Impacts of the Pacific–Japan and Circumglobal Teleconnection Patterns on the Interdecadal Variability of the East Asian Summer Monsoon

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ABSTRACT

Based on the Twentieth Century Reanalysis (20CR) dataset, the dominant modes of interdecadal variability of the East Asian summer monsoon (EASM) are investigated through a multivariate empirical orthogonal function analysis (MV-EOF). The first mode (EA1) is characterized by an anomalous cyclone centered over Taiwan and an anomalous anticyclone centered over the Bohai Sea. These phenomena are part of the meridional wave–like teleconnection pattern propagating poleward from the southern tropical western North Pacific (WNP), referred to as the interdecadal Pacific–Japan (PJ) pattern. The interdecadal PJ pattern is driven by negative anomalous convective heating over the southern tropical WNP, which is associated with the interdecadal Pacific oscillation (IPO) and the interdecadal Indian Ocean basin mode (IOBM). The amplitude of the EA1 and its contribution to the total variance of the EASM decrease remarkably after the 1960s. The second MV-EOF mode (EA2) is characterized by cyclone anomalies extending from northeastern China to Japan, which are part of a circumglobal wave train. Given the spatial scale of the wave train in the zonal direction (wavenumber 5), as well as the fact that it possesses barotropic structures and propagates along the Northern Hemispheric jet stream, it is referred to herein as the interdecadal circumglobal teleconnection (CGT) pattern. The interdecadal CGT pattern is associated with the forcing from the Atlantic multidecadal oscillation (AMO). Though the interdecadal PJ and CGT patterns are derived from the 20CR dataset, they are carefully verified through comparisons with various observational and reanalysis datasets from different perspectives.

1. Introduction

The East Asian summer monsoon (EASM) experienced dramatic interdecadal changes during the latter half of the twentieth century [see reviews by Zhou et al. (2009a) and Hsu et al. (2014)]. The major changes

included the western Pacific subtropical high being extended westward (Hu 1997; Gong and Ho 2002; Zhou et al. 2009b); the northward wind along the East Asian coast having weakened, which caused a decrease in northward moisture transport (Ding et al. 2008); the Asian jet stream being shifted southward (Yu et al. 2004); tropospheric temperatures over East Asia decreasing significantly (Yu et al. 2004; Yu and Zhou 2007); and the land–sea thermal contrast across the East Asian continent and marginal oceans weakening (Ding et al. 2008). All these phenomena indicate a weakening of the EASM circulation. Meanwhile, precipitation along the Yangtze River valley increased, while that over south China and north China decreased (Hu 1997; Yu et al. 2004; Ding et al. 2008).

The weakening of the EASM has been studied from several different perspectives. Some studies have

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attributed this trend to tropical forcing (Yang and Lau 2004; Zhou et al. 2008; C. Li et al. 2010; H. Li et al. 2010). Based on the numerical experiments of atmospheric general circulation models driven by global and tropical sea surface temperature anomalies (SSTAs), C. Li et al. (2010) demonstrated that the weakening of the EASM is primarily caused by tropical SST interdecadal variations. H. Li et al. (2010) proposed that tropospheric cooling over East Asia, an important feature of the weakening EASM (Yu et al. 2004; Yu and Zhou 2007), is triggered by the interdecadal variation of convective heating over the South China Sea through an anomalous meridional vertical overturning circulation pattern and is further maintained by an in situ positive vertical motion–moisture–radiation feedback process.

The weakening of the EASM has also been attributed to the weakening of atmospheric heating over the Tibetan Plateau (Ding et al. 2009; Liu et al. 2012), the global warming caused by the increasing concentrations of greenhouse gases (GHGs) in the atmosphere (Zhu et al. 2012), and the increased level of air pollution across East Asia (Menon et al. 2002; Qian et al. 2009; He et al. 2013; Wang et al. 2013; Song et al. 2014).

Importantly, most of the above-mentioned studies focused on the latter half of the twentieth century, primarily as a result of the rich observational and reanalysis data available for this period. However, there are two problems that are inevitably hard to address because of the relatively short time span. First, it is difficult to distinguish the interdecadal variability of the EASM internally generated in the climate system from its response to the external forcings, which include anthropogenic forcing (e.g., GHGs and aerosols) and natural forcing (e.g., volcanic eruptions and solar activity). Second, it is difficult to identify whether a forcing factor responsible for the interdecadal change of the EASM is an internal fluctuation of the climate system or an external forcing.

