



Mid-Holocene net precipitation changes over China: model–data comparison



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ABSTRACT

Many efforts have been made to reconstruct the moisture conditions over China during the mid-Holocene, approximately 6000 calendar years ago. However, most of them have been performed at the single site level or local scale, and the nationwide distribution of the mid-Holocene precipitation and net precipitation (precipitation minus evaporation) changes from both proxy data and simulations remains unclear. Here we first selected 36 out of 51 climate models participating in the Paleoclimate Modeling Intercomparison Project (PMIP) for their demonstrable ability to simulate the baseline climate and for the availability of evaporation data. Our analysis of the ensemble mean results of the 36 models shows that the mid-Holocene annual precipitation, evaporation, and net precipitation were 3.0%, 0.9%, and 6.9% more than the baseline period, respectively, and seasonally all three variables decreased in boreal winter and spring but increased in boreal summer and autumn on the national scale. For that period, both the pattern and magnitude of the above changes differed between the models and the sub-regions, and the interactive ocean effect had little impact overall on the country. Compared with the wetter-than-present climates derived from the records at 64 out of 69 sites across China, the models agreed qualitatively with the multi-proxy data in most parts of China, except Xinjiang and the areas between the middle and lower reaches of the Yangtze and Yellow River valleys, where drier-than-baseline climates were obtained from the 36 models.

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1. Introduction

Short instrumental records hamper our knowledge of climate change on decadal and longer timescales. Insights into the facts and mechanisms of past climate and environmental changes are thus essential for better understanding present and future climates. The mid-Holocene is a well-known period approximately 6000 years before present when the climate and environment differed from the present day, and it provides an excellent opportunity to examine how the climate system responds to changes in the latitudinal and seasonal distribution of insolation due to orbital forcing. In recent decades, considerable effort has been dedicated to

the synthesis of proxy data and simulations as well as model–data comparisons for the mid-Holocene worldwide (e.g., Joussaume and Taylor, 1995; Guiot et al., 1999; Tarasov et al., 1999; Masson-Delmotte et al., 2006; Peyron et al., 2006; Braconnot et al., 2007; Zhang et al., 2010). It has been found that climate models are able to reproduce many of the robust qualitative large-scale features of reconstructed climate change, consistent with the understanding of orbital forcing (Jansen et al., 2007). On the regional scale, however, simulations have been found to be opposite the reconstructions of annual and winter (December–January–February) temperature changes in China (Jiang et al., 2012). An unresolved question at this stage is how the mid-Holocene moisture conditions are derived from both climate models and single-site-based proxy data over the country.

Using individual climate models of different complexities, several numerical experiments have been undertaken to address the mid-Holocene climate over China (Wang, 1999, 2000, 2002; Chen et al., 2002; Wei and Wang, 2004; Zheng et al., 2004; Zheng

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Table 1

Basic information on the general circulation models used in the present study.

Model ID		Project	Atmospheric resolution	Length of run analyzed (year)	Baseline period
01	CCC2.0	PMIP1 (AGCM)	T32L10	10	Modern
02	CCM3	PMIP1 (AGCM)	T42L18	8	Modern
03	CCSR1	PMIP1 (AGCM)	T21L20	10	Modern
04	CNRM-2	PMIP1 (AGCM)	T31L19	10	Modern
05	CSIRO	PMIP1 (AGCM)	R21L9	15	Modern
06	ECHAM3	PMIP1 (AGCM)	T42L19	10	Modern
07	GEN2	PMIP1 (AGCM)	T31L18	10	Modern
08	GFDL	PMIP1 (AGCM)	R30L20	25	Modern
09	GISS-IIP	PMIP1 (AGCM)	72 × 46, L9	10	Modern
10	LMCELMD4	PMIP1 (AGCM)	48 × 36, L11	15	Modern
11	LMCELMD5	PMIP1 (AGCM)	64 × 50, L11	15	Modern
12	MRI2	PMIP1 (AGCM)	72 × 46, L15	10	Modern
13	UGAMP	PMIP1 (AGCM)	T42L19	20	Modern
14	UIUC11	PMIP1 (AGCM)	72 × 46, L14	10	Modern
15	UKMO	PMIP1 (AGCM)	96 × 73, L19	50	Modern
16	YONU	PMIP1 (AGCM)	72 × 46, L7	10	Modern
17	CCSM3.0	PMIP2 (AOGCM)	T42L18	50	Pre-industrial
18	CSIRO-Mk3L-1.0	PMIP2 (AOGCM)	R21L18	1000	Pre-industrial
19	CSIRO-Mk3L-1.1	PMIP2 (AOGCM)	R21L18	1000	Pre-industrial
20	ECBILTCLIOVECODE	PMIP2 (AOGCM)	T21L3	100	Pre-industrial
21	ECHAME5-MPIOM1	PMIP2 (AOGCM)	T31L20	100	Pre-industrial
22	ECHAM53-MPIOM127-LPJ	PMIP2 (AOGCM)	T31L19	100	Pre-industrial
23	FGOALS-1.0 g	PMIP2 (AOGCM)	R42L9	100	Pre-industrial
24	FOAM	PMIP2 (AOGCM)	R15L18	100	Pre-industrial
25	GISSmodelE	PMIP2 (AOGCM)	72 × 46, L17	50	Pre-industrial
26	IPSL-CM4-V1-MR	PMIP2 (AOGCM)	96 × 72, L19	100	Pre-industrial
27	MIROC3.2	PMIP2 (AOGCM)	T42L20	100	Pre-industrial
28	MRI-CGCM2.3.4fa	PMIP2 (AOGCM)	T42L30	150	Pre-industrial
29	MRI-CGCM2.3.4nfa	PMIP2 (AOGCM)	T42L30	150	Pre-industrial
30	UBRIS-HadCM3M2	PMIP2 (AOGCM)	96 × 73, L19	100	Pre-industrial
31	ECBILTCLIOVECODE-veg	PMIP2 (AOVGCM)	T21L3	100	Pre-industrial
32	ECHAM53-MPIOM127-LPJ-veg	PMIP2 (AOVGCM)	T31L19	100	Pre-industrial
33	FOAM-veg	PMIP2 (AOVGCM)	R15L18	100	Pre-industrial
34	MRI-CGCM2.3.4fa-veg	PMIP2 (AOVGCM)	T42L30	100	Pre-industrial
35	MRI-CGCM2.3.4nfa-veg	PMIP2 (AOVGCM)	T42L30	100	Pre-industrial
36	UBRIS-HadCM3M2-veg	PMIP2 (AOVGCM)	96 × 73, L19	100	Pre-industrial
37	BCC-CSM1.1	PMIP3 (AOVGCM)	T42L26	100	Pre-industrial
38	CCSM4	PMIP3 (AOGCM)	288 × 192, L26	301	Pre-industrial
39	CNRM-CM5	PMIP3 (AOGCM)	256 × 128, L31	200	Pre-industrial
40	CSIRO-Mk3-6-0	PMIP3 (AOGCM)	192 × 96, L18	100	Pre-industrial
41	CSIRO-Mk3L-1-2	PMIP3 (AOGCM)	64 × 56, L18	500	Pre-industrial
42	EC-EARTH-2-2	PMIP3 (AOGCM)	320 × 160, L62	40	Pre-industrial
43	FGOALS-g2	PMIP3 (AOVGCM)	128 × 60, L26	100	Pre-industrial
44	FGOALS-s2	PMIP3 (AOVGCM)	128 × 108, L26	100	Pre-industrial
45	GISS-E2-R	PMIP3 (AOGCM)	144 × 90, L40	100	Pre-industrial
46	HadGEM2-CC	PMIP3 (AOVGCM)	192 × 145, L60	35	Pre-industrial
47	HadGEM2-ES	PMIP3 (AOVGCM)	192 × 145, L38	102	Pre-industrial
48	IPSL-CM5A-LR	PMIP3 (AOVGCM)	96 × 95, L39	500	Pre-industrial
49	MIROC-ESM	PMIP3 (AOVGCM)	T42L80	100	Pre-industrial
50	MPI-ESM-P	PMIP3 (AOGCM)	T63L47	100	Pre-industrial
51	MRI-CGCM3	PMIP3 (AOGCM)	320 × 160, L48	100	Pre-industrial

and Yu, 2009; Zhou and Zhao, 2010; Liu et al., 2010a). They have well explained the increase of surface temperature and the intensification of monsoon, as suggested by proxy data, over China during the mid-Holocene summer (June–July–August). At the same time, these experiments have shown a large inter-model spread in the magnitude and sign of the mid-Holocene precipitation changes. Among these simulations, for example, the mid-Holocene summer precipitation increased consistently over eastern China (Wang, 1999), while it increased in southern and northeastern China but decreased in central and northern China (Zheng and Yu, 2009). For that period, the annual precipitation increased over western China, northern China, and most parts of southern China, but decreased in the middle and lower reaches of the Yangtze River valley and coastal southern China (Zheng et al., 2004), while large orbital-induced variations of annual

precipitation occurred only in northeastern China (Liu et al., 2010a). Such model-dependent uncertainties make it of particular interest to integrate the outputs of multiple climate models to analyze the similarities and differences between the model results of precipitation. Next, dynamic ocean and vegetation are two key components of the climate system, and their effects have been identified as important for the mid-Holocene climate (e.g., Kutzbach et al., 1996; Ganopolski et al., 1998; Zhao et al., 2005; Braconnot et al., 2007; Jansen et al., 2007; Dallmeyer et al., 2010). However, these components have not or have only been partly taken into account in the aforementioned experiments with atmospheric general circulation models (AGCMs) (Wang, 1999, 2000, 2002; Chen et al., 2002), regional climate models nested within AGCMs (Zheng et al., 2004; Liu et al., 2010a), an asynchronously coupled atmosphere–ocean general circulation model (Wei and Wang, 2004), and fully coupled

atmosphere–ocean general circulation models (AOGCMs) (Zheng and Yu, 2009; Zhou and Zhao, 2010). It remains unclear how annual and seasonal precipitation and evaporation over China respond to the mid-Holocene orbital forcing and slight changes in atmospheric concentrations of greenhouse gases in the simulations of current AOGCMs and fully coupled atmosphere–ocean–vegetation general circulation models (AOVGCMs). Hereafter AOGCMs plus AOVGCMs are referred to as coupled general circulation models (CGCMs).

