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Mid-Holocene East Asian summer monsoon strengthening: Insights from Paleoclimate Modeling Intercomparison Project (PMIP) simulations

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ABSTRACT

The East Asian summer (June–July–August) monsoon (EASM) is typically thought to have been stronger during interglacial periods based on spatially sparse proxy data. On a large scale, however, whether this view is true and if so, its underlying dynamic mechanisms remain unclear. Using all pertinent experiments within the Paleoclimate Modeling Intercomparison Project (PMIP), here we present an analysis of the EASM during the mid-Holocene, 6000 years ago. Supporting the paleodata, the mid-Holocene EASM, as measured by regionally averaged meridional wind at 850 hPa, became stronger than the baseline period in 27 out of 28 PMIP models with a demonstrable ability to simulate the modern EASM climatology. On average, the EASM strengthened by 32% across all the models and by a larger magnitude in 23 coupled models (35%) than in five atmospheric models (20%). It is proposed that 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 was responsible for the EASM strengthening during the mid-Holocene.

1. Introduction

The East Asian monsoon is composed of tropical and subtropical monsoons and features southerly winds during summer (June–July–August) and northerly winds during winter (December–January–February) in the lower troposphere (e.g., Tao and Chen, 1987; Ding, 1994). Usually, its intensity in meridional winds has been inferred to become stronger in summer but weaker in winter during interglacial periods of the Quaternary, which is speculated to result from changes in global ice volume and/or orbitally induced solar insolation changes (e.g., Liu and Ding, 1998; Jian et al., 2001; Wang et al., 2008a; Cheng et al., 2009; Wang, 2009). At the East Asian scale, however, whether this interpretation of extremely sparse proxy data is correct remains unclear. And if it is true, the underlying dynamic mechanism remains unidentified.

The mid-Holocene provides a good opportunity for examining how the East Asian monsoon responds to changes of ~5% in the seasonal distribution of the incoming solar radiation at the top of the atmosphere in the Northern and Southern Hemispheres (Berger, 1978). Based on the previous experiments of individual climate models, the mid-Holocene East Asian summer monsoon (EASM) appeared to have been stronger overall during the mid-Holocene (e.g., Wang, 1999, 2000; Chen et al., 2002; Marzin and Braconnot, 2009; Zhou and Zhao, 2009, 2010; Liu et al., 2010). Similar results came from the part of the Paleoclimate Modeling Intercomparison Project (PMIP) simulations (Wang et al., 2010; Zhao and Harrison, 2012). On the other hand, however, there is a large degree of model-dependent uncertainties in both the spatial pattern and magnitude of the mid-Holocene EASM changes among those studies. For example, significant changes in the large-scale EASM circulation during that period were registered only over eastern China north of 30°N in the experiments using a regional climate model (Liu et al., 2010) but over the whole of eastern China in the experiments using a coupled climate model (Marzin and Braconnot, 2009). In addition, whether those climate models can reliably reproduce the present EASM remains unknown, although it is directly related to the confidence of the results. As a matter of fact, it has been revealed that some of the PMIP models failed to describe the present climatological EASM circulation (Jiang and Lang, 2010; see Section 2.2 of this study). Using such models to address the EASM may give wrong conclusions. Furthermore, ocean dynamics has been regarded as a key component in the mid-Holocene climate system (e.g., Braconnot et al., 2007; Ohgaito and Abe-Ouchi, 2009). However, it was not taken into account in most of the earlier experiments with atmospheric models, which may hamper our understanding of the mid-Holocene EASM.

Recently, the mid-Holocene East Asian summer climate was examined using 12 coupled atmosphere–ocean general circulation models (AOGCMs) within the PMIP phase two (PMIP2), and the EASM was

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Table 1
Basic information for the 51 PMIP models, together with SCCs and CRMSEs (units: m s^{-1}) of summer meridional wind at 850 hPa between each baseline simulation and the NCEP–NCAR reanalysis data for the period 1981–2000 (Kalnay et al., 1996) within the region of 20°–45°N and 105°–135°E. The 28 models that had positive SCC values statistically significant at the 95% confidence level (Model ID shown in boldface) were chosen for analysis in this study. N/A, not available.

