Interdecadal Variations of the East Asian Winter Monsoon in CMIP5 Preindustrial Simulations

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ABSTRACT

In this study, focusing on the interdecadal time scale, we investigate the internal variability of the East Asian winter monsoon (EAWM) using output from 19 coupled models' long-term preindustrial control (piControl) simulations within phase 5 of the Coupled Model Intercomparison Program (CMIP5). In total, we identify 53 cases of significant interdecadal weakening of the EAWM from these 19 piControl simulations. In most weakening cases, both the Siberian high and the East Asian trough are significantly weakened. The East Asian jet stream in the upper troposphere shifts poleward. Southerly wind anomalies are evident over East Asia in the lower troposphere. At the same time, both the Arctic Oscillation (AO) and the North Pacific Oscillation are in their positive phases. Associated anomalous anticyclonic circulation can be found over the North Pacific. Additionally, the North Pacific shows negative Pacific decadal oscillation (PDO)-like sea surface temperature (SST) anomalies. In contrast, we also analyzed 49 cases of significant strengthening of the EAWM, and the atmospheric and oceanic anomalies show opposite signals with the weakening cases. This suggests that internal variabilities of the climate system can also cause interdecadal variations of the EAWM. In addition, the phase shifting of the AO is likely the main reason for the EAWM's interdecadal variations in the unforced long-term simulations. Further numerical experiments using the Community Atmosphere Model, version 4 (CAM4), deny the causal relationship between the interdecadal variations of EAWM and PDO-like SST anomalies. This study also implies that the internal variabilities of the climate system could contribute to the observed interdecadal weakening of the EAWM around the mid-1980s.

1. Introduction

The East Asian winter monsoon (EAWM) is one of the most active climate systems in the boreal winter. It has great impacts on the weather and climate of China and surrounding regions (Lau and Li 1984; Ding 1994; He et al. 2007). Based on the observational studies, the EAWM exhibits significant interannual variabilities that are usually accompanied by anomalous cold surges (Gu et al. 2008; Yang et al. 2018), snowfall (Sun et al. 2010; Wang and He

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2013), rainfall (Jia and Ge 2017), and haze pollution (Li et al. 2016; Wang and Chen 2016) over East Asia. On this time scale, the EAWM is strongly affected by El Niño–Southern Oscillation (ENSO) (Zhang et al. 1996; Wang et al. 2000; Zhou et al. 2007; Wang and He 2012). Usually, the EAWM is weaker (stronger) when El Niño (La Niña) occurs (Wang et al. 2000). In addition, the North Atlantic Oscillation (Wu and Huang 1999), the Arctic Oscillation (AO) (Gong et al. 2001; Wu and Wang 2002; He et al. 2017; Li et al. 2018), and autumn Arctic sea ice (Liu et al. 2012; C. Sun et al. 2016; Wang and Liu 2016) can also influence the EAWM through both thermodynamic and dynamic processes.

In recent decades, research on the interdecadal changes of the EAWM has raised more concerns. They are the background conditions of the interannual variations and modulate long-term changes in the East Asian climate (Wang and Fan 2013). Some studies indicate that the EAWM experienced significant weakening in the mid-1980s (Xu et al. 1999; Wang and He 2012; Miao et al. 2018b). Usually, reasons for the interdecadal changes of the East Asian climate are very complex (Ding et al. 2014). Influences from external forcings on the East Asian climate (Wang et al. 2013; Miao et al. 2016; Jiang et al. 2017; Zhou 2017; Chen and Dong 2019; Miao et al. 2018a; Tian et al. 2018) and even on the large-scale Pacific climate (Wang et al. 2012; Xiao et al. 2017; Miao et al. 2018c) are significant. A recent modeling study suggested that both greenhouse gases and natural external forcings played important roles in weakening the EAWM and related changes over the North Pacific in the mid-1980s (Miao et al. 2018b). In this process, influences from the internal variabilities cannot be neglected. For example, Ding et al. (2014) noted that the Pacific decadal oscillation (PDO) and the EAWM are significantly negatively correlated on the interdecadal time scale in the observations. In addition, some previous studies indicated that on multidecadal time scales, a weaker EAWM is linked to a warm phase of the Atlantic multidecadal oscillation (AMO), and vice versa (Li and Bates 2007; Wang et al. 2009). However, in the observations, the time of phase transient for the PDO and AMO is not consistent with the interdecadal weakening of the EAWM around the mid-1980s. Therefore, how these internal modes affect decadal variations of the EAWM needs further investigation.