These two problems may be partially solved by following two strategies. First, based on limited instrumental measurements, analysis of the interdecadal variability of the EASM can extend back to the early twentieth century or even the late nineteenth century (Ding et al. 2008; Lei et al. 2011; Qian and Zhou 2014). These studies indicated that the long-term changes in the EASM can be mainly attributed to the responses to internal fluctuations, rather than to external forcing (Ding et al. 2008; Lei et al. 2011; Zhou et al. 2013). However, because the observational data before the 1950s are confined to very limited surface variables, and are highly inadequate in both spatial coverage and temporal frequency, it is difficult to perform mechanistic analyses.

The other strategy considered involves carrying out numerical simulations using coupled general circulation models (GCMs). Lei et al. (2014) analyzed the links between the EASM and the internal variability mode of the climate system in the long-term pre-industrial control simulations of a coupled GCM, which explicitly excluded external radiative forcing. The simulated EASM showed interdecadal variability with amplitudes comparable to those in observational data. However, the simulated large-scale fields were not consistent with the observations. Based on the multimodel separate forcing runs from phase 5 of the Coupled Model Intercomparison Project (CMIP5), Song et al. (2014) argued that the weakening of the EASM is significantly forced by aerosol emissions, while the forcing by GHGs partially offsets the weakening effect. However, they also recognized that the strategy of the multimodel ensemble mean eliminated the potential effects of the internal variability of the climate system.

The release of the Twentieth Century Reanalysis (20CR) dataset provides us with another possible strategy to address the problem. The 20CR dataset assimilates observational synoptic surface pressure and sea level pressure and provides a dynamically and physically consistent set of regular meteorological variables for the period of 1871–2012. In the present study, based on this long-term dataset, we explicitly separate the interdecadal variability of the EASM from externally forced global climate change, and then investigate the mechanisms responsible for the interdecadal variability. The results based on the 20CR are further verified by using other independent observational precipitation and temperature datasets.

The remainder of the paper is organized as follows. In section 2, the datasets and analysis methods are introduced. In section 3, the two leading modes of the interdecadal variability of the EASM are extracted. Sections 4 and 5 investigate the large-scale circulation anomalies and related physical processes associated with the first and second modes, respectively. Finally, the key findings of the study are summarized in section 6.

2. Datasets and methods

a. Datasets

This study is primarily based on the atmospheric circulation results from the 20CR dataset, which covers the period from 1871 to the present (Compo et al. 2011). The analysis was performed using an ensemble Kalman

filter data assimilation method. It only assimilated the observational surface pressure and sea level pressure and, thus, could be extended back to 1871. The global atmospheric model, which produced the first guess for the analysis, was driven by observational SST results from the HadISST version 1.1 dataset (HadISST1.1; Rayner et al. 2003). Therefore, the SST dataset was also used in the study to obtain consistent results. The horizontal resolutions of 20CR and HadISST1.1 are $2^\circ \times 2^\circ$ and $1^\circ \times 1^\circ$, respectively. Because SST observations in the tropical ocean are very sparse before 1920 (Dai 2013), we focus on the period of 1920–2012.

The vorticity and streamfunction used in the study were calculated using the zonal and meridional components from 20CR via spherical harmonics with T42 truncation. To obtain spatially smooth fields, the amplitudes of the spherical harmonic coefficients at high frequencies were reduced by multiplying $\exp\{-[n(n+1)/N(N+1)]^r\}$, as in Sardeshmukh and Hoskins (1984). In this study, n , N , and r are equal to 42, 24, and 8, respectively. Under the parameter setting, the tape weight of mode 24 will decrease to $\exp(-1)$.