Based on a great deal of reconstruction work, it has been proposed that the regional climate of China underwent generally wetter conditions during the mid-Holocene (see Section 4 of this study). Those proxy data form a solid foundation for qualitative model–data comparisons of the moisture conditions over the country. The question then arises as to the extent to which reconstructions are compatible with available simulations over China. Note that unlike the previous few model–data comparisons based on individual model results and limited records (Wang, 1999; Chen et al., 2002; Zheng et al., 2004; Liu et al., 2010a), comparisons between multiple climate models and multiple proxy data are more helpful for examining the nature and cause of the mid-Holocene climate change. Previously, the increase of the mid-Holocene summer precipitation was obtained by 12 CGCMs within the Paleoclimate Modeling Intercomparison Project (PMIP) phase 2 (PMIP2), and it was found to generally agree with annually resolved records at 24 sites over China (Wang et al., 2010a). However, a fair model–data comparison should be annual vs. annual rather than summer vs. annual, while reconstructed moisture conditions should be compared directly with changes in net precipitation (precipitation minus evaporation) rather than indirectly with precipitation, as evaporation is a key variable for moisture. In addition, in the work of Wang et al. (2010a) there was quite a limited number and an uneven geographical distribution of proxy data sites over China; only part of the PMIP2 CGCMs were used; and a previous generation of climate models that participated in the PMIP phase 1 (PMIP1) were not included, so it is impossible to evaluate the role of an interactive ocean through the comparison of different types of PMIP simulations.

Taken together, an analysis is made in this paper of the mid-Holocene net precipitation changes over China from the perspective of multiple and reliable climate models and proxy data. The key questions for the mid-Holocene are (1) how annual and seasonal precipitation, evaporation, and net precipitation changed over China, (2) whether there was a detectable interactive ocean effect on moisture conditions over the country, and (3) the extent to which simulations are compatible with proxy data.

2. Data

2.1. Model, reanalysis, and proxy data

This study was based on all available simulations for the mid-Holocene climate under the framework of the PMIP at the moment, including experiments using 16 AGCMs in the PMIP1, 20 CGCMs in the PMIP2, and 15 CGCMs in the PMIP phase 3 (PMIP3) within the framework of the Coupled Model Intercomparison Project phase 5 (CMIP5). For the mid-Holocene experiment, the core forcing lies in orbitally induced changes of $\sim 5\%$ in the seasonal distribution of the incoming solar radiation at the top of the atmosphere in the Northern and Southern Hemispheres (Berger, 1978). In addition, the atmospheric CO_2 concentration was set to 280 ppm for the mid-Holocene instead of 345 ppm in 1985 for the modern (baseline) period in the PMIP1. The atmospheric CO_2 concentration was held constant at 280 ppm, and the atmospheric CH_4 concentration was set to 760 ppb for the pre-industrial

(baseline) period and 650 ppb for the mid-Holocene in the PMIP2. In the PMIP3, the atmospheric concentrations of CO_2 , CH_4 , and N_2O varied from the pre-industrial levels of 284 ppm, 791 ppb, and 275 ppb to 280 ppm, 650 ppb, and 270 ppb during the mid-Holocene, respectively. For both the baseline and mid-Holocene experiments, sea surface temperatures were fixed at the present values in AGCMs but were simulated by oceanic general circulation models in CGCMs, and the vegetation was simulated by equilibrium or dynamic global vegetation models in AOVGCMs but was fixed at the present vegetation in the other models. The outputs of 51 climate models were provided by international modeling groups and were archived in the PMIP and/or CMIP5 database from which we downloaded the data of concern. Basic information on the models and data is provided in Table 1. More details were given by Joussaume and Taylor (1995) and Braconnot et al. (2007) and are available online at <http://pmip.lscce.ipsl.fr/> and <http://cmip-pcmdi.llnl.gov/cmip5/>.

The reanalysis data used to assess the ability of the models to simulate the baseline annual precipitation climatology over China were the long-term mean precipitation taken from the CPC Merged Analysis of Precipitation (CMAP) for the period 1979–2000 (Xie and Arkin, 1997). These data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at <http://www.esrl.noaa.gov/psd>. Considering that atmospheric horizontal resolution differs from model to model, all model and reanalysis data were aggregated to a relatively mid-range resolution of 96×48 (longitude $\times$ latitude, an equivalent grid spacing of roughly $3.75^\circ \times 3.75^\circ$). The ensemble mean of multiple climate models was obtained with the same weights across the models of analysis.

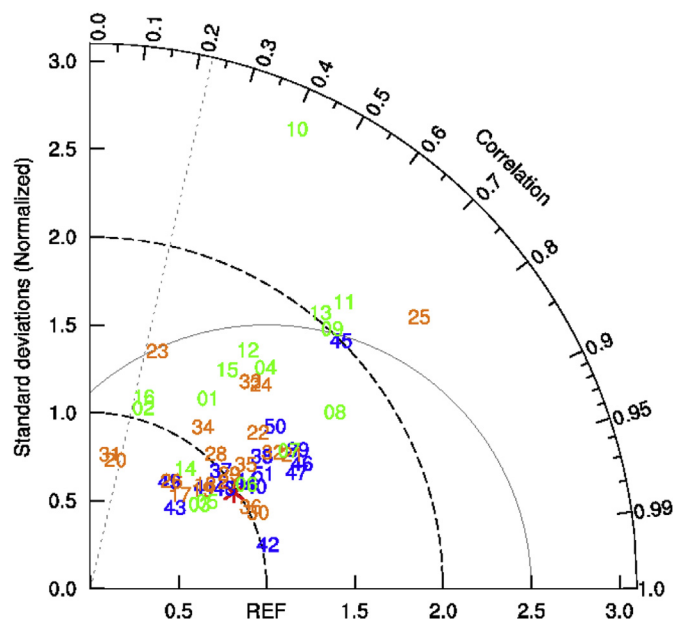


Fig. 1. Taylor diagram (Taylor, 2001) for displaying normalized pattern statistics of climatological annual precipitation over China between the 51 PMIP models for the baseline period and the CMAP data for the period 1979–2000 (Xie and Arkin, 1997). Each number represents a Model ID (See Table 1); green, orange, and blue represent the PMIP1, PMIP2, and PMIP3 models, respectively; red star represents the ensemble mean of the 36 models chosen for analysis; and the CMAP is considered as the reference (REF). The standard deviation and CRMSD are normalized by the CMAP standard deviation. The radial distance from the origin is the normalized standard deviation of a model; the SCC between a model and the reference is given by the azimuthal position of the model, with oblique dotted line showing the 95% confidence level; and the normalized CRMSD between a model and the reference is their distance apart. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