In fact, it is difficult to use only an observation-based analysis to investigate the internal variabilities of the climate system at the interdecadal and longer time scales due to the limitation of observational data length and the influence of mixed external forcing signals. Thus, coupled climate models become a useful tool to explore

such processes and their associated mechanisms (Lei et al. 2014). As the external forcings remain constant, the internal dynamics of the coupled atmosphere–ocean–land–cryosphere system induce internal variability on various time scales (Hasselmann 1976). Thus, many previous studies compared unperturbed control simulations with observations to detect internal variabilities and externally forced climate changes. Stouffer et al. (2000) analyzed the internal variability of surface air temperature (SAT) in three 1000-yr coupled model integrations and suggested that the observed warming of $\sim 0.5^{\circ}\text{C}$ over the twentieth century is not due to internally generated variability. Lei et al. (2014) explored the interdecadal natural variability of summer rainfall over China using multicentury simulations of the HadCM3 model and concluded that both anthropogenic and natural factors could play a role in recent changes in Chinese summer rainfall. Furthermore, Polvani and Smith (2013) suggested that the recent observed positive trend in Antarctic sea ice lies well within the natural variability shown in CMIP5 coupled models. Control simulations can also be used to investigate the mechanisms of observed phenomena (e.g., Kug et al. 2006; Cui et al. 2013; Yan et al. 2018). For example, a recent study analyzed the dynamic processes accounting for the observed linkage between the Atlantic meridional overturning circulation and Atlantic multidecadal variability using control simulations from the CMIP3 and CMIP5 (Yan et al. 2018). Focusing on the EAWM, can the internal variability of the climate system cause the interdecadal variation of EAWM as observed around the mid-1980s? And what is the reason for the process? These issues remain unresolved.

To address the abovementioned issues, in this study, we investigate the interdecadal variations of the EAWM using multiple long-term preindustrial simulations within the CMIP5. In section 2, we describe the data and methods used here. In section 3, we evaluate the multimodels' performance in simulating the EAWM. In section 4, we investigate the interdecadal variations of the EAWM in the preindustrial simulations and the associated physical mechanisms. The conclusions and discussion are given in section 5.

2. Data and method

Model results, including historical and 500-yr preindustrial control (piControl) simulations from 28 coupled models within the CMIP5 (Taylor et al. 2012), are used in this study. The details for these models are illustrated in Table 1. The historical simulations are integrated with both anthropogenic and natural external forcings. For the piControl simulations, however, the models impose

TABLE 1. Descriptions of the CMIP5 models used in this study.

No.	Model	Institute	Atmospheric resolution (lat × lon)
1	BCC-CSM1.1	BCC (China)	64 × 128
2	BNU-ESM	BNU (China)	64 × 128
3	CanESM2	CCCma (Canada)	64 × 128
4	CMCC-CMS	CMCC (Italy)	96 × 192
5	CNRM-CM5	CNRM-CERFACS (France)	128 × 256
6	ACCESS1.0	CSIRO-BOM (Australia)	145 × 192
7	ACCESS1.3	CSIRO-BOM (Australia)	145 × 192
8	CSIRO Mk3.6.0	CSIRO-QCCCE (Australia)	96 × 192
9	FIO-ESM	FIO (China)	64 × 128
10	INM-CM4	INM (Russia)	120 × 180
11	IPSL-CM5A-LR	IPSL (France)	96 × 96
12	FGOALS-g2	IAP-THU (China)	60 × 128
13	MIROC-ESM	MIROC (Japan)	64 × 128
14	MIROC4h	MIROC (Japan)	320 × 640
15	MIROC5	MIROC (Japan)	128 × 256
16	HadGEM2-ES	MOHC (United Kingdom)	144 × 192
17	MPI-ESM-LR	MPI-M (Germany)	96 × 192
18	MPI-ESM-MR	MPI-M (Germany)	96 × 192
19	MPI-ESM-P	MPI-M (Germany)	96 × 192
20	MRI-CGCM3	MRI (Japan)	160 × 320
21	GISS-E2-H	NASA-GISS (United States)	90 × 144
22	GISS-E2-R	NASA-GISS (United States)	90 × 144
23	CCSM4	NSF-DOE-NCAR (United States)	192 × 288
24	CESM1(BGC)	NSF-DOE-NCAR (United States)	192 × 288
25	NorESM1-M	NCC (Norway)	96 × 144
26	GFDL CM3	NOAA-GFDL (United States)	90 × 144
27	GFDL-ESM2G	NOAA-GFDL (United States)	90 × 144
28	GFDL-ESM2M	NOAA-GFDL (United States)	90 × 144

nonevolving preindustrial conditions. The last 500 years in each piControl simulation are analyzed in this study.