The results derived from 20CR are verified through comparisons with the following observational and reanalysis datasets. 1) The atlas of seasonal mean precipitation percentage anomalies over east China, spanning 1880–2007, is used (Wang et al. 2000). This dataset combines instrumental observations and proxy data, and includes 71 stations in east China (Fig. 1). It is thus referred to as the 71-station precipitation dataset. 2) Global land precipitation results from 1901 to 2009 in the Climatic Research Unit (CRU) time series dataset, version 3.10, are examined (Harris et al. 2014). This is a high-resolution gridded observational dataset, with a horizontal resolution of $0.5^\circ \times 0.5^\circ$. 3) The CRUTEM3 global historical land surface air temperature dataset is used to represent the period from 1850 to the present; this dataset is a collaborative product of the Met Office Hadley Centre and the CRU (Brohan et al. 2006). CRUTEM3 is a gridded dataset, with a horizontal resolution of $5^\circ \times 5^\circ$. 4) The Japanese 55-year Reanalysis Project (JRA-55) dataset (Ebita et al. 2011), produced by the Japan Meteorological Agency (JMA), is included. This reanalysis dataset covers the period from 1958 to 2012, with a horizontal resolution of $1.25^\circ \times 1.25^\circ$. 5) The ERA-20C dataset is an atmospheric reanalysis of the twentieth century produced by the European Centre for Medium-Range Weather Forecasts (ECWMF). The reanalysis dataset covers the period 1900–2010, with a horizontal resolution of approximately 125 km (Poli et al. 2013).

FIG. 1. Latitude–longitude locations of the 71 stations in the precipitation dataset.

b. Methods

1) EXTRACTION OF INTERDECADAL SIGNAL

In this paper, we focus on the interdecadal variability of the EASM. Hence, we first filtered out the variability shorter than 7 yr through use of a Lanczos filter (Duchon 1979), and then we removed the signals associated with the global-mean SST through the following method (Mann and Emanuel 2006; Ting et al. 2009). The low-pass-filtered fields were regressed onto the low-pass-filtered time series of the global mean SST. The residual terms of the regression, which are dominated by the interdecadal variability, are what we need.

2) MULTIVARIATE EMPIRICAL ORTHOGONAL FUNCTION ANALYSIS

Multivariate empirical orthogonal function (MV-EOF) analysis is an extension of conventional EOF analysis, and can be used to extract dominant patterns with coherent spatial phase relationships from multi-field data (Wang 1992). In this study, MV-EOF analysis was applied to the June–August (JJA) mean 850-hPa wind vectors over the EASM region (10° – 45° N, 100° – 145° E), in which the variability shorter than 7 yr and associated with global-mean SST was removed using the methods introduced above. The analysis steps taken were as follows. First, normalized anomaly series for zonal and meridional wind components were separately obtained. Second, the combined matrix of the normalized zonal and meridional wind series was decomposed as the conventional EOF analysis. Finally, the first three empirical functions obtained were converted into spatial patterns of zonal and meridional wind components. The

large-scale atmospheric circulation pattern and SSTAs associated with these dominant modes were obtained by regressing low-pass-filtered fields onto the corresponding normalized principal component (PC) time series.

3) SIGNIFICANCE TESTS

Low-pass filtering reduces the effective sample sizes of time series remarkably. However, the degree of reduction is difficult to estimate accurately. Hence, we used a nonparameter method to replace the conventional Student's t test for identifying the significance of correlation and regression analyses. The method was developed by Ebisuzaki (1997) and is referred to as the random-phase test. Consider two time series: A and B . Simply, the significance of the correlation between A and B , $r(A, B)$, can be tested using the following two steps. First, we construct N different time series randomly, all of which have the same power spectrum but different temporal phases with A , through a discrete Fourier analysis. Second, we calculate the correlations between B and these random-phase time series. If $r(A, B)$ is equal to or greater than 95%, or equal to or less than 5%, of the correlations from the random-phase time series, the 10% statistical significance level is attained. In the present study, N was set to 5000. The significance of regression analysis was also tested using a similar method.

4) DEFINITION OF THE IPO AND AMO

An EOF analysis was applied to 7-yr low-pass-filtered JJA-mean near-global observed SSTs to extract the globally dominant interdecadal fluctuations of SST for the period of 1920–2012. The first three dominant modes account for 41.4%, 11.0%, and 5.5% of the total variances, respectively, and are well separated from each other according to the criteria of North et al. (1982). The first dominant mode is associated with global warming (figure not shown). The second and third modes represent the interdecadal Pacific oscillation (IPO, e.g., Power et al. 1999; Meehl and Hu 2006) and Atlantic multidecadal oscillation (AMO, e.g., Kushnir 1994; Delworth and Mann 2000), respectively (Figs. 2a,b). The corresponding normalized PC time series are defined as the summertime IPO and AMO indices, respectively (Fig. 2c). The AMO index is highly correlated with the 7-yr low-pass-filtered convectional AMO index, which is defined as the SST averaged over 0° – 60° N, 0° – 80° W minus the SST averaged over 60° S– 60° N [$r = 0.69$; Trenberth and Shea (2006)].

