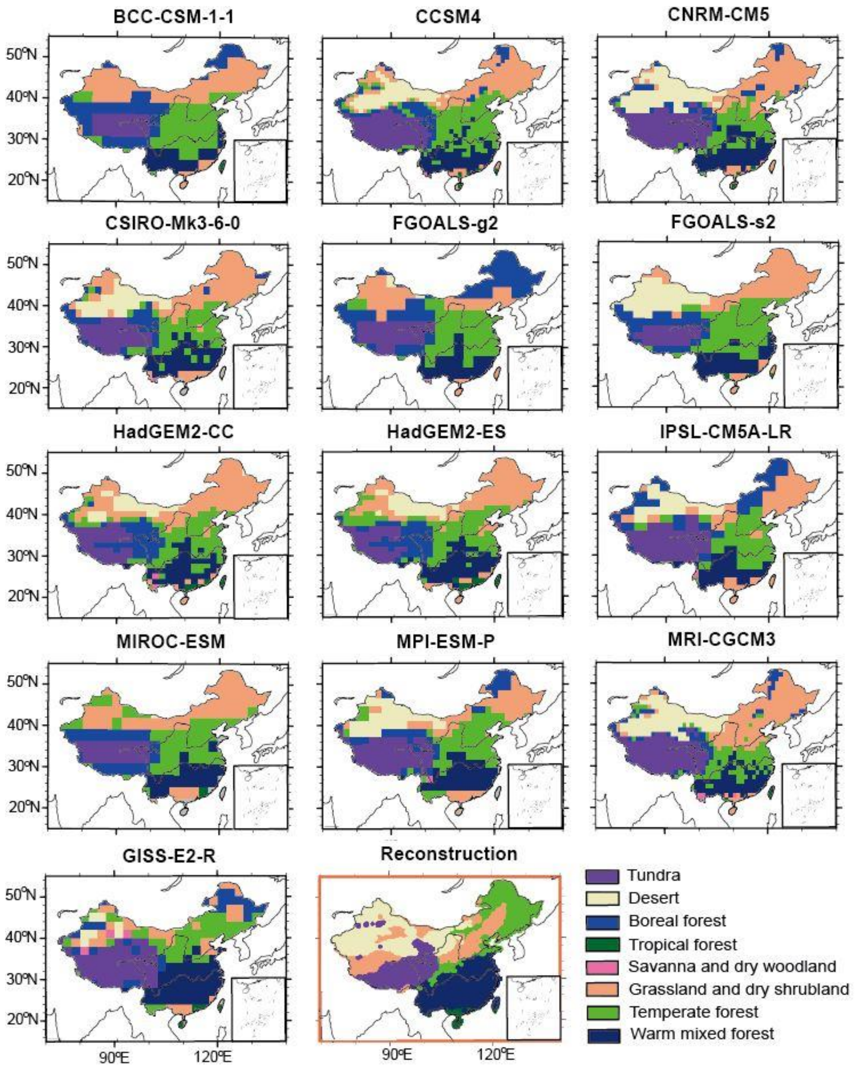

Figure 5. Comparison of interpolated megabiomes distribution (plot in red rectangle) with the simulated spatial pattern from BIOME4 for each model during mid-Holocene.