The monthly sea level pressure (SLP) from the Hadley Centre's HadSLP2 dataset (Allan and Ansell 2006) and the geopotential height and the wind fields from the NCEP–NCAR reanalysis data (Kalnay et al. 1996) are used here to evaluate the models' performances in simulating the East Asian winter (December–February) climate and to analyze interdecadal climate changes. To obtain the EAWM index for a long period, the Twentieth Century Reanalysis, version 2 (20CR V2), data covering the period of 1871–2012 are adopted (Compo et al. 2011). In addition, the AO index calculated using these data was downloaded from the website (https://www.esrl.noaa.gov/psd/data/20thC_Rean/timeseries/monthly/AO/) to examine the AO–EAWM relationship in the observation. Furthermore, the PDO index is obtained from the website (<http://research.jisao.washington.edu/pdo/PDO.latest.txt>) to illustrate the observed PDO–EAWM relationship.

In this study, the integrated EAWM index, which includes the Siberian high, East Asian trough (EAT), and East Asian jet stream (EASJ) (He and Wang 2012), is used to detect interdecadal changes in the EAWM. This index is calculated as

$$\begin{aligned} \text{EAWMI} = & \frac{1}{3} \times \text{Stand}[\overline{\text{SLP}}(40^{\circ}\text{--}60^{\circ}\text{N}, 80^{\circ}\text{--}125^{\circ}\text{E})] \\ & - \frac{1}{3} \times \text{Stand}[\overline{\text{Z500}}(25^{\circ}\text{--}45^{\circ}\text{N}, 110^{\circ}\text{--}145^{\circ}\text{E})] \\ & + \frac{1}{3} \times \text{Stand}[\overline{\text{U300}}(25^{\circ}\text{--}40^{\circ}\text{N}, 80^{\circ}\text{E--}180^{\circ}) \\ & - \overline{\text{U300}}(45^{\circ}\text{--}60^{\circ}\text{N}, 60^{\circ}\text{--}160^{\circ}\text{E})]. \end{aligned}$$

$\overline{\text{SLP}}$ means the area-averaged SLP, $\overline{\text{Z500}}$ means the area-averaged geopotential height at 500 hPa (Z500), and $\overline{\text{U300}}$ means the area-averaged zonal wind at 300 hPa (U300). “Stand” denotes standardization. Its positive (negative) values reflect a stronger (weaker) EAWM. In addition, we use the empirical orthogonal function (EOF) to calculate the PDO index, which is the leading principal component of North Pacific sea surface temperature (SST) anomalies (poleward of 20°N) (Mantua et al. 1997). Furthermore, the AO index is defined as the first EOF mode of the SLP anomalies in the extratropical Northern Hemisphere (20°–90°N) (Thompson and Wallace 1998). The North Pacific Oscillation (NPO) index is defined as the normalized difference in the area-averaged SLP between two regions (25°–40°N, 130°–170°E and 50°–65°N, 130°–170°E) (Guo and Sun 2004).

Pearson's linear correlation is adopted to describe the correlation between the EAWM index and the other climate indices (i.e., AO, PDO, and NPO). To obtain the interdecadal signals, low-pass Lanczos filtering is used on the indices before calculating the correlation. The effective degree of freedom for the filtered series is calculated as

$$N_e = N_o \frac{1 - r_1 r_2}{1 + r_1 r_2},$$

where N_o is the sample number, and r_1 and r_2 are autocorrelations at one time interval of the two series (Bretherton et al. 1999).

To identify significant interdecadal variations of the EAWM in the long-term simulations, the moving t -test method (subseries length equals 20 years) is used on the simulated EAWM index. The statistic T is calculated as

$$T(i) = \frac{(M_2 - M_1)}{\sqrt{\left(\frac{1}{L_1} + \frac{1}{L_2}\right) \left[\frac{(L_1 - 1)S_1^2 + (L_2 - 1)S_2^2}{L_1 + L_2 - 2} \right]}}$$

where i denotes the i th point in the series; and L_1 , M_1 , and S_1 are the length, mean value, and variance, respectively, of the subseries before the i th point. The terms L_2 , M_2 , and S_2 are those of the subseries after the i th point. The T values exceeding the 0.05 significance level denote significant interdecadal changes of the EAWM. Times of abrupt change are determined when the T value reaches a maximum/minimum during each period of 40 years. At the same time, the time interval between every two abrupt changes in interdecadal variations must be larger than 40 years, which can prevent double counting of one case of interdecadal variation in long-term simulations. In addition, the multicasen ensemble mean (MCE) in the multimodel simulations are analyzed, and the multicasen consistency method is adopted to evaluate the robustness of the MCE. The multicasen consistency is defined as the percentage of individual cases sharing the same sign as the MCE.

Additionally, some numerical experiments are performed to investigate influences from the PDO-like SST anomalies on the East Asian winter climate. The model used is the Community Atmosphere Model, version 4 (CAM4), which is the atmospheric component of the Community Earth System Model, version 1.0.5 (CESM1.0.5) (Gent et al. 2011). The horizontal resolution is $1.9^\circ \times 2.5^\circ$, and the vertical direction has 26 layers.