5) WAVE ACTIVITY FLUX

The wave activity flux for stationary Rossby waves embedded in a zonally asymmetric climatological-mean flow was diagnosed, which represents the directions of propagation of the wave energy (Takaya and Nakamura

2001). Its horizontal components in pressure coordinates are

$$W = \frac{1}{2|\mathbf{u}|} \left\{ \begin{array}{l} \bar{u}(\psi_x'^2 - \psi'\psi_{xx}') + \bar{v}(\psi_x'\psi_y' - \psi'\psi_{xy}') \\ \bar{u}(\psi_x'\psi_y' - \psi'\psi_{xy}') + \bar{v}(\psi_y'^2 - \psi'\psi_{yy}') \end{array} \right\}. \quad (1)$$

Here, overbars and primes denote mean states and low-pass-filtered anomalies, respectively. The quantity $\mathbf{u} = (u, v)$ denotes the horizontal wind velocity, ψ streamfunctions, and f the Coriolis parameter.

3. Characteristics of the dominant modes of the EASM on the interdecadal time scale

a. Dominant modes derived from 20CR

The first two MV-EOF modes of the preprocessed JJA-mean 850-hPa wind vectors over the EASM region during 1920–2012 [see sections 2b(1) and 2b(2)] are shown in Figs. 3a,b. They account for 22.1% and 17.8% of the total variances, respectively, and can be distinguished from each other according to the criteria of North et al. (1982).

For the first mode (EA1), East Asia is dominated by a meridionally arranged anomalous cyclone centered over Taiwan, and an anomalous anticyclone centered over the Bohai Sea (Fig. 3a). As we will discuss below, the meridionally arranged anomalous cyclone and anticyclone are part of the Pacific–Japan (PJ) pattern on the interdecadal time scale. Corresponding to the positions of the anomalous cyclone and anticyclone, the mode contributes substantially to the variance of the meridional winds over southeastern China, the Philippine Sea, and the Bohai Sea and its adjacent areas (Fig. 3c).

An important feature of the EA1 mode is that the amplitude of its PC time series (PC-EA1) during 1967–2012 decreases by about 70% relative to 1920–67 (Fig. 3e). Correspondingly, the contribution of EA1 to the total variance of the 850-hPa wind over the EASM region decreases from 32.4% to 4.3%. We will discuss this feature in section 6b.

The predominant feature of the second mode (EA2) is a strong anomalous cyclone extending from northeastern China to Japan. To the south, there is another weak anomalous cyclone, which covers southeastern China (Fig. 3b). The mode accounts for more than 50% of the variance in the meridional wind over northeastern China and the east of Japan (Fig. 3d). As we will discuss below, the strong anomalous cyclone is associated with a circumglobal teleconnection (CGT) pattern on the interdecadal time scale.

The third mode is dominated by an anomalous cyclone over the subtropical western North Pacific (WNP)

FIG. 2. Spatial patterns of the (a) IPO and (b) AMO derived from the second and third EOF modes of 7-yr low-pass-filtered JJA-mean near-global SST (40°S – 60°N) from 1920 to 2012 (K). (c) Corresponding normalized PC time series of the IPO and AMO indices.

(figure not shown). Compared with the first two modes, this mode contributes less to the variance of the meridional winds over the East Asian continent (figure not shown). Hence, we focus on the first two modes in this paper.

To test the reliabilities of EA1 and EA2, we try to apply a similar EOF analysis to the other long-term reanalysis dataset (ERA-20C). The PC time series of the first two modes are highly correlated with PC-EA1 and PC-EA2, respectively, with correlation coefficients reaching 0.66 and 0.71 (Fig. 3e). Though the PC time series show the high correlations, the spatial patterns of the dominant modes derived from the ERA-20C show some differences from those from the 20CR, especially for the second mode (see Fig. S1 in the supplementary material), which will be discussed below. In this study, we focus on

the 20CR. All of the figures derived from the ERA-20C are shown in the supplementary material.