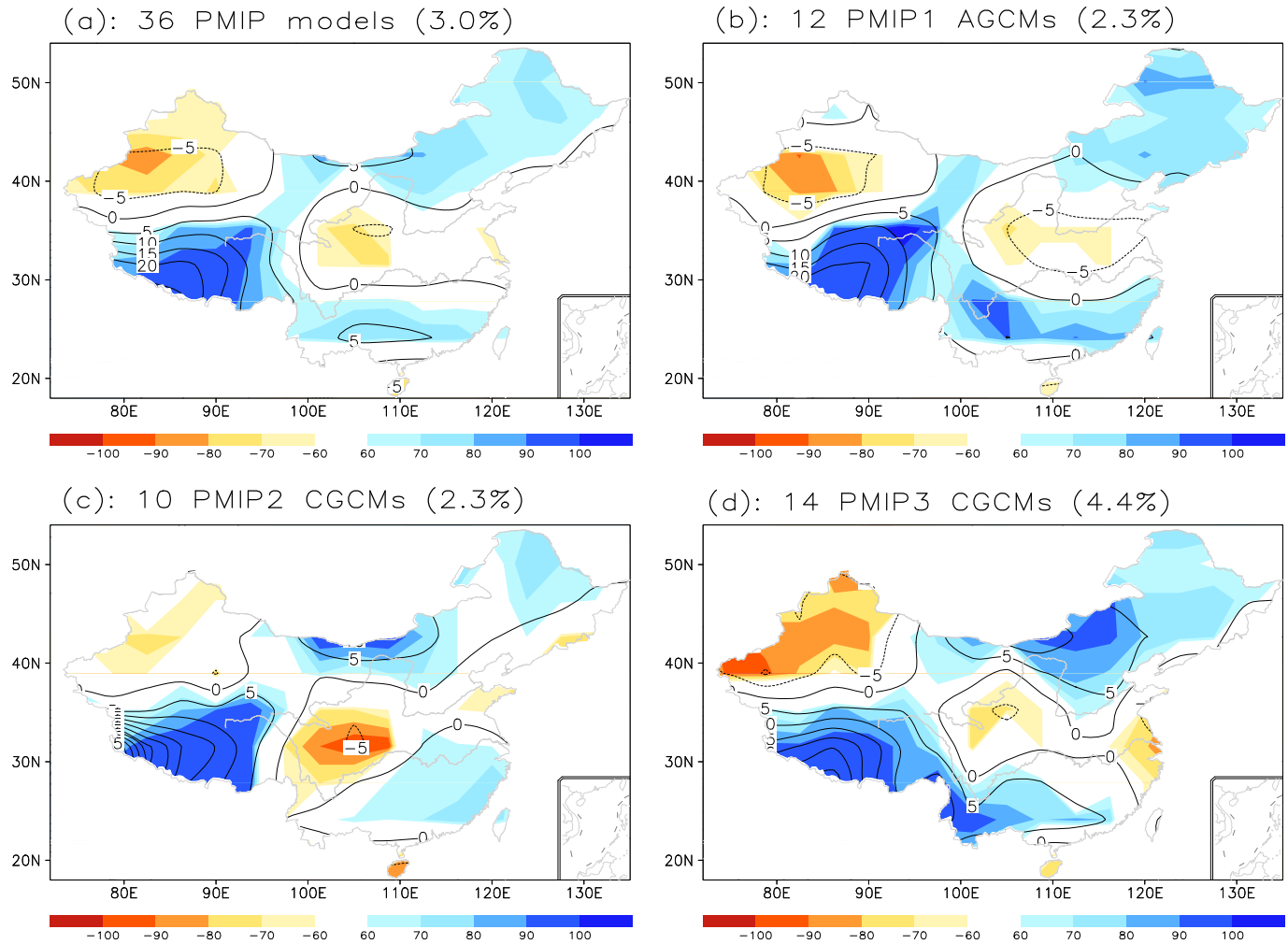


Fig. 2. Percentage changes in annual precipitation (contour, units: %) during the mid-Holocene, with reference to the baseline period, for the ensemble mean of the (a) 36 PMIP models, (b) 12 PMIP1 AGCMs, (c) 10 PMIP2 CGCMs, and (d) 14 PMIP3 CGCMs. In each panel, the consistency index of the models (units: %) in simulating the direction of the changes (namely, the percentage of the number of models agreeing on the sign of the change according to the algorithm of Wang (2005), the same below) in annual precipitation is shown in shading, and regionally averaged change in China is given in parentheses.

The proxy data used to compare the model results were reconstructions of the mid-Holocene precipitation and/or moisture changes over China. These data were mostly expressed in a qualitative manner and were composed of records of ice cores, lake cores, palaeosols, peat, pollen, sediments, and stalagmites at 74 sites across the country. All these data and the corresponding references are detailed in the model–data comparison in Section 4.

2.2. Evaluation of 51 PMIP climate models

Whether climate models can reliably reproduce the geographical distribution, magnitude, and spatial variability of the baseline period annual precipitation climatology over China determines the confidence of their results for the mid-Holocene. Therefore, based on 77 grid points across the Chinese mainland, spatial correlation coefficients (SCCs) between the CMAP data and baseline simulations were calculated model by model, as was the standard deviation and centered root mean square difference (CRMSD) of each baseline simulation with respect to the CMAP data. The SCCs were used to quantify the similarity between

simulated and observed spatial patterns, and the normalized standard deviation and CRMSD by the CMAP standard deviation were used to measure the spatial variability and internal model error of the models, respectively. The Taylor diagram in Fig. 1 shows that the SCCs ranged from 0.13 to 0.97; the normalized standard deviations ranged from 0.67 to 2.86; and the normalized CRMSDs ranged from 0.26 to 2.62. These values indicate that the abilities of the models differed from one another, and some models failed to simulate the basic features of the observed annual precipitation climatology for the baseline period. Accordingly, four thresholds were arbitrarily set to identify reliable climate models. First, the SCC had to be positive and statistically significant at the 95% confidence level, namely, larger than 0.23; second, the normalized standard deviation had to be larger than 0.5 and less than 2.0; third, the normalized CRMSD had to be less than 1.5; and fourth, evaporation data had to be available, as they are necessary for calculating net precipitation. In this manner, 12, 10, and 14 models were finally chosen from the 16 PMIP1, 20 PMIP2, and 15 PMIP3 models for analysis based on the results presented in Fig. 1, respectively. Note that the SCCs were 0.77, 0.72 and 0.89, while the normalized CRMSDs were

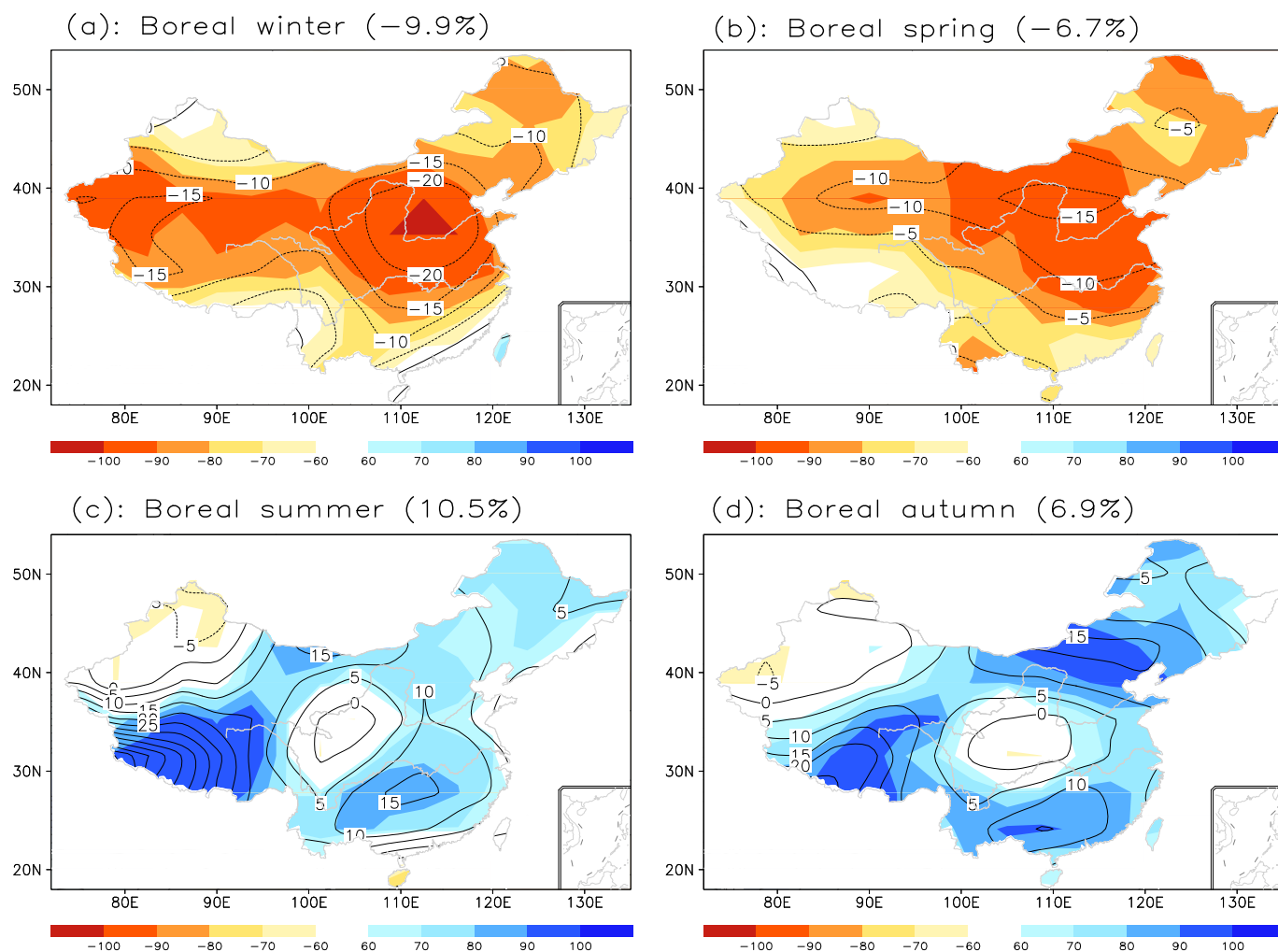


Fig. 4. Percentage changes in seasonal precipitation (contour, units: %) during the mid-Holocene, with reference to the baseline period, for the ensemble mean of the 36 PMIP models. In each panel, the consistency index of the models (units: %) in simulating the direction of the changes in seasonal precipitation is shown in shading, and regionally averaged change in China is given in parentheses.

precipitation decreased by 0–25% over China and by more than 10% over the region of approximately 30°–45°N, particularly in the middle and lower reaches of the Yangtze and Yellow River valleys (Fig. 4a). This large-scale precipitation decrease in eastern China was related to the strengthening of the mid-Holocene East Asian winter monsoon. It can be observed in Fig. 5a and c that anomalous northerly winds prevailed in eastern China due to orbitally induced increases in land–sea thermal contrasts and sea level pressure gradients between continental Asia and the western North Pacific. Accordingly, more cold and dry air from the high latitudes entered East Asia, suppressing the warm and moist air from the low latitudes. In turn, precipitation decreased in eastern China. In fact, this reverse relationship between the East Asian winter monsoon strength and precipitation in eastern China has been reported for the modern period (e.g., Wang and Chen, 2010). In spring (March–April–May), precipitation decreased in 35 of the 36 PMIP models (Fig. 3c), with an average of –6.9%, –6.4%, –6.8%, and –6.7% for the ensemble mean of PMIP1, PMIP2, PMIP3, and all PMIP models, respectively. In MME-PMIP, the geographical distribution of spring precipitation changes was generally similar

to the above winter pattern, but with an overall smaller magnitude (Fig. 4b).