3. Evaluation of the CMIP5 models and CAM4

First, we evaluate the CMIP5 models' performances in simulating winter climatology over East Asia. Focusing on variations of the EAWM, especially on the circulation, we

FIG. 1. Taylor diagram of climatological winter SLP (hPa), Z500 (m), and U300 (m s^{-1}) during 1967–2004 over East Asia (20° – 50°N , 100° – 145°E).

mainly assess the simulated SLP, Z500, and U300 over the East Asian region (20° – 50°N , 100° – 145°E) in the CMIP5 historical simulations. The Taylor diagram is used to show the quantitative evaluation (Fig. 1), which includes the spatial correlation coefficient (SCC) and the ratio of standard deviation (RSD) between the models and the observations. In the following sections, we analyze the model results, which exhibit better performances in simulating the East Asia winter climate based on the Taylor diagram. That is, the SCC must be at least 0.9, and the RSD must be between 0.75 and 1.25, which are employed in previous studies (e.g., Jiang and Tian 2013).

For the SLP, the SCC range is from 0.74 (MIROC-ESM) to 0.98 (ACCESS1.0; HadGEM2-ES). We exclude six models with an SCC less than 0.9. They are IPSL-CM5A-LR, FGOALS-g2, MIROC-ESM, MIROC4h, CCSM4, and CESM1(BGC). Most RSD values are between 0.75 and 1.25, except for GISS-E2-R (0.65) and IPSL-CM5A-LR (1.28). For Z500, the SCCs are larger than 0.99, and the RSDs are near 1.0 in most models. For U300, the SCCs are larger than 0.95 in all models. However, the RSDs are larger than 1.25 in CSIRO Mk3.6.0, IPSL-CM5A-LR and MRI-CGCM3, and these three models are thus excluded. Overall, nine models [CSIRO Mk3.6.0, IPSL-CM5A-LR, FGOALS-g2, MIROC-ESM, MIROC4h, MRI-CGCM3, GISS-E2-R, CCSM4, and CESM1(BGC)] are excluded, and the remaining 19 models, which show better performances in simulating the climatology of the EAWM, are used to investigate the internal variabilities of the EAWM on the interdecadal time scale.

In addition, some previous studies have indicated that the PDO patterns (e.g., Yim et al. 2015; Wang and Miao,

2018), the AO pattern (e.g., Zuo et al. 2013), and the AMO pattern (e.g., Han et al. 2016) in most CMIP5 coupled models are in good agreement with the observation. According to detailed information from these previous evaluations, the models analyzed in the present study have reliable simulations of these modes. Thus, we will not repeat the evaluation of these internal modes in this study.

For the CAM4, We carried out a “F_2000” simulation forced by the observed climatological (1986–2005) SST and sea ice concentration (SIC). The results show that CAM4 can simulate well the present East Asian winter climate (figure not shown). It is a good starting point to address the following issues.

4. Internal variability of the EAWM

a. The observed and simulated interdecadal weakening of the EAWM

Figure 2a illustrates the observed EAWM index and its variation on an interdecadal time scale. The larger (smaller) values of this index denote a stronger (weaker) observed EAWM. As shown in the 9-yr running mean of the EAWM index, the EAWM undergoes significant interdecadal weakening during 1967–2006. The EAWM is relatively strong during 1967–86 but becomes weaker during 1987–2006. The t value of the moving t test reaches a minimum in 1986 (Fig. 2b), which suggests that there is an abrupt change in the EAWM during the mid-1980s. We thus choose two 20-yr subperiods (i.e., 1967–86 and 1987–2006) to investigate this observed interdecadal change in the EAWM. As shown in Fig. 3a, negative SLP anomalies can be found over the northern Asian continent, whereas positive SLP anomalies are evident over southern China, indicating that the Siberian high is weakened during the latter period. Correspondingly, significant southwesterly wind anomalies are observed over northern East Asia in the lower troposphere (Fig. 3b). It is not conducive to the southward invasion of the cold air from high latitudes to East Asia. In addition, during the latter period, the EAT becomes shallower, and the EAJS shifts poleward (Figs. 3c,d). Therefore, the results indicate that the EAWM underwent a significant interdecadal weakening after the mid-1980s. As noted in a previous study, external forcings are likely to play an important role in this weakening (Miao et al. 2018b). However, how the internal variabilities contribute to interdecadal changes of the EAWM remains unclear. In the following section, this observed interdecadal weakening of the EAWM is used to make the model–data comparison.