The EA1 and EA2 modes have counterparts in the observations. A similar EOF analysis is applied to the observational CRU land precipitation results over the same domain. The obtained first two dominant modes account for 15% and 12.3% of the total variances. Their PC time series are highly correlated with PC-EA1 and PC-EA2, respectively, with correlation coefficients reaching between 0.59 and 0.43 (Fig. S2 in the supplementary material).

b. Corresponding precipitation anomalies

To explore the precipitation anomaly patterns associated with EA1 and EA2, we calculated the correlations between low-pass-filtered precipitation anomalies

FIG. 3. The dominant (a) EA1 and (b) EA2 modes of JJA-mean 850-hPa wind vectors over the EASM region (10°–45°N, 100°–145°E) for the period of 1920–2012 in which the variability of <7 yr and associated with the global-mean SST have been removed (m s^{-1}). Variance contributions of the two modes are noted in the top-right corner. (c),(d) Spatial distributions of the 850-hPa meridional wind variance explained by the two modes (%). (e) Normalized PC time series of the two modes (thick solid lines) and normalized PC time series of the first and second modes derived from the ERA-20C (thin dashed lines).

from three different datasets and the PC-EA1 and PC-EA2, respectively (Fig. 4). Importantly, the precipitation anomaly patterns from 20CR should be dynamically consistent with the circulation anomalies

shown in Figs. 3a,b. Hence, the reliabilities of the EA1 and EA2 modes can be verified by comparing the precipitation anomaly patterns from 20CR with those from the observational datasets.

FIG. 4. Spatial distributions of the correlations between the PC-EA1 time series and low-pass-filtered JJA-mean precipitation anomalies from the (a) 20CR, (b) CRU, and (c) 71-station dataset. (d)–(f) As in (a)–(c), but for the EA2 mode. White dots represent values reaching the 10% significance level. Gray shading on land areas denotes missing observations. The boxes enclosed with dashed lines are referenced in Fig. 5.

The precipitation anomaly pattern associated with EA1 from 20CR exhibits a meridional dipole structure, with positive correlations over the southeastern coast of China and the northern tropical WNP, and negative correlations over northeastern China and southern Japan, both of which reach the 10% significance level (Fig. 4a). The positive and negative precipitation anomalies correspond to the cyclone and anticyclone anomalies centered over Taiwan and the Bohai Sea, respectively (Fig. 3a). The precipitation anomaly patterns from the CRU and 71-station datasets also exhibit dipole structures, though the correlations are weaker than those from 20CR (Figs. 4b,c). The main difference is that the positive correlation centers from the two observational datasets are shifted westward relative to that from 20CR. However, it is worth noting that some positive correlations are seen over Taiwan and the northern Philippines in the CRU data (Fig. 4b), suggesting that the positive precipitation anomalies over the northern tropical WNP in 20CR should be realistic.

The predominant feature of the precipitation anomalies associated with EA2 from 20CR is a positive

anomalous precipitation belt extending from continental East Asia to Japan (Fig. 4d). For the CRU dataset, significant positive correlations are seen in southeastern and northwestern China, consistent with those from 20CR, while correlations in northeastern China and Japan are opposite to those from 20CR (Fig. 4e). The spatial pattern of correlations in eastern China from the 71-station dataset is generally the same as that from the CRU dataset (Fig. 4f). The difference between the observational data and 20CR in northeastern China is discussed in section 6b.

The above results indicate that the precipitation correlation patterns from 20CR show some similarities with the observations for both modes. To further verify the reliability of the two modes derived from 20CR, in Fig. 5 we show the temporal evolutions of the area-averaged precipitation anomalies over northeastern (boxes in Figs. 4a,c) and southeastern China (boxes in Figs. 4d,f), which are closely associated with the EA1 and EA2 modes, respectively.