In summer, the mid-Holocene precipitation increased in all 36 PMIP models, averaging 9.2%, 10.1%, 12.1%, and 10.5% in MME-PMIP1, MME-PMIP2, MME-PMIP3, and MME-PMIP, respectively (Fig. 3d). Based on MME-PMIP, precipitation slightly decreased in central and northern Xinjiang and the region of approximately 30°–38°N and 98°–108°E, but increased in the rest of the country, particularly in most parts of the Qinghai-Tibetan Plateau, where the increase was more than 15% and up to 50% on its southern margin (Fig. 4c). Note that because summer precipitation accounts for more than half the total annual precipitation over China [for example, 55% for the modern period 1960–2009 (Sui et al., 2013)], the spatial pattern of summer precipitation change was generally similar to the annual result (Fig. 2a) over the country, except in the middle and lower reaches of the Yangtze and Yellow River valleys, where, as mentioned before, winter and spring precipitation decreased by more than 10%. In eastern China, the precipitation increase was closely related to a strengthened monsoon circulation during the mid-Holocene summer. Based on the ensemble mean of 35 of the

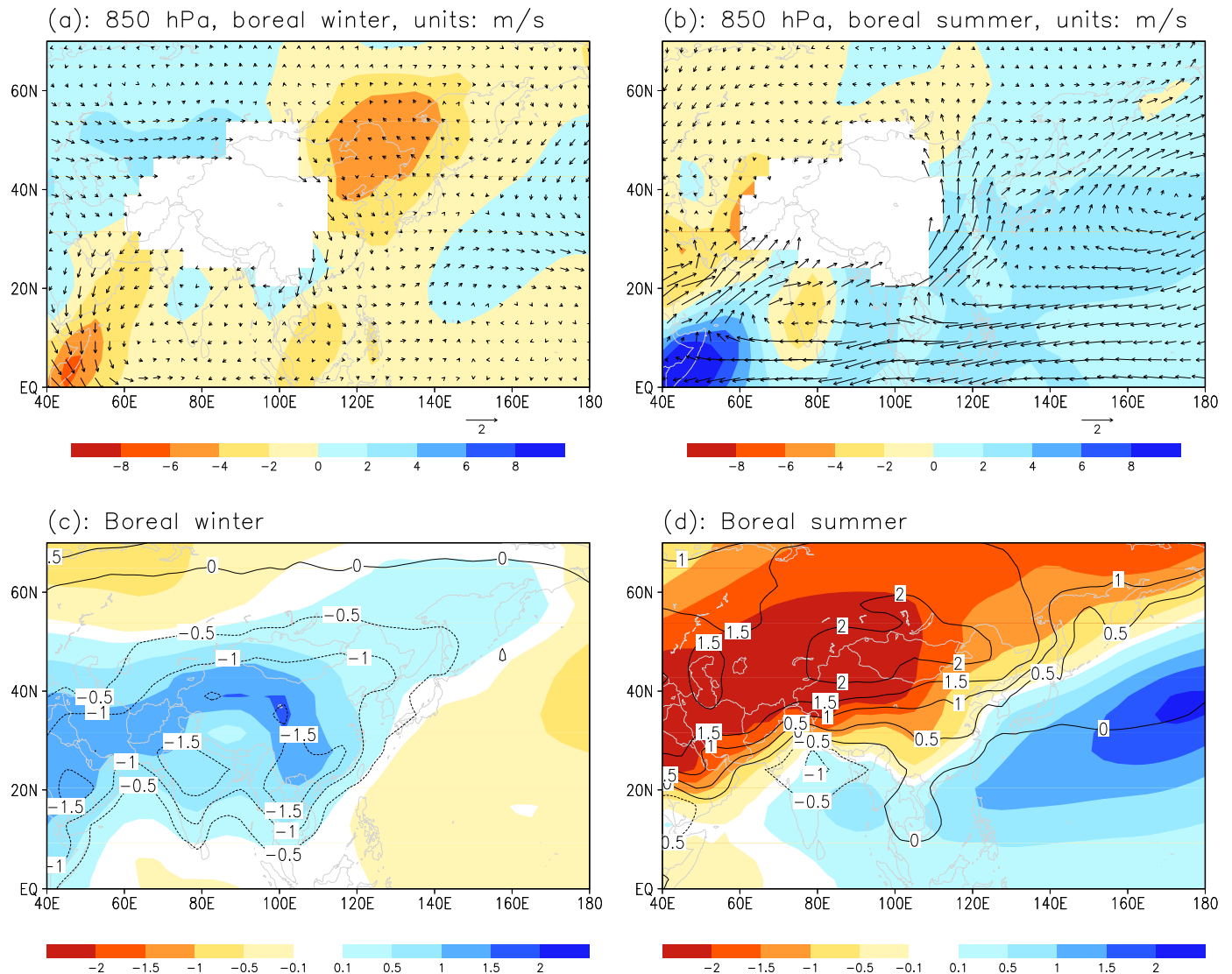


Fig. 5. Mid-Holocene–baseline anomalies of (a) winter and (b) summer winds, together with the baseline period meridional wind climatology (shading; northward wind speed is positive), for the ensemble mean of the 35 PMIP models (excluding EC-EARTH-2-2 for which wind data are not available), in which regions with an elevation above 1500 m are left blank. Also shown are the accompanying mid-Holocene–baseline anomalies of (c) winter and (d) summer surface air temperature (contour, units: K) and sea level pressure (shading, units: hPa).

36 PMIP models (excluding EC-EARTH-2-2 with wind data not available), anomalous southerly winds prevailed in the lower troposphere in East Asia during that period because of an enhanced land–sea thermal contrast and, hence, sea level pressure gradient between the East Asian continent and adjacent oceans as a result of orbital forcing (Fig. 5b and d). These changes are consistent with the results of the 28 PMIP models with a demonstrable ability to simulate the modern East Asian summer monsoon climatology (Jiang et al., 2013). In addition, for that period there was similar pattern and magnitude in large-scale summer precipitation changes in China between the results of MME-PMIP1 and MME-PMIP2 or MME-PMIP3, indicating little interactive ocean effect. This is generally in line with the multi-model result (Zhao and Harrison, 2012) but is in disagreement with the result of either positive (Wei and Wang, 2004) or negative (Liu et al., 2004; Marzin and Braconnot, 2009) effects obtained from individual models. In autumn (September–October–November), precipitation increased in 34 of the 36

PMIP models, with a nationwide average of 6.3%, 6.7%, 7.8%, and 6.9% for the ensemble mean of PMIP1, PMIP2, PMIP3, and all PMIP models, respectively (Fig. 3e). On the whole, the autumn precipitation changes in MME-PMIP were similar in distribution to the summer case, but with an overall smaller magnitude (Fig. 4d).

3.2. Evaporation

With reference to the baseline period, the mid-Holocene annual evaporation varied from –6% to 12% over China in MME-PMIP (Fig. 6a). The annual evaporation decreased in Xinjiang, south-western China and coastal northern China but increased in the rest of the country, displaying a similar pattern to the annual precipitation changes in northern and western China (Fig. 2a). Meanwhile, the model agreements were higher than 60% in most parts of China, except central and southeastern China. On the national scale, the MME-PMIP annual evaporation increased by an average of 0.9%. For

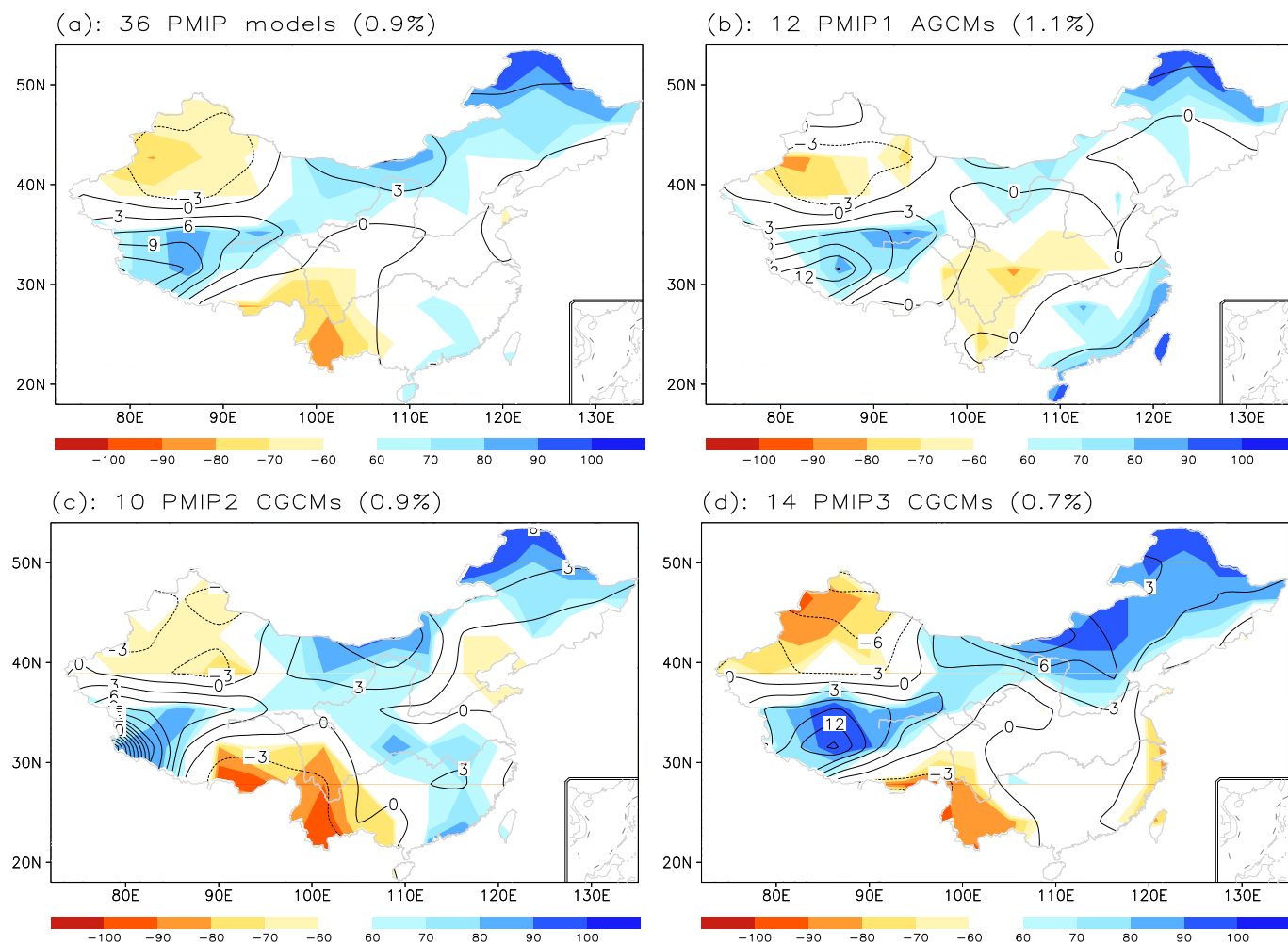


Fig. 6. Percentage changes in annual evaporation (contour, units: %) during the mid-Holocene, with reference to the baseline period, for the ensemble mean of the (a) 36 PMIP models, (b) 12 PMIP1 AGCMs, (c) 10 PMIP2 CGCMs, and (d) 14 PMIP3 CGCMs. In each panel, the consistency index of the models (units: %) in simulating the direction of the changes in annual evaporation is shown in shading, and regionally averaged change in China is given in parentheses.

individual models, the regionally averaged annual evaporation increased in 23 of the 36 PMIP models but decreased in the remaining 13 models (Fig. 7a). When viewed in terms of AGCMs and CGCMs, the annual evaporation increased by a similar magnitude for MME-PMIP1 (1.1%), MME-PMIP2 (0.9%), and MME-PMIP3 (0.7%). Moreover, the geographical distribution of large-scale annual evaporation change generally agreed among the three sets of experiments, although there were regional differences, such as larger and more consistent changes in Xinjiang, northern China, and the Qinghai-Tibetan Plateau in the PMIP3 models than in the PMIP1 and PMIP2 models (Fig. 6b–d). These results imply the interactive ocean effect on the mid-Holocene annual evaporation over China was limited as a whole.