In fact, similar interdecadal weakening of the EAWM can be found in the CMIP5 piControl simulations. Based

FIG. 2. (a) The EAWM index (gray bars) and its decadal component (9-yr running mean; line) for the period of 1948–2017 in the observation. (b) The moving t test values (gray bars) with two subseries (each duration is 20 years), and the 0.05 significance level (dashed lines). The maximum value corresponds to two subseries from 1967 to 2006 [black bar in (a)].

on the detection by using the t -test method, there are in total 53 significant interdecadal weakening cases of EAWM in the selected 19 piControl simulations (Table 2). As shown in Fig. 4a, the 9-yr running mean of the EAWM indices all show interdecadal weakening of the EAWM, especially their MCE. We further examine the large-scale common characteristics of these interdecadal weakening of the EAWM in the different coupled models.

Figure 5a shows the MCE of the differences in SLP between two subperiods in all weakening cases. Negative SLP anomalies can be found over the Arctic and Siberian regions, which show a positive AO pattern. These negative SLP anomalies are surrounded by the positive ones. Two positive SLP anomaly centers are located at the North Pacific and the Mediterranean, respectively. Particularly over the North Pacific, the positive SLP anomalies are much stronger, suggesting a positive NPO and a weakened Aleutian low. The multicas consistency indicates that more than 90% of the weakening cases show positive AO and NPO patterns (Fig. 5b). Correspondingly, anticyclonic circulation anomalies are evident over the North Pacific, and southerly wind anomalies can be found over the Asian continent in the lower troposphere (Fig. 6a). The multicas consistency for wind anomalies is larger than 90% over East Asia and the North Pacific

FIG. 3. The differences in winter (a) SLP (hPa), (b) 850-hPa wind fields (UV850) (m s^{-1}), (c) Z500 (m), and (d) U300 (m s^{-1}) between two subperiods of 1987–2006 and 1967–86. They are calculated based on (a) the HadSLP2 and (b)–(d) the NCEP–NCAR datasets, respectively. Areas exceeding the 95% confidence level are denoted with dots in (a), (c), and (d) or shaded gray in (b) based on the Student's t test.

(Figs. 6b,c). These results suggest that the common features of the interdecadal weakening cases of the EAWM are a positive AO/NPO and an associated anomalously anticyclonic circulation. In the middle troposphere, more than 90% of the weakening cases show positive Z500

TABLE 2. Number of EAWM weakening and strengthening cases selected in each model. The gaps between two cases are at least 40 years.

No.	Model	EAWM weakening	EAWM strengthening
1	BCC-CSM1.1	2	4
2	BNU-ESM	4	3
3	CanESM2	3	3
4	CMCC-CMS	2	2
5	CNRM-CM5	2	2
6	ACCESS1.0	3	1
7	ACCESS1.3	3	2
8	FIO-ESM	2	1
9	INM-CM4	2	2
10	MIROC5	2	2
11	HadGEM2-ES	3	4
12	MPI-ESM-LR	3	2
13	MPI-ESM-MR	5	4
14	MPI-ESM-P	1	1
15	GISS-E2-H	4	2
16	NorESM1-M	4	4
17	GFDL CM3	3	5
18	GFDL-ESM2G	1	2
19	GFDL-ESM2M	4	3
Sum		53	49

anomalies over the midlatitude Asian–Pacific region (Figs. 7a,b). In contrast, negative Z500 anomalies can be found over high-latitude regions; the multicas consistency is also larger than 90% in those regions. This meridional dipole pattern indicates that the EAT is weakened during the latter period. In the upper troposphere, negative (positive) U300 anomalies are evident south (north) of 40°N over the Asian–Pacific regions (Fig. 8a). The multicas consistency is larger than 90% over these regions (Fig. 8b), suggesting that the EAJS shifts poleward in most EAWM weakening cases. Overall, all the members of the EAWM system, including the Siberian high, the low-level circulation, the EAT, and the EAJS, match well the anomalous AO/NPO patterns and show an interdecadal weakening of the EAWM in these cases.

b. Simulated interdecadal strengthening of the EAWM

In addition, we also find 49 cases of significant interdecadal strengthening of the EAWM in the CMIP5 simulations (Table 2). In these cases, the 9-yr running means of the EAWM indices increase during the latter subperiod (Fig. 4b). As indicated by anomalous spatial patterns, the SLPs increase over the mid- and high-latitude Asian regions (Fig. 5c), and the Z500s decrease over northeastern China and southern Japan (Fig. 7c), implying a strengthened Siberian high and a deepened East Asian trough. Northeasterly wind anomalies are

FIG. 4. The EAWM indices (9-yr running mean; gray) of the selected (a) weakening and (b) strengthening cases of the EAWM in the 19 CMIP5 models and their ensemble mean (black). The red line in (a) stands for the observed EAWM index for the period of 1967–2006.

evident over East China (Fig. 6d), and the EAJS shifts equatorward (Fig. 8c). In these cases, the EAWM experiences significant interdecadal strengthening.