The area-averaged precipitation anomalies over northeastern China from both 20CR and the 71-station

FIG. 5. (a) PC-EA1 time series (shading) and the area-averaged JJA-mean precipitation anomalies over northern China (30° – 42° N, 110° – 123° E; boxes in Figs. 4a,c) from the 20CR (red line) and 71-station (blue line) datasets (mm day^{-1}) in which the variability of <7 yr and associated with global-mean SST have been removed. (b) As in (a), but for the PC-EA2 time series over southern China (22° – 30° N, 105° – 120° E; boxes in Figs. 4d,f).

dataset are generally in opposite phase to the PC-EA1 time series. The correlation between the precipitation time series from the 71-station dataset and PC-EA1 time series is -0.65 , reaching the 10% significant level. Interestingly, the amplitudes of the precipitation time series during 1967–2007 derived from the 71-station datasets decrease by about 55% relative to 1920–66, consistent with the PC-EA1 time series (Figs. 3e and 5a).

In terms of the PC-EA2 time series, the EA2 mode is in positive phase during 1923–55 and 1993–2009, but in negative phase during 1956–92 (Fig. 5b). The phase transitions are highly consistent with the area-averaged precipitation anomalies over southeastern China from both the 20CR and 71-station datasets (Fig. 5b). The correlation between the precipitation time series from the 71-station dataset and PC-EA2 time series is 0.6 , reaching the 10% significant level.

The reliability of the EA1 and EA2 modes has therefore been preliminarily verified through comparison with station and gridded observational precipitation data. In the following sections, the two modes are further verified through comparisons with observations from other perspectives.

4. Origin of the EA1 mode

a. The PJ pattern on the interdecadal time scale

To investigate the large-scale circulation anomalies associated with the EA1 mode, the corresponding 850- and 200-hPa vorticity anomalies are shown in Fig. 6.

There are meridional wave-like circulation anomalies extending from the Philippine Sea to East Asia in the lower troposphere, with an anomalous cyclone centered over Taiwan, and anomalous anticyclones centered over the Philippine and Bohai Seas (Fig. 6a). The meridionally arranged wavelike pattern closely resemble the PJ pattern originally defined on the interannual or intra-seasonal time scales (e.g., Nitta 1987; Huang and Sun 1992; Kosaka and Nakamura 2006; Hsu and Lin 2007). In the upper troposphere, there are also meridionally arranged anomalous cyclones and anticyclones with alternating signs, which shift poleward relative to the low-level wave train by about a quarter of a wavelength (Figs. 6a,b). The phase shift with height indicates that the teleconnection pattern is a superposition of baroclinic and barotropic modes, which is a key property of the conventional PJ pattern, as noted by Kosaka and Nakamura (2006).

To explore the wave energy propagation associated with EA1, the wave activity fluxes were calculated for both the upper and lower troposphere (Figs. 6a,b). Poleward energy propagation from the tropical WNP to East Asia is seen in the lower troposphere, but not in the upper troposphere. In terms of the previous study by Kosaka and Nakamura (2006), for the conventional PJ pattern, although the meridional wave-like pattern can be seen in both the upper and lower troposphere, the poleward energy dispersion from the tropical WNP to the middle latitudes only occurs in the lower troposphere, because there is a strong meridional vertical shear in the mean wind and southerly wind components

FIG. 6. (a) Low-pass-filtered JJA-mean 850-hPa vorticity regressed onto the PC-EA1 time series (shading, 10^{-6} s^{-1}) and corresponding wave activity flux (vectors, $\text{m}^2 \text{ s}^{-2}$). (b) As in (a), but for 200 hPa. Vorticity anomalies exceeding the 10% significance level are white dotted.

are confined to the lower troposphere. Therefore, the wave energy propagation property associated with EA1 is also consistent with the conventional PJ pattern.

The dynamical similarities between the large-scale circulation anomalies associated with EA1 and the conventional PJ pattern demonstrated above suggest that the former can be considered to be a PJ pattern on the interdecadal time scale (hereafter referred to as the interdecadal PJ pattern). It should be noted that the interdecadal PJ pattern also has some differences from the convective PJ pattern. For example, for the convective PJ pattern, the direction of propagation of the wave train is deflected eastward somewhat, while the interdecadal PJ pattern does not exhibit this feature. On the other hand, the low-level wave train of the interdecadal PJ pattern shifts poleward by about 5° of latitude relative to that of the convective PJ pattern (cf. Fig. 6a and Fig. 4b in Kosaka and Nakamura 2006).