Model ID		Project	Atmospheric resolution	Length of run analyzed (year)	SCC	CRMSE
01	CCC2.0	PMIP1 (AGCM)	T32L10	10	0.07	1.58
02	CCM3	PMIP1 (AGCM)	T42L18	8	0.23	1.46
03	**CCSR1**	PMIP1 (AGCM)	T21L20	10	0.32	1.10
04	CNRM-2	PMIP1 (AGCM)	T31L19	10	0.14	1.52
05	CSIRO	PMIP1 (AGCM)	R21L9	15	0.02	1.17
06	**ECHAM3**	PMIP1 (AGCM)	T42L19	10	0.67	0.75
07	**GEN2**	PMIP1 (AGCM)	T31L18	10	0.56	0.86
08	GFDL	PMIP1 (AGCM)	R30L20	25	−0.24	1.82
09	GISS-IIP	PMIP1 (AGCM)	72×46, L9	10	−0.16	1.80
10	**LMCELMD4**	PMIP1 (AGCM)	48×36, L11	15	0.30	2.14
11	**LMCELMD5**	PMIP1 (AGCM)	64×50, L11	15	0.30	1.24
12	MRI2	PMIP1 (AGCM)	72×46, L15	10	−0.43	2.57
13	UGAMP	PMIP1 (AGCM)	T42L19	20	0.01	1.95
14	UIUC11	PMIP1 (AGCM)	72×46, L14	10	−0.42	1.63
15	UKMO	PMIP1 (AGCM)	96×73, L19	50	−0.28	1.54
16	YONU	PMIP1 (AGCM)	72×46, L7	10	−0.72	2.30
17	**CCSM3.0**	PMIP2 (AOGCM)	T42L18	50	0.70	0.81
18	CSIRO-Mk3L-1.0	PMIP2 (AOGCM)	R21L18	1000	−0.30	1.48
19	CSIRO-Mk3L-1.1	PMIP2 (AOGCM)	R21L18	1000	−0.19	1.34
20	ECBILTCLIOVECODE	PMIP2 (AOGCM)	T21L3	100	N/A	N/A
21	ECHAME5-MPIOM1	PMIP2 (AOGCM)	T31L20	100	0.11	1.16
22	ECHAM53-MPIOM127-LPJ	PMIP2 (AOGCM)	T31L19	100	0.22	1.06
23	FGOALS-1.0 g	PMIP2 (AOGCM)	R42L9	100	0.06	2.48
24	FOAM	PMIP2 (AOGCM)	R15L18	100	−0.26	1.79
25	**GISSmodelE**	PMIP2 (AOGCM)	72×46, L17	50	0.70	0.84
26	**IPSL-CM4-V1-MR**	PMIP2 (AOGCM)	96×72, L19	100	0.72	1.01
27	**MIROC3.2**	PMIP2 (AOGCM)	T42L20	100	0.57	1.34
28	**MRI-CGCM2.3.4fa**	PMIP2 (AOGCM)	T42L30	150	0.33	1.07
29	**MRI-CGCM2.3.4nfa**	PMIP2 (AOGCM)	T42L30	150	0.81	0.57
30	**UBRIS-HadCM3M2**	PMIP2 (AOGCM)	96×73, L19	100	0.46	1.26
31	ECBILTCLIOVECODE-veg	PMIP2 (AOVGCM)	T21L3	100	N/A	N/A
32	ECHAM53-MPIOM127-LPJ-veg	PMIP2 (AOVGCM)	T31L19	100	0.20	1.07
33	FOAM-veg	PMIP2 (AOVGCM)	R15L18	100	−0.28	1.80
34	**MRI-CGCM2.3.4fa-veg**	PMIP2 (AOVGCM)	T42L30	100	0.36	0.95
35	**MRI-CGCM2.3.4nfa-veg**	PMIP2 (AOVGCM)	T42L30	100	0.85	0.48
36	**UBRIS-HadCM3M2-veg**	PMIP2 (AOVGCM)	96×73, L19	100	0.51	1.28
37	**BCC-CSM1.1**	PMIP3 (AOVGCM)	T42L26	100	0.66	0.84
38	**CCSM4**	PMIP3 (AOGCM)	288×192, L26	301	0.52	0.99
39	**CNRM-CM5**	PMIP3 (AOGCM)	256×128, L31	200	0.77	0.73
40	**CSIRO-Mk3-6-0**	PMIP3 (AOGCM)	192×96, L18	100	0.25	1.10
41	CSIRO-Mk3L-1-2	PMIP3 (AOGCM)	64×56, L18	500	−0.25	1.39
42	EC-EARTH-2-2	PMIP3 (AOGCM)	320×160, L62	40	N/A	N/A
43	**FGOALS-g2**	PMIP3 (AOVGCM)	128×60, L26	100	0.80	0.94
44	**FGOALS-s2**	PMIP3 (AOVGCM)	128×108, L26	100	0.31	1.44
45	**GISS-E2-R**	PMIP3 (AOGCM)	144×90, L40	100	0.75	0.78
46	**HadGEM2-CC**	PMIP3 (AOVGCM)	192×145, L60	35	0.79	0.72
47	**HadGEM2-ES**	PMIP3 (AOVGCM)	192×145, L38	102	0.78	0.75
48	**IPSL-CM5A-LR**	PMIP3 (AOVGCM)	96×95, L39	500	0.66	1.11
49	**MIROC-ESM**	PMIP3 (AOVGCM)	T42L80	100	0.43	1.96
50	**MPI-ESM-P**	PMIP3 (AOGCM)	T63L47	100	0.63	0.73
51	**MRI-CGCM3**	PMIP3 (AOGCM)	320×160, L48	100	0.29	1.02