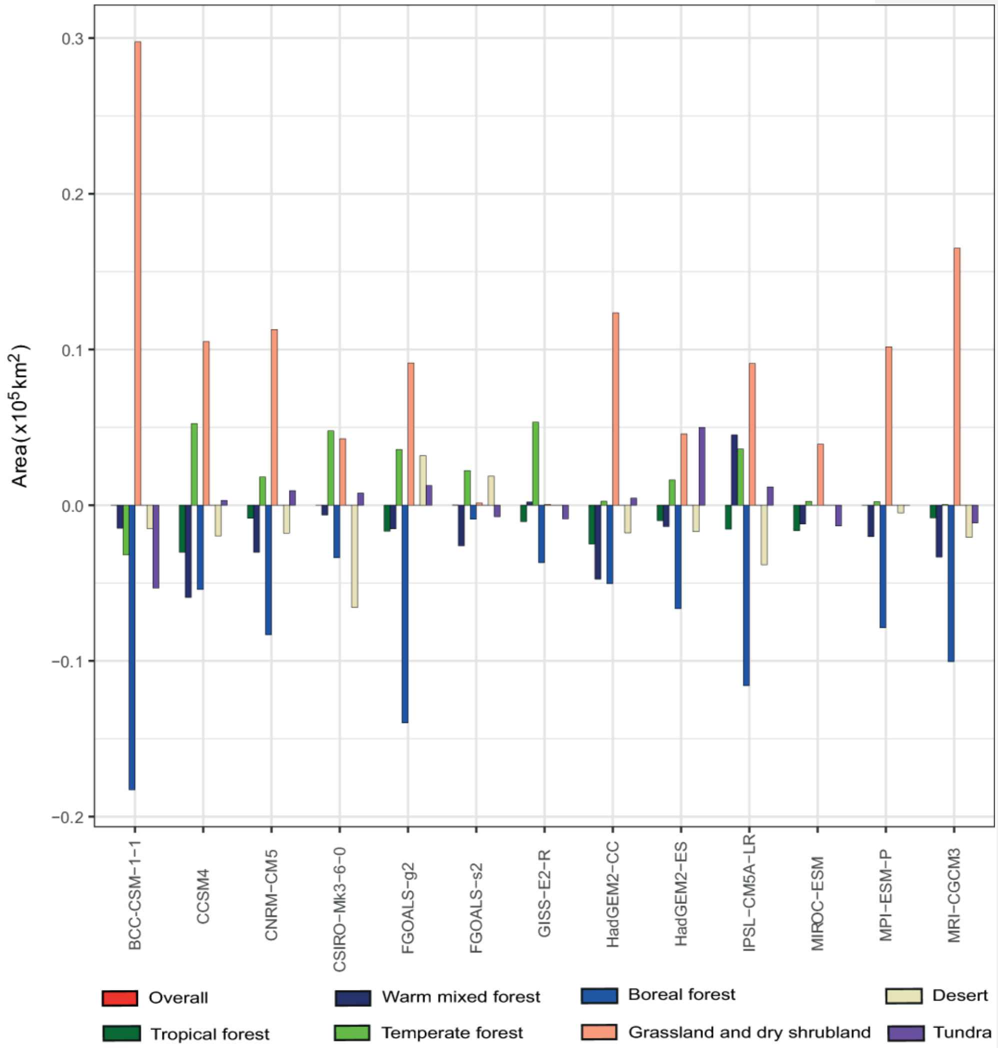

Figure 6. Changes in the extent of each megabiome as a consequence of simulated climate changes for each model, both expressed as change relative to the PI extent of same megabiome. ~~(TrFo: Tropical forest, WaMxFo: Warm mixed forest, TeFo: Temperate forest, BoFo: Boreal forest, Gra/Sh: Grassland and dry shrubland, Sav/Wo: Savanna and dry woodland, Desert: Desert, Tund: Tundra)~~