At the same time, positive SLP anomalies are evident over the Arctic regions, which are accompanied by negative SLP anomalies over the North Pacific and North Europe (Fig. 5c). It suggests a negative AO phase and a negative NPO phase in most interdecadal strengthening cases of the EAWM (Fig. 5d). As a result, cyclonic circulation anomalies are seen over the North Pacific (Fig. 6d). The multicase consistencies for the wind fields are larger than 90% over the Asian–Pacific regions (Figs. 6e,f). Overall, significant interdecadal strengthening cases of the EAWM can also be found in the CMIP5 piControl simulations. The EAWM members and the associated large-scale circulation show changes that are opposite to the weakening cases.

c. Mechanisms for the EAWM interdecadal variations

Based on observational studies, the decadal variations of the East Asian winter climate are closely related to the natural variabilities of the ocean (e.g., Li et al. 2009; J. Sun et al. 2016), and phase shifting of the PDO is likely one of the most important reasons for that (e.g., Zhu and Yang 2003; Ding et al. 2014). Indeed, in most cases of interdecadal weakening of the EAWM, we can find similar, anomalously negative PDO-like SST patterns in the later subperiods relative to the former ones. Positive SST anomalies are evident over the western North Pacific (Fig. 9a). The maximum positive anomalies are observed over the Kuroshio–Oyashio Extension region. Additionally, these positive SST anomalies are surrounded by negative ones in the North Pacific. Particularly in the high-latitude North Pacific, the negative SST anomalies are relatively stronger. It suggests that the PDO enters its negative phase from the former subperiod to the latter

one. Changes in the MCE of the PDO indices further confirm this phase shifting (Fig. 10a). In the interdecadal strengthening cases of the EAWM, the changes in the PDO are reversed (Figs. 9c and 10b). Thus, the weakening (strengthening) of the EAWM generally correlates with the negative (positive) phase of the PDO. However, the PDO phase transition occurs later than the interdecadal variation of the EAWM, implying that the PDO may not be the cause of the interdecadal variations of the EAWM. We calculate the correlation coefficients of the low-pass-filtered PDO and EAWM indices in each 500-yr piControl simulation (Fig. 11a). The results show that the relationships between the PDO and the EAWM are close in most models (14 of 19 models). The correlation coefficients are positive in 18 models and significant ($p < 0.05$) in 11 models. Nevertheless, changes in the EAWM lead the PDO in these long-term simulations (Fig. 12). In most models, the simulated EAWM indices lead the PDO indices by 2–4 years, suggesting that the PDO cannot be the reason for the interdecadal weakening (strengthening) of the EAWM in the piControl simulations.

We carry out some additional CAM4 experiments to examine the influence of the PDO on the EAWM. The simulation is set up using the “F_1850” configuration. The atmospheric composition constant is set in the year 1850. A total of five simulations are carried out (Table S1 in the online supplemental material). All the simulations are integrated for 40 years, and the averages of winters in the last 30 years are analyzed. The first simulation is a control simulation, which is forced by the CAM4’s pre-industrial climatological SST and sea ice boundary conditions. This control simulation is herein abbreviated as EXP1. In the second simulation (EXP2), an anomalously negative PDO-like SST pattern is added to the climatological SST boundary condition (shown in Fig. 9a). Specifically, only the SST anomalies where the multicase consistency is larger than 70% are added into the North

FIG. 5. (a) The simulated MCE of the differences in winter SLP (hPa) between the two subperiods in the interdecadal weakening cases of the EAWM and (b) their multicase consistency (%). (c), (d) As in (a) and (b), but for the interdecadal strengthening cases of the EAWM.

Pacific region (20°–60°N, 110°E–100°W). Similarly, an anomalously positive PDO-like SST pattern (Fig. 9c) is added into the climatological SST in the third simulation (EXP3). The differences between EXP2 (EXP3) and EXP1 reflect the impacts of the PDO-like SST anomalies in the piControl simulations on the climate. Furthermore, we perform sensitivity simulations named EXP4 and EXP5. They are similar to EXP2 and EXP3, but the

added SST anomalies are doubled in these two simulations. The CAM4 simulations show that the PDO-like SST pattern could not cause significant changes in the EAWM in the AGCM experiments, even when the SST anomalies are doubled (Figs. S1 and S2). These results confirm that the PDO is unlikely to be the reason for the interdecadal variations of the EAWM, as suggested by the CMIP5 coupled model results.

FIG. 6. (a) The simulated MCE of the differences in winter UV850 (m s^{-1}) between the two subperiods in the interdecadal weakening cases of the EAWM, and (b),(c) their multicase consistency (%). (d)–(f) As in (a)–(c), but for the interdecadal strengthening cases of the EAWM.