On the seasonal scale, both the spatial pattern and magnitude of the mid-Holocene evaporation changes differed from the above annual results (Fig. 7b–e and 8). In winter, 31 of the 36 models reproduced less than baseline evaporation averaged over China during the mid-Holocene, with an average of -3.4% , -4.0% , -5.0% , and -4.1% for MME-PMIP1, MME-PMIP2, MME-PMIP3, and MME-PMIP, respectively (Fig. 7b). Based on MME-PMIP, winter evaporation decreased across almost the whole China, except coastal southeastern China, and by an overall larger magnitude in northern

China (Fig. 8a). Like winter, all but one model reproduced less spring evaporation for that period compared with the baseline period, with a nationwide average of -4.1% , -5.3% , -5.1% , and -4.7% for the ensemble mean of PMIP1, PMIP2, PMIP3, and all PMIP models, respectively (Fig. 7c). The MME-PMIP spring evaporation was consistently reduced over China, except coastal southeastern China and southernmost Tibet (Fig. 8b). For both winter and spring, the mid-Holocene evaporation reduction was at least partly due to decreased precipitation (Fig. 4a–b) and temperature (Fig. 5c), as heat, humidity, and air movement are key factors influencing evaporation. Previously, winter and spring temperatures had been revealed to significantly decrease over China in response to a negative radiative forcing due to changes in the earth's orbital parameters and atmospheric concentrations of greenhouse gases (Jiang et al., 2012).

In the mid-Holocene summer, all but one model reproduced more evaporation averaged over China compared with the baseline period (Fig. 7d). Summer evaporation increased by 5.9% , 5.3% , 4.8% , and 5.4% for the ensemble mean of PMIP1, PMIP2, PMIP3, and all PMIP models, respectively. According to MME-PMIP, summer evaporation increased in almost the whole China, except in the east coastal region, southernmost Tibet, and central Xinjiang (Fig. 8c).

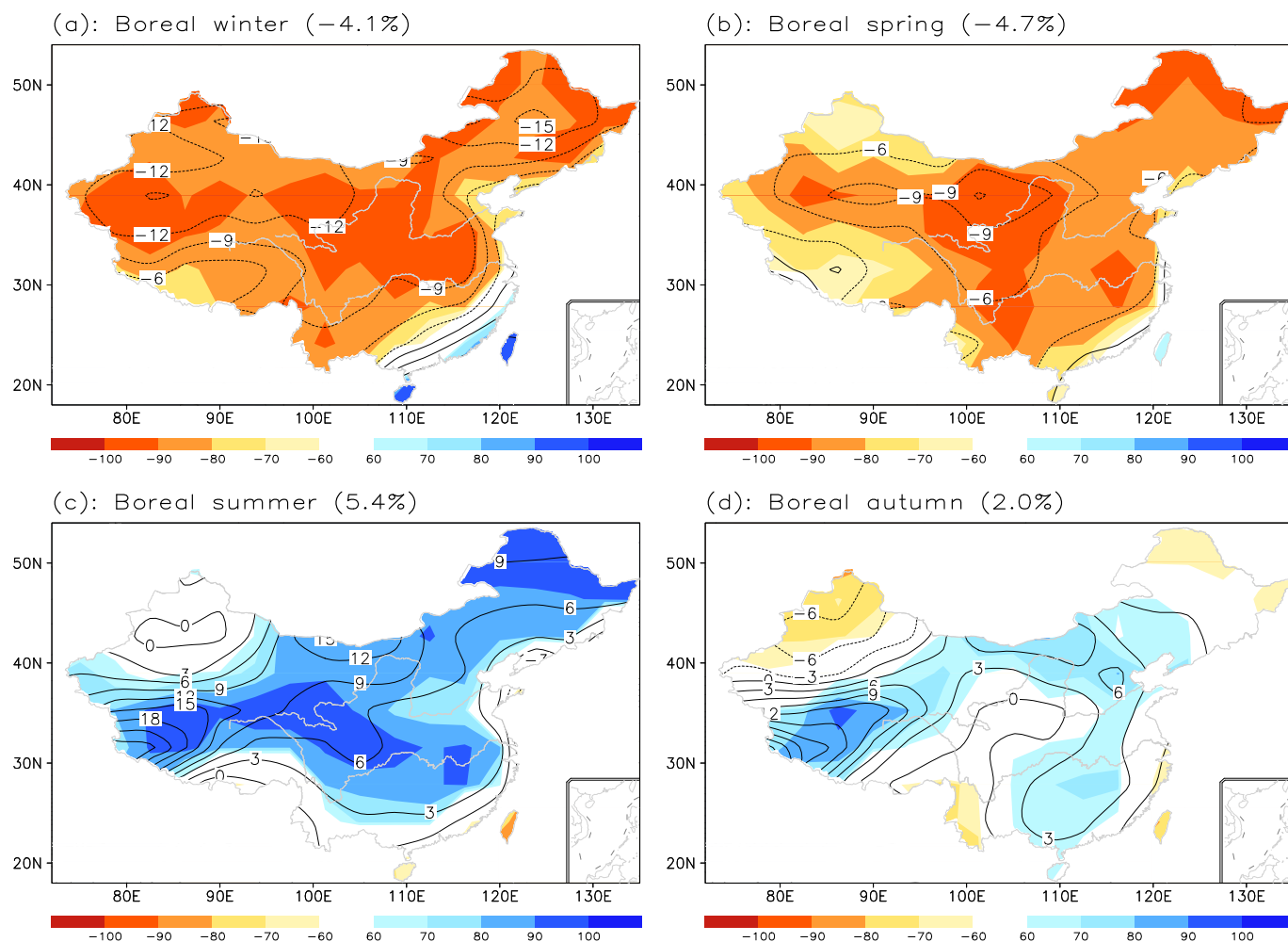


Fig. 8. Percentage changes in seasonal evaporation (contour, units: %) during the mid-Holocene, with reference to the baseline period, for the ensemble mean of the 36 PMIP models. In each panel, the consistency index of the models (units: %) in simulating the direction of the changes in seasonal evaporation is shown in shading, and regionally averaged change in China is given in parentheses.

decreased in most parts of the country, while the opposite held true for summer and autumn on the large scale.

4. Model–data comparison

Given that most proxy data are analyzed and expressed at individual sites and that there has not been a comprehensive overview of available reconstruction records over the whole country in the literature, we collected proxy data site by site. Afterward, two preconditions were arbitrarily set to choose relatively reliable records of the mid-Holocene climate. First, the records had to be published in peer-reviewed journals, which guaranteed the corresponding proxy data and analysis method having been critically reviewed and accepted by the experts in the field of reconstruction; and second, the records had to draw a clear conclusion about the mid-Holocene precipitation and/or moisture conditions over China. In this way, the records of ice cores, lake cores, palaeosols, peat, pollen, sediments, and stalagmites at 74 sites were finally chosen for model–data comparison. For details and references of the records, please refer to Table 2.

There are 13 records of lake cores, peat, pollen, sediments, and stalagmite for precipitation over China (Table 2), all of which

indicate that the mid-Holocene precipitation was more than the present level (Fig. 12a). This result is consistent with the proxy data published before the beginning of the 1990s, in which precipitation was estimated to be tens to hundreds of millimeters more than at present in northern China and Tibet, leading to high lake levels, the freshening of inland lakes, the development of large lakes and swamps in North and Northeast China, and the appearance of multi-layered palaeosols in the eolian sand and loess areas (Shi et al., 1993). On the one hand, the MME-PMIP results of annual precipitation (Fig. 2a) agree qualitatively with the records of the lake core, pollen, and sediment at Hulun lake (Wen et al., 2010), the pollen and sediment at Tongjiang (Yang and Wang, 2003), the pollen at Bayanchagan lake (Guiot et al., 2008; Jiang et al., 2010), the pollen and sediment at Diaojiao lake (Shi and Song, 2003), the pollen and lake core at Daihai lake (Xiao et al., 2004; Xu et al., 2010), the pollen at Baiyangdian lake (Xu et al., 1988), the pollen and lake core at Qinghai lake (Kong et al., 1990), the lake core and pollen at Ren Co lake and Hidden lake (Tang et al., 2000), and the peat and pollen at Dahu (Zhou et al., 2004). Quantitatively, however, the models underestimated the reconstructed magnitude of the increase at sites in Northeast and North China, where annual precipitation was