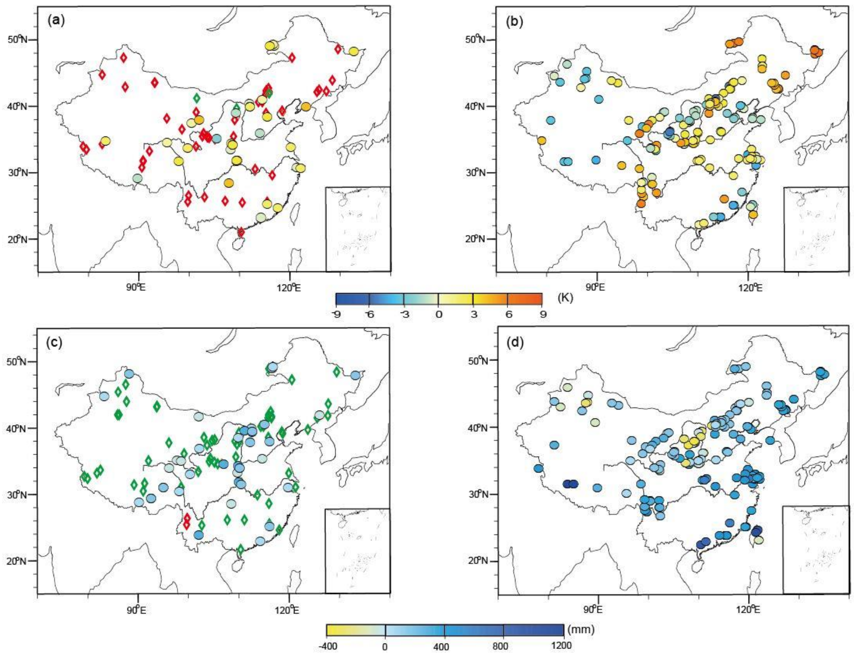

Figure 7: Comparison between the climate reconstruction and previous reconstruction over China. (a) Previous temperature results. Diamond is the qualitative reconstruction, red is the temperature increase and green is the temperature decrease; Circle is quantitative reconstruction; (b) Mean annual temperature reconstruction in this study; (c) Previous precipitation results, diamond is the qualitative reconstruction, red is the precipitation increase and green is the precipitation decrease; Circle is the quantitative reconstruction; (d) Mean annual precipitation reconstruction in this study.

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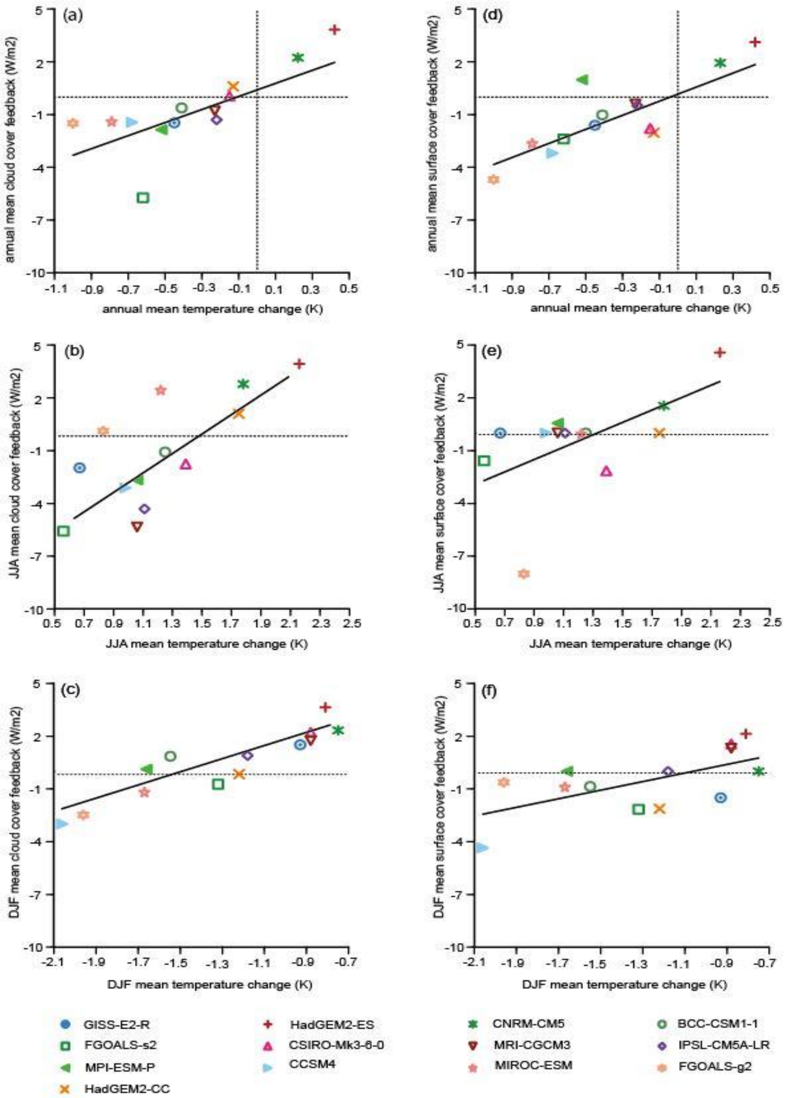