noted to become stronger (Wang et al., 2010). However, no attention was paid in their work to the spatial pattern, magnitude, and dynamic mechanism behind the EASM change during that period. Moreover, they only used some of the PMIP2 AOGCMs, which makes it impossible to evaluate the effect of ocean on the EASM through the comparison of the different types of PMIP simulations. Using 17 atmospheric general circulation models (AGCMs) within the PMIP phase one (PMIP1) and 11 AOGCMs within the PMIP2, Zhao and Harrison (2012) discussed the mid-Holocene EASM through precipitation change. Since precipitation and monsoon relationship in East Asia is not direct as it is in the tropics such as in India (e.g., Tao and Chen, 1987; Ding, 1994), it may be more relevant to directly use low-tropospheric winds instead of precipitation to address the monsoon in East Asia. Again, whether those models can reliably reproduce the modern East Asian climate was neglected in their study. Collectively, all of the aforementioned factors stress the need to specifically examine the mid-Holocene EASM using multiple reliable climate models and estimate the role of interactive ocean therein. Particularly, it is interesting to investigate what the EASM was like during the mid-Holocene in the simulations of state-of-the-art climate models participating in the latest PMIP phase three (PMIP3) under the framework of the Intergovernmental Panel on Climate Change Fifth Assessment Report.

Within the PMIP project, 51 climate models have been used to simulate the mid-Holocene climate to date. Part of the PMIP earlier experiments have improved our knowledge of the mid-Holocene African and Indian tropical monsoon changes (e.g., Joussaume et al., 1999; Braconnot et al., 2002), for example. Given that the mid-Holocene surface air temperature changes over China obtained from the PMIP1 and PMIP2 models agree in general with multi-proxy data during boreal summer, and that the opposite of this situation is true during boreal winter (Jiang et al., 2012), an analysis was made in this study of all available simulations within the PMIP database to examine the mid-Holocene EASM changes, as well as the dynamic mechanisms behind the most common changes.