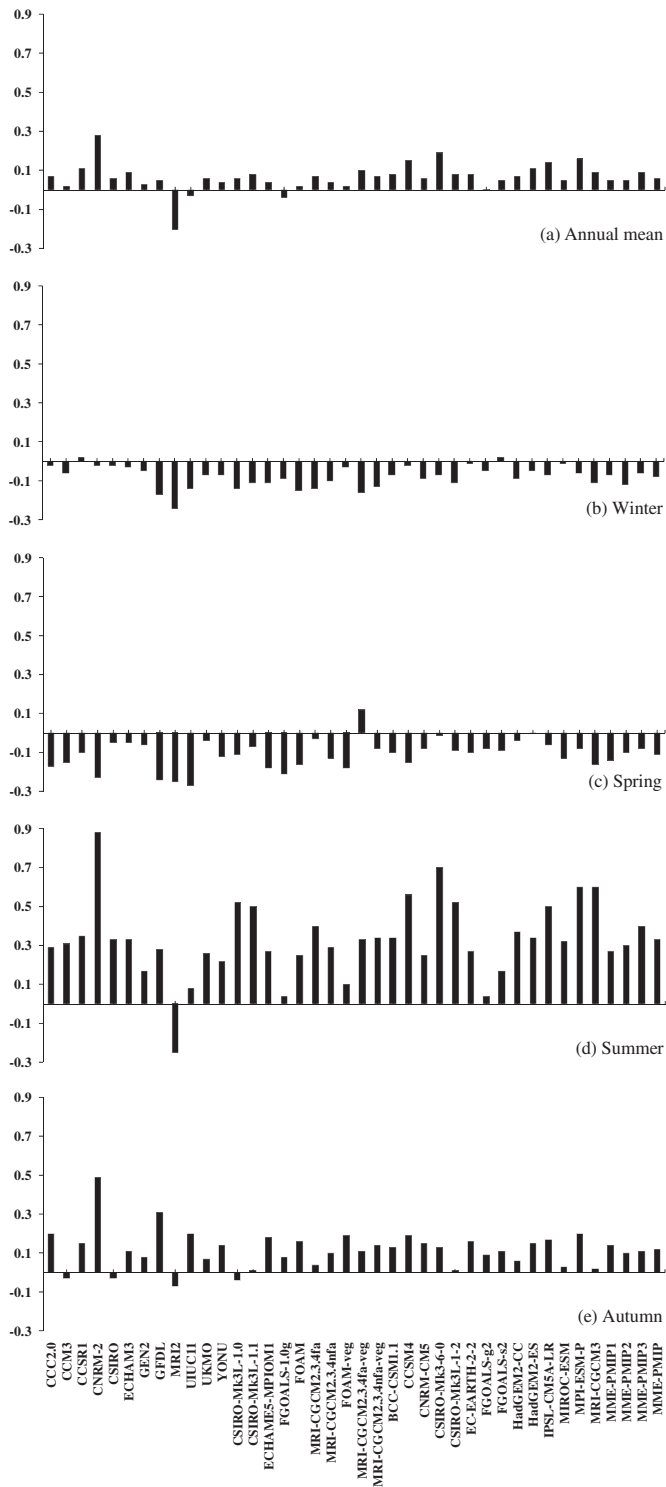


Fig. 9. Changes in regionally averaged annual and seasonal net precipitation (units: mm/day) over China during the mid-Holocene with respect to the baseline period.

estimated to increase by approximately 50 mm at Hulun lake, approximately 150–200 mm at Tongjiang, approximately 30–60% at Bayanchagan lake, approximately 80–200 mm at Diaojiao lake, approximately 40 mm at Daihai lake, and approximately 200 mm at Baiyangdian lake (Table 2). On the other hand, model–data disagreements occurred at Aibi lake (Wu et al., 1996), Heshang Cave (Hu et al., 2008), Mianyang (Yang et al., 1998), and Xinjiang (Shi et al., 1993), where the lesser precipitation simulated by MME-PMIP (Fig. 2a) conflicts with the greater precipitation suggested by the proxy data (Table 2 and Fig. 12a). Note that compared with the present day, the mid-Holocene annual precipitation was also reconstructed to be higher across most parts of China using pollen and/or plant macrofossil data (Bartlein et al., 2011), while it was reconstructed to be generally higher in southern China south of approximately 35°N and Northeast China, but lower or similar to today in Northwest and North China, by applying an inverse modeling technique to pollen data (Guiot et al., 2008), implying a degree of uncertainty in precipitation reconstruction for the latter two regions.

Unlike the extremely sparse distribution of the precipitation reconstructions, most of the collected proxy data provide information of the mid-Holocene moisture conditions. There are records of ice cores, lake cores, palaeosols, peat, pollen, sediments, and stalagmites at 69 sites across China (Table 2). As shown in Fig. 12b, 64 of the 69 records indicate that the mid-Holocene climate was wetter than the present level over the country. On the large scale, a qualitative comparison clearly shows that the aforementioned drier climates derived from the MME-PMIP annual net precipitation changes (Fig. 10a) are of opposite sign to the wetter conditions suggested by the proxy data in Xinjiang and the areas between the middle and lower reaches of the Yangtze and Yellow River valleys. Meanwhile, model–data agreements are registered in the rest of the country, except northern Northeast China where proxy data are not yet available. It should be stressed that although a quality control of the models is performed in Section 2.2, the 36 models chosen for analysis still cannot perfectly reproduce the precipitation climatology over China for the baseline period; and the models differ from one another in the mid-Holocene annual net precipitation changes on the national and regional scales (see Section 3.3), although the model agreements are more than 60% in most parts of China, such as North and South China, the areas between the middle reaches of the Yangtze and Yellow River valleys, Tibet, and southern China (Fig. 10a). Considering there is a large variability in topography and regional climate over East Asia, the smoothed representation of topography is unrealistic in the current coarse-resolution models and hence hampers their accuracy over China (Jiang et al., 2005; Gao et al., 2006); and also there are processes operating in the real world that are fully or mostly missing from the current models, such as carbon and nitrogen dynamics (e.g., Cao and Woodward, 1998; Thornton et al., 2007) and permafrost (e.g., Wania et al., 2009) and soil (e.g., Kutzbach et al., 1996) components in the climate system. Accordingly, there is a level of uncertainty in the climate simulations. Besides, another source of uncertainty lies in the proxy data. It can be observed in Table 2 that in western Inner Mongolia, drier climates were reconstructed at the Juyanze, Zhuyeze, and Toudaohu lakes (Chen et al., 2003), but wetter climates were reconstructed at the adjacent sites of the Badain Jaran desert (Yang et al., 2010), Juyan lake (Chen et al., 2008), Qingtu lake (Long et al., 2010), Yima lake (Chen et al., 1999), and Zhuyeze lake (Long et al., 2012). Particularly, both drier and wetter conditions were derived from the lake core records at Zhuyeze lake (Chen et al., 2003; Long et al., 2012). In addition, drier climates at Moon lake (Liu et al., 2010b) conflicted with wetter climates at Hulun lake (Yang et al., 1995), and normal

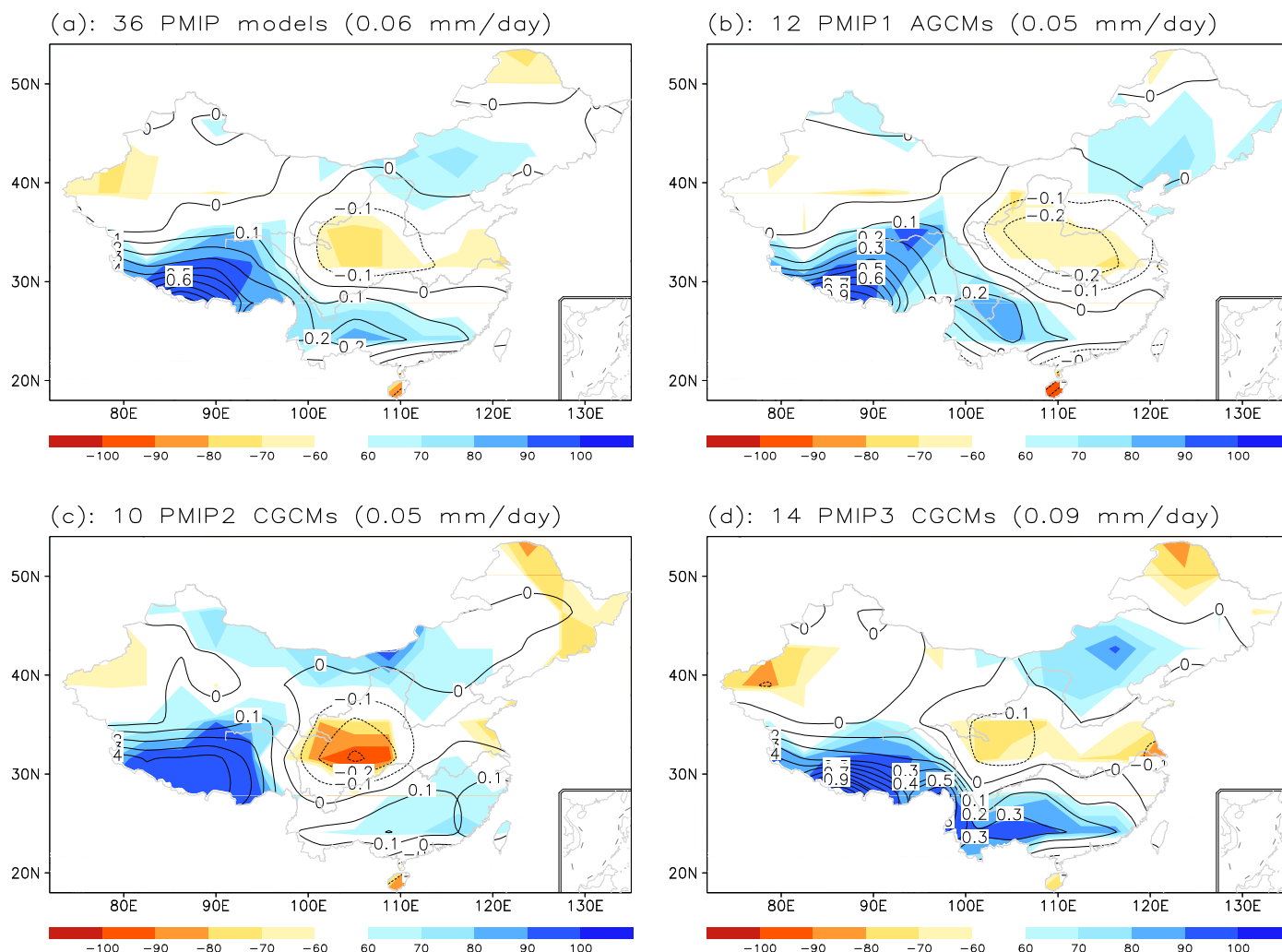


Fig. 10. Mid-Holocene–baseline anomalies of annual net precipitation (contour, units: mm/day) for the ensemble mean of the (a) 36 PMIP models, (b) 12 PMIP1 AGCMs, (c) 10 PMIP2 CGCMs, and (d) 14 PMIP3 CGCMs. In each panel, the consistency index of the models (units: %) in simulating the direction of the changes in annual net precipitation is shown in shading, and regionally averaged change in China is given in parentheses.

conditions at Poyang lake (Ma et al., 2004) disagreed qualitatively with wetter climates at Mianyang (Yang et al., 1998) and at other surrounding sites. Because logically there is only one truth, these discrepancies between records emphasize that the proxy data and method used for climatic reconstruction need to be carefully evaluated and validated.