Figure 8. Scatter plots showing temperature, cloud cover feedback and surface albedo feedback changes during the MH. The values shown are the simulated 30-year mean anomaly (MH-PI) for the 13 models. **a**, annual mean temperature relative to the annual mean cloud cover feedback and d, annual surface albedo feedback. b, Summer (JJA) mean temperature relative to the summer mean cloud cover feedback and **e**, Summer surface albedo feedback. **c**, Winter (DJF) mean temperature relative to the summer mean cloud cover feedback and **f**, Winter surface albedo feedback. The horizontal and vertical lines in plots represent the value of 0.

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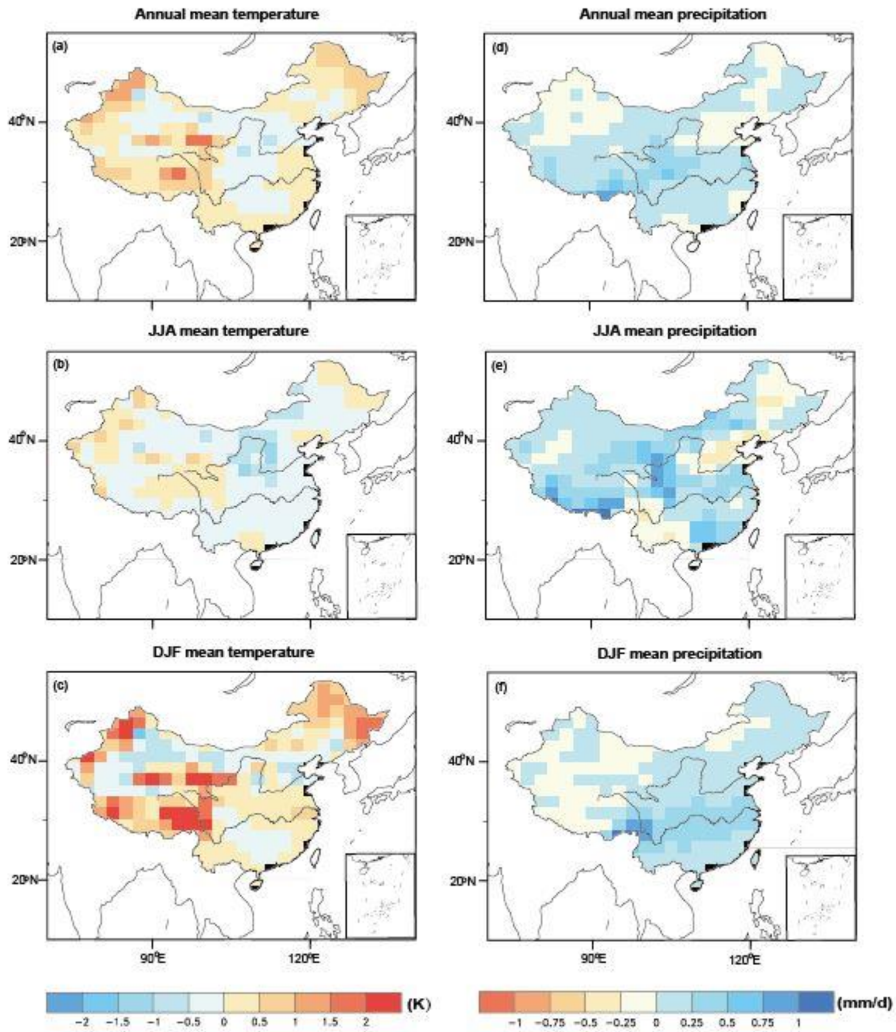

Figure 9. Climate anomalies between the two experiments (6 ka and 6 ka_VEG) conducted in CESM version 1.0.5. The anomalies (6 ka_VEG-6 ka) of temperature and precipitation at both annual and seasonal scale are presented, and all these climate variables are calculated as the last 50-year means from two simulations.

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