In addition to the natural variabilities in the ocean, the interdecadal variations of the EAWM are also related to major modes of natural variability in atmospheric circulation (summarized in Ding et al. 2014). As mentioned above, the SLP anomalies in the EAWM weakening

(strengthening) cases resemble the positive (negative) phase of the AO/NPO, respectively (Fig. 5). In each coupled model, we calculate the winter AO and NPO indices in the 500-yr piControl simulations and the correlation coefficients between the 9-yr low-pass-filtered

FIG. 7. (a) The simulated MCE of the differences in winter Z500 (m) between the two subperiods in the interdecadal weakening cases of the EAWM and (b) their multicase consistency (%). (c),(d) As in (a) and (b), but for the interdecadal strengthening cases of the EAWM.

FIG. 8. (a) The simulated MCE of the differences in winter U300 (m s^{-1}) between the two subperiods in the interdecadal weakening cases of the EAWM and (b) their multicase consistency (%). (c),(d) As in (a) and (b), but for the interdecadal strengthening cases of the EAWM.

AO/NPO and EAWM indices (Figs. 11b,c). We find that the correlation coefficients between AO and EAWM indices are significantly negative in all the models at the 0.05 significance level. For the NPO and EAWM indices, the correlation coefficients are all negative and significant in the most models. The weakening (strengthening) of the

EAWM is thus highly correlated with the positive (negative) phase of the AO/NPO. We further examine the AO and NPO indices in the models' EAWM weakening (strengthening) cases (Figs. 10c-f) and find that the AO and NPO also experience an interdecadal phase shift. The phase shifting of the MCEs of the AO and NPO indices is

FIG. 9. (a) The simulated MCE of the differences in winter SST ($^{\circ}\text{C}$) between the two subperiods in the interdecadal weakening cases of the EAWM and (b) their multicase consistency (%). (c),(d) As in (a) and (b), but for the interdecadal strengthening cases of the EAWM.

FIG. 10. The winter (a) PDO, (c) AO, and (e) NPO indices (9-yr running mean; gray) of the EAWM weakening cases in the models and their MCE (black). The blue lines are the MCE of the EAWM index in the EAWM weakening cases in the models that presented in Fig. 4. (b),(d),(f) As in (a), (c), and (e), but for the EAWM strengthening cases.

consistent with those of the EAWM, and the interdecadal changes of the MCEs of the AO indices are larger. This means that the AO could play an important role in causing interdecadal variations of the EAWM. Both the NPO phase shifting and PDO-like SST anomalies are possibly caused by the interdecadal variations of the AO, which needs further investigation.

We further show the cross-correlation coefficients between the low-pass-filtered AO and EAWM indices for the 500-yr simulation in each model. As shown in Fig. 13, the correlation coefficients are minimized and become significant at the zero point in all the simulations, which implies that the AO is in phase with the EAWM at a decadal time scale. To confirm this inferred linkage, we

also examine the ensemble mean of the regression map of the EAWM-related variables on the AO index (9-yr low-pass filtered) in each model's 500-yr piControl simulation. As shown in Fig. 14a, during the positive phase of the AO, negative SLP anomalies can be seen over the Arctic and Siberian regions. In contrast, positive SLP anomalies are evident over the North Pacific and the North Atlantic. Both the Siberian high and the Aleutian low are thus weakened. Correspondingly, anomalous anticyclonic circulation can be found over the North Pacific, and southerly winds are obvious over the northern Asian continent and eastern China (Fig. 14b). In the middle troposphere, positive Z500 anomalies over the midlatitude Asian-Pacific region reveal that the EAT is weakened

FIG. 11. The correlation coefficient between the winter values of (a) PDO, (b) AO, and (c) NPO and the EAWM index for the 500-yr piControl simulations (the 9-yr low-pass filter is employed on the all indices). The symbols indicate the significance level.

(Fig. 14c). In the upper troposphere, the EAJ is weakened and shifted poleward (Fig. 14d). The patterns for the anomalous atmospheric circulations resemble those in the EAWM weakening cases shown in Figs. 5–8, and vice versa (not shown). Therefore, the phasing shifting of the AO should be the main reason for the interdecadal variations of the EAWM in the piControl simulations.

5. Discussion and conclusions

In this study, we investigate the internal variability of the EAWM on the interdecadal time scale using the piControl simulations output from CMIP5 coupled models. Nineteen simulations from the selected coupled models are analyzed here. A total of 53 cases of significant interdecadal weakening of the EAWM can be found in these 500-yr piControl simulations. We further illustrate the ensemble differences in the EAWM-related atmospheric circulations between two subperiods of these cases to find the commonalities among them. The result indicates that when the EAWM weakens in the piControl simulations, positive AO and NPO patterns can be found

in more than 90% of cases. Correspondingly, anticyclonic circulation anomalies are obvious over the North Pacific, and southerly wind anomalies can be found over the Asian continent in the lower troposphere. In addition, the EAT in the midtroposphere is weakened, and the EAJ in the upper troposphere is weakened and shifted poleward. These simulated changes resemble the observed interdecadal weakening of EAWM around the mid-1980s. In instances of interdecadal strengthening of the EAWM, the anomalous patterns are opposite. We further investigate the mechanisms for the interdecadal variations of the EAWM in the piControl simulations. The result suggests that the interdecadal phase shifting of the AO is likely the main reason for the EAWM interdecadal variations in the piControl simulations.