5. Conclusion

In this study, the mid-Holocene annual and seasonal precipitation, evaporation, and net precipitation changes over China were first examined using the results of the PMIP experiments undertaken by 36 reliable climate models, and they were then compared with available proxy data of precipitation and moisture conditions. The primary conclusions are as follows.

- (1) The mid-Holocene annual precipitation (evaporation) averaged over China increased in 31 (23) of the 36 PMIP models and by an average of 3.0% (0.9%) compared with the baseline period. Regionally averaged precipitation (evaporation) decreased by 9.9% (4.1%) in winter and by 6.7% (4.7%) in spring but increased by 10.5% (5.4%) in summer and by 6.9%

(2.0%) in autumn. The spatial patterns of the changes in annual and seasonal precipitation and evaporation were similar on the large scale.

- (2) The mid-Holocene net precipitation over China increased in 33 of the 36 PMIP models and by an average of 6.9% or 0.06 mm/day compared with the baseline period. Regionally, the annual net precipitation decreased in Xinjiang but increased in the rest of western China, while it decreased in northern Northeast China and the middle and lower reaches of the Yangtze and Yellow River valleys but increased in the rest of eastern China. Seasonally, net precipitation change was qualitatively consistent among the models, with an average change of −10.0% in winter, −10.1% in spring, 18.6% in summer, and 20.4% in autumn over the country.
- (3) A comparison of atmospheric and coupled model simulations indicated that the interactive ocean effect had little impact overall on annual and seasonal precipitation, evaporation (except in autumn), and net precipitation over China during the mid-Holocene.
- (4) Based on the records of precipitation at 13 sites and of moisture conditions at 69 sites, both annual precipitation

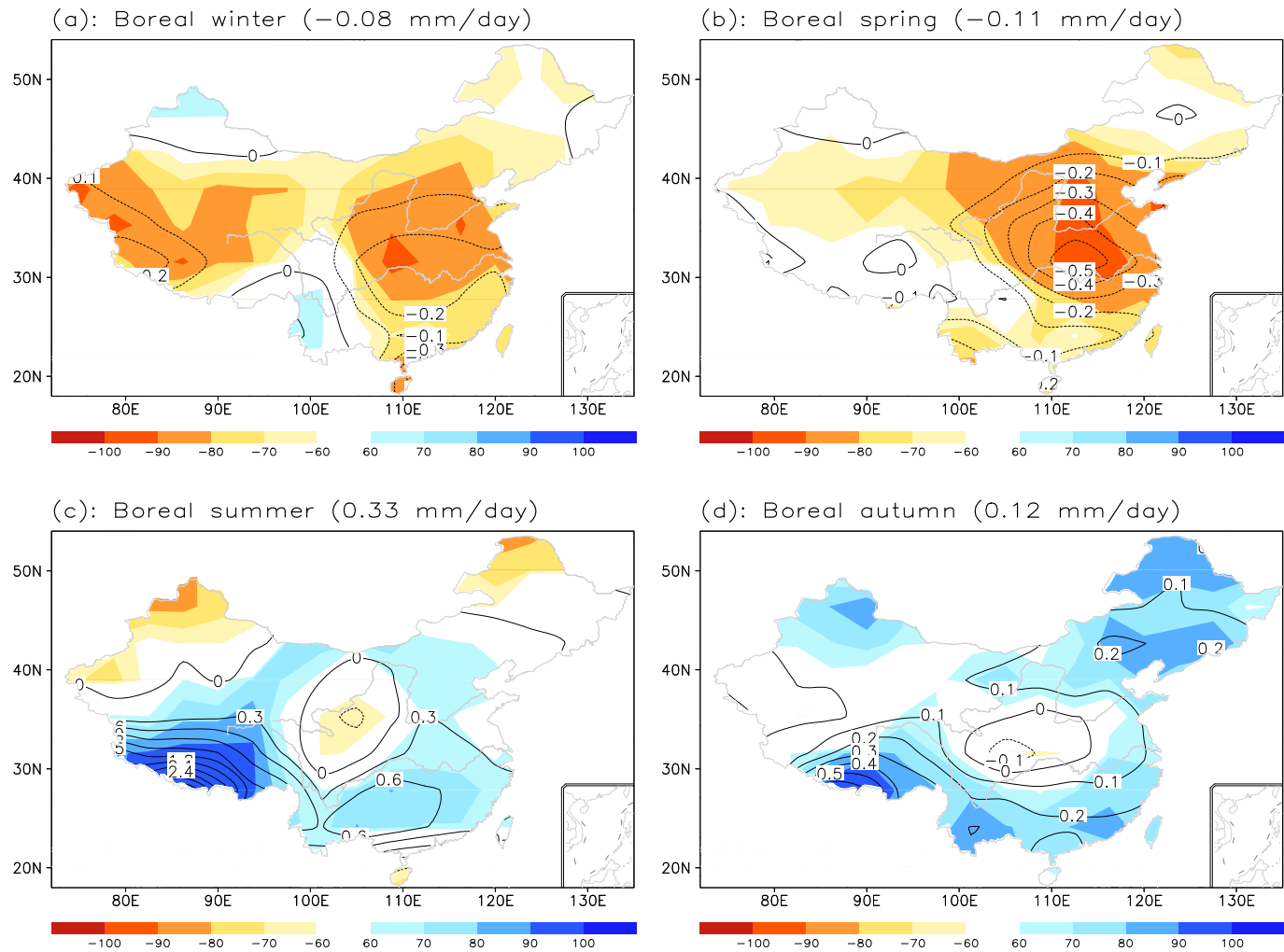


Fig. 11. Mid-Holocene–baseline anomalies of seasonal net precipitation (contour, units: mm/day) for the ensemble mean of the 36 PMIP models. In each panel, the consistency index of the models (units: %) in simulating the direction of the changes in seasonal net precipitation is shown in shading, and regionally averaged change in China is given in parentheses.

Table 2
Proxy data providing estimates of the changes in annual precipitation (ΔP) and/or net precipitation ($\Delta P - \Delta E$) between the mid-Holocene and the present day over China. Data types: 1, lake core; 2, pollen; 3, sediment; 4, palaeosol; 5, peat; 6, stalagmite; 7, ice core.

Site ID	Data type	Latitude (°N)	Longitude (°E)	Elevation (m ASL)	Interval (ka)	$\Delta P - \Delta E$	ΔP	Reference
01 Aibi lake	1, 2, 3	44.88	82.88	194	10.2	Wetter	~26% more	Wu et al. (1996)
02 Angulinao lake	1, 3	41.35	114.39	1310	8.4	Wetter		Zhai et al. (2000)
03 Baahar Nuur lake	1, 3	39.10	109.20	1450	13.9	Wetter		Feng et al. (2005)
04 Badain Jaran desert	3, 5	39.00–40.00	101.00–103.00	1000–1500	10.0	Wetter		Yang et al. (2010)
05 Baimapo	4	34.17	109.32	650	20.6	Wetter		Zhou et al. (1994)
06 Baiyangdian lake	2	38.85	116.00	7	11.0	Wetter	~200 mm more	Xu et al. (1988)
07 Balikun lake	2, 1	43.62	92.77	1575	16.7	Wetter		Tao et al. (2010)
08 Bangong Co lake	1, 2	33.67	79.00	4241	10.0	Wetter		Gasse et al. (1996)
09 Barkol lake	1, 3	43.70	92.83	1580	9.4	Wetter		Xue and Zhong (2008)
10 Baxie	4	35.58	103.57	2000	12.3	Wetter		Zhou et al. (1994)
11 Bayanchagan lake	2	41.65	115.21	1355	12.5	Wetter	More	Guiot et al. (2008)
11 Bayanchagan lake	2	41.65	115.21	1355	12.5	Wetter	~30–60% more	Jiang et al. (2010)
12 Beizhuangcun	4	34.50	109.50	950	26.1	Wetter		Zhou et al. (1994)
13 Bosten lake	1, 3, 2	42.08	87.05	1500	12.0	Wetter		Zhong and Shu (2001)
14 Bosten lake	1, 3	41.95	86.78	1048	8.5	Wetter		Mischke and Wünnemann (2006)
15 Central Inner Mongolia	4, 2, 3	38.61–40.30	109.95–110.41	1037–1312	11.5	Wetter		Sun et al. (2006)
16 Changbaishan	5	40.67–44.50	125.33–131.33	500–900	10.0	Wetter		Zhao et al. (2002)

Table 2 (continued)