As shown in Table 2, there are few cases of significant interdecadal weakening and strengthening of the EAWM in each 500-yr simulation. The average number of weakening and strengthening cases is approximately $2.8 (500 \text{ yr})^{-1}$ and $2.6 (500 \text{ yr})^{-1}$, respectively. This means that the probability of interdecadal variations of the EAWM is very low in an unforced climate system.

FIG. 12. The cross-correlation coefficient between the winter PDO and EAWM index for the 500-yr piControl simulations (9-yr low-pass filtered). The positive value of x axis means that PDO leads EAWM index, and vice versa. The dashed lines indicate the 0.05 significance level.

Though the internal variability of the climate system can cause interdecadal weakening of the EAWM, the associated large-scale circulation anomalies exhibit some differences from those observed in the mid-1980s mainly over the North Pacific. It implies that their root causes could be different. As noted by our previous study (Miao et al. 2018b), the multimodel ensemble of the CMIP5 historical simulations, which excludes internal variability of the climate system, can reproduce well the weakening shift of the EAWM in the observation. It means that the external forcing agencies are likely to play a dominate role in causing the observed interdecadal weakening of EAWM in the mid-1980s. Compared with the piControl simulations, in addition, the simulated weakening in the CMIP5 historical simulations indeed resembles the observed one better. The differences between the piControl simulations and observation/historical simulations also confirm the important

influences from external forcings on the interdecadal weakening of the EAWM around the mid-1980s. In fact, it is difficult to quantify the relative contributions of the external forcing and the internal variability to the observed interdecadal weakening of the EAWM due to nonlinearity of the climate system. This present result suggests that the internal variability of the climate system may also contribute to the observed interdecadal weakening of EAWM in the mid-1980s. If it is true, the role of the internal variability could be secondary based on the CMIP5 multimodel results.

Our study emphasizes the AO's role in causing the interdecadal variations of the EAWM in the no transient external agents forced climate system. The correlation coefficients between the 9-yr low-pass-filtered AO and EAWM indices are significantly negative in all the models at the 0.05 significance level (Fig. 11b). In the observation, during the period of 1951–2012, the

FIG. 13. The cross-correlation coefficient between the winter AO and EAWM index for the 500-yr piControl simulations (9-yr low-pass filtered). The positive value of x axis means that AO leads the EAWM index, and vice versa. The dashed lines indicate the 0.05 significance level.

correlation coefficient between the EAWM and the AO indices (9-yr running mean) is -0.84 ($p = 0.08$; Fig. S3), similar to the relationship between them in the piControl simulations. And the observed AO phase shifting could contribute to the interdecadal weakening of the EAWM around the mid-1980s (He and Wang 2012). However, during a longer period (1872–2012), the correlation coefficient between them is -0.43 (non-significant). It means that the AO–EAWM relationship is unstable in the observation. We further examined the relationship between the AO and EAWM in the CMIP5 historical simulations. More than half the models cannot reproduce the significant correlation between the AO and EAWM (Fig. S4), which is very different from the piControl simulations. The external forcings, which can regulate both the AO (e.g., Shindell et al. 2001; Wang et al. 2012) and the EAWM (e.g., Miao et al. 2016, 2018a), could be one of the reasons for the observed

unstable AO–EAWM relationships. Some further studies are needed on this point.

In the observation, the correlation coefficient between EAWM and PDO is only 0.32 (nonsignificant) for the period of 1901–2012 (Fig. S5). In addition, the PDO phase shifting occurred around the late 1970s, which is earlier by 5–6 years relative to the interdecadal weakening of the EAWM around the mid-1980s. This also confirms our previous conclusion that the PDO phase shifting could not be the reason for the interdecadal variations of the EAWM.

As noted in the introduction, ENSO has significant impacts on the EAWM at the interannual time scale. The positive (negative) phase of ENSO favors a weaker (stronger) EAWM. On the interdecadal time scale, however, the influence from ENSO is not significant. As shown in Fig. 9, there are no significant SST anomalies over the tropical eastern Pacific. This suggests that

FIG. 14. The ensemble mean of the regression map of the winter (a) SLP (hPa), (b) UV850 (m s^{-1}), (c) Z500 (m), and (d) U300 (m s^{-1}) on the AO index in each model's 500-yr piControl simulation. The atmospheric variables and AO index are both 9-yr low-pass filtered.

ENSO has no influence on the interdecadal variations of the EAWM in the piControl simulations.

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