Site ID	Data type	Latitude (°N)	Longitude (°E)	Elevation (m ASL)	Interval (ka)	$\Delta P - \Delta E$	ΔP	Reference
17 Cuoe lake	2, 3	31.47	91.51	4532	10.5	Wetter		Wu et al. (2006)
18 Dadiwan	2, 3	35.01	105.91	1400	11.2	Wetter		An et al. (2003)
19 Dagushan	2, 3	39.92	123.66	5	8.0–2.5	Wetter		Laboratory of Quaternary palynology and laboratory of radiocarbon, Kweiyang Institute of Geochemistry, Academia Sinica (1978)
20 Dahu	5, 2	24.25	115.03	250	18.0	Wetter	~200 mm more	Zhou et al. (2004)
21 Dahu	2, 5	24.68	115.00	255	18.3	Wetter		Xiao et al. (2007)
22 Daihai lake	2	40.58	112.69	1221	12.0	Wetter	~40 mm more	Xu et al. (2010)
22 Daihai lake	2, 1	40.58	112.69	1221	10.2	Wetter	More	Xiao et al. (2004)
23 Daziying	2, 5	39.70	118.99	5	9.8	Wetter		Li and Liang (1985)
24 Diaojiao lake	2, 3	41.30	112.35	1800	10.1	Wetter		Song et al. (1996)
24 Diaojiao lake	2, 3	41.30	112.35	1800	10.1	Wetter	~80–200 mm more	Shi and Song (2003)
25 Dingxi	4	35.52	104.54	1950	8.9	Wetter		Feng et al. (2005)
26 Dongganchi	2	39.53	115.78	49	15.8	Wetter		Zhang and Kong (1999)
27 Dongge cave	6	25.28	108.08	680	15.4	Wetter		Zhang et al. (2004)
28 Erhai lake	1, 2, 3	25.78	100.19	1974	10.8	Wetter		Zhou et al. (2003)
29 Gonong Co	2, 3	34.63	92.15	4670	19.2	Wetter		Li et al. (1995)
30 Guliya	7	35.28	81.48	6200	125.0	Wetter		Thompson et al. (1997)
31 Gushantun bog	3	42.00	126.00	500	13.5	Wetter		Wang and Liu (2001)
32 Ha'ni	1, 2, 3	42.23	126.52	900	13.1–4.5	Wetter		Yu et al. (2008)
33 Haoluku lake	3, 2	42.96	116.76	1295	10.2	Wetter		Wang et al. (2001)
34 Heshang cave	6	30.45	110.42	294	9.4		8% more	Hu et al. (2008)
35 Hidden lake	1, 2	29.81	92.54	4980	14.0		~200 mm more	Tang et al. (2000)
36 Huguangyan Maar lake	1, 2	21.15	110.28	23	13.0	Wetter		Wang et al. (2007)
37 Hulu river	3, 2	35.00	106.00	1540	8.0–3.0	Wetter		Mo et al. (1996)
38 Hulun lake	2, 3	48.90	116.50	544	19.9	Wetter		Yang et al. (1995)
39 Hulun lake	1, 2, 3	49.13	117.51	545	11.0		~50 mm more	Wen et al. (2010)
40 Jingbo lake	1, 2	43.90	128.80	350	9.6	Wetter		Li et al. (2011a)
41 Juyan lake	2	41.80	101.80	892	10.7	Wetter		Chen et al. (2008)
42 Juyanze lake	1, 3, 2	41.89	101.85	892	9.4	Drier		Chen et al. (2003)
43 Kouka lake	1, 3	34.01	97.24	4530	16.3	Wetter		Mischke et al. (2008)
44 Longzhong basin	2, 4	35.00–35.55	104.52–105.91	1400–1889	12.2	Wetter		Tang and An (2007)
45 Manas lake	1, 3, 2	45.75	86.00	251	37.0	Wetter		Rhodes et al. (1996)
46 Maohebei	2, 5	39.50	119.17	50	10.3	Wetter		Li and Liang (1985)
47 Mianyang	2	30.20	113.22	24	10.0	Wetter	More	Yang et al. (1998)
48 Moon lake	1, 3, 2	47.51	120.87	1190	21.0	Drier		Liu et al. (2010b)
49 Naleng lake	2, 1	31.10	99.75	4200	11.7	Wetter		Cramer et al. (2010)
50 Nam Co lake	1, 3	30.84	90.90	4718	8.4	Wetter		Lin et al. (2008)
50 Nam Co lake	2, 1	30.84	90.90	4718	8.4	Wetter		Li et al. (2011b)
51 Otindag	4, 3	41.41–43.69	114.97–117.66	1200–1400	9.9	Wetter		Zhou et al. (2008)
52 Poyang lake	1, 3	29.03	116.14	8	7.9	Normal		Ma et al. (2004)
53 Qinghai lake	2, 1	36.55	99.60	3196	11.0		At least 100 mm more	Kong et al. (1990)
54 Qingtu lake	3	39.05	103.67	1309	9.5–2.5	Wetter		Long et al. (2010)
55 Ren Co lake	1, 2	30.73	96.68	4450	18.0		~200 mm more	Tang et al. (2000)
56 Renjiahutong	4	35.75	109.42	1100	13.0	Wetter		Zhou et al. (1994)
57 Rutog	3, 2	33.39	79.73	4265	6.5	Wetter		Wang et al. (2010b)
58 Shanbao cave	6	31.67	110.43	1902	11.5–2.1	Wetter		Shao et al. (2006)
59 Siling Co lake	1, 3	31.60	89.05	4530	12.8	Wetter		Kashiwaya et al. (1995)
60 Sujiawan	2, 3	35.54	104.52	1700	8.9	Wetter		An et al. (2003)
61 Sumxi Co lake	1, 3	34.62	81.03	5058	13.0	Wetter		Gasse et al. (1991)
62 Tanghongling	2, 3	48.35	129.67	465	9.0	Wetter		Yang and Wang (2002)
63 Tongjiang	2, 3	48.08	133.25	60	8.0	Wetter	150–200 mm more	Yang and Wang (2003)
64 Toudaohu lake	1, 3, 2	38.42	105.12	1351	6.3	Drier		Chen et al. (2003)
65 Ulungur lake	1, 3	47.22	87.15	478	9.9	Wetter		Jiang et al. (2007)
66 Wutonggou	3	44.39	87.86	429	18.3	Wetter		Li and Fan (2011)
67 Xiangshui cave	6	25.25	110.92	400	6.0	Wetter		Zhang et al. (2003)
68 Xianrendong cave	6	25.83	103.50	1810	8.0	Wetter		Zhang et al. (2009)
69 Yiema lake	1, 3	39.10	103.67	1312	16.0	Wetter		Chen et al. (1999)
70 Zhuyeze lake	1, 3, 2	39.01	103.34	1320	15.2	Drier		Chen et al. (2003)
71 Zhuyeze lake	1	39.17	104.16	1291	80	Wetter		Long et al. (2012)
72 Zigê Tangco	1, 3	32.08	90.84	4560	10.5	Wetter		Wu et al. (2007)
73 Zige tang lake	1, 2	32.00	90.90	4560	10.8	Wetter		Herzschuh et al. (2006)
74 Zoige	2	33.90	102.55	3396	20.0	Wetter		Liu et al. (1995)

and net precipitation were generally higher than the present level over China during the mid-Holocene. Qualitatively, the models disagreed with the multi-proxy data in Xinjiang and the areas between the middle and lower reaches of the Yangtze and Yellow River valleys where drier-than-baseline

climates were obtained from the 36 models, while model–data agreements were presented in the rest of the country. There are uncertainties in both the model simulations and in the proxy data, as discussed in Section 4, which require further studies.

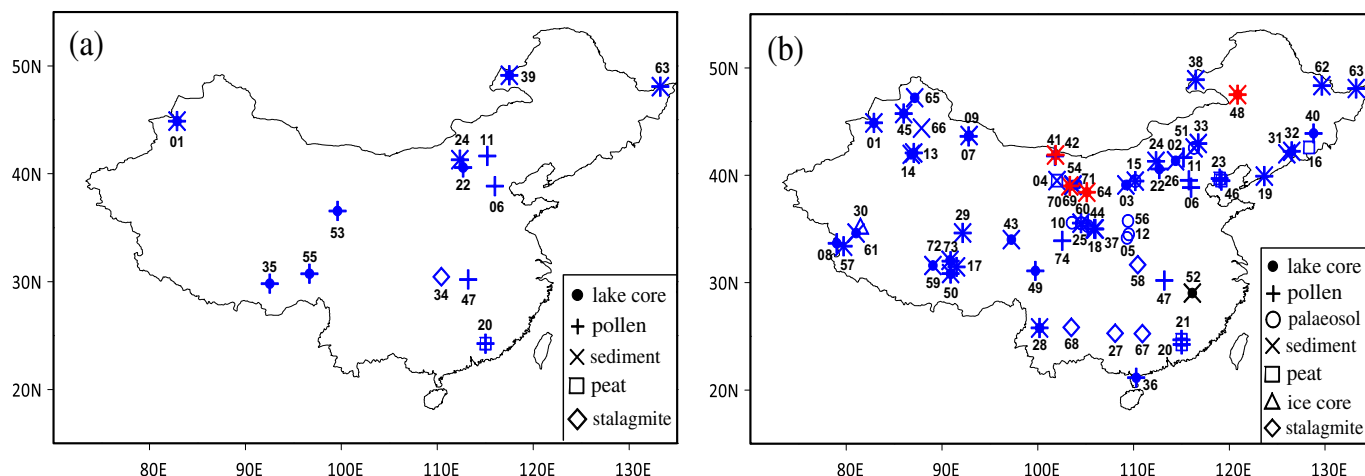


Fig. 12. Proxy estimates of the changes in annual (a) precipitation at 13 sites and (b) net precipitation at 69 sites during the mid-Holocene relative to the present period, in which blue, black, and red symbols represent wetter, normal, and drier conditions, respectively, and number represents site ID (see Table 2 for details and references). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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