To verify the reliability of the interdecadal PJ pattern derived from 20CR, the spatial distributions of the correlations between the PC-EA1 time series and the low-pass-filtered surface air temperature (SAT) anomalies from 20CR and CRUTEM3 are presented in Fig. 7. Both datasets show meridional negative–positive–negative

FIG. 7. Spatial distributions of the correlations between the PC-EA1 time series and low-pass-filtered JJA-mean surface air temperature anomalies from (a) 20CR and (b) CRUTEM3. Anomalies exceeding the 10% significance level are white dotted. Gray shading on land areas denotes missing observations.

SAT anomalies along 120°E , approximately. Considering the complex factors that may influence the surface temperature aside from the large-scale circulation and large uncertainties in the observational data, especially before the Second World War, the apparent similarities between Figs. 7a and 7b should support the existence of the interdecadal PJ teleconnection pattern derived from 20CR, though they do not reach the 10% significance level.

The 850- and 200-hPa vorticity anomalies associated with the first EOF mode derived from the ERA-20C and corresponding wave activity fluxes are checked (Fig. S3 in the supplementary material). It is clear that ERA-20C captures the meridional wave-like teleconnection pattern propagating poleward from the southern tropical WNP, which is consistent with 20CR. However, the zonal scale of the wave train in ERA-20C is larger than

FIG. 8. (a) Low-pass-filtered JJA-mean SST regressed onto the PC-EA1 time series (K). (b) As in (a), but for precipitation (shading, $10^{-2} \text{ Pa s}^{-1}$) and 850-hPa wind (vectors whose zonal and meridional components exceed the 10% significance level, m s^{-1}). SST and precipitation anomalies exceeding the 10% significance level are white dotted.

the counterpart in 20CR (Fig. 6a and Fig. S3a). These results indicate that the wave train is reliable marker of the important role of the interdecadal PJ pattern in the interdecadal variability of the EASM, but there are uncertainties in its spatial pattern.

b. Tropical forcing responsible for the interdecadal PJ teleconnection

To investigate the mechanisms responsible for the maintenance of the interdecadal PJ pattern, the SST and precipitation anomalies associated with EA1 are shown in Fig. 8. The SSTAs in the Pacific show an IPO-like pattern, with warm SSTAs in the tropical Pacific and cold SSTAs in the midlatitude North Pacific (Figs. 2a and 8a). Meanwhile, the tropical Indian Ocean is covered by basinwide warm SSTAs, which are referred to as the interdecadal Indian Ocean basin mode (interdecadal IOBM) by analogy with the basin mode on the interannual time scale (Han et al. 2014; Wang et al. 1999).

As noted in many previous studies, the conventional PJ pattern is driven by anomalous convective heating over the tropical WNP (e.g., Nitta 1987). On the

interdecadal time scale, the suppressed convection over the southern tropical WNP may play a central role, which, according to the Gill model (Gill 1980), drives anticyclone anomalies centered over the Philippine Sea (Fig. 8b). The atmospheric perturbation propagates poleward as Rossby waves and forms the interdecadal PJ pattern. Interestingly, the suppressed convection corresponds to underlying warm SSTAs. The opposite signs of the SST and precipitation anomalies (Figs. 8a,b) suggest that the suppressed convection is not caused by local forcing of underlying SSTAs, but by remote forcing.

In contrast to the suppressed convection over the southern tropical WNP, the patterns of convection over the South China Sea and northern tropical WNP are greatly enhanced. Since there are no significant SSTAs in the area, the enhanced convection is speculated to be caused by low-level convergence anomalies associated with the anomalous cyclone center of the interdecadal PJ pattern. After the positive precipitation anomalies are established, they in turn tend to reinforce the anomalous cyclone.

FIG. 9. The normalized summertime IPO index (red line) and the normalized PC-EA1 time series (blue line). The green line represents the JJA-mean area-averaged SSTAs in the tropical Indian Ocean (20°S – 10°N , 55° – 100°E) with variability of <7 yr and associated with global-mean SST removed.

It is found that the SST anomaly pattern associated with EA1 resembles the IPO pattern (Fig. 8a). To further explore the relationships between the IPO, interdecadal IOBM, and the EA1 mode, we calculated the correlations among the IPO index, the interdecadal IOBM index, and the PC-EA1 time series (Fig. 9). Here, the interdecadal IOBM index is defined as the area-averaged JJA-mean SSTAs in the tropical Indian Ocean (20°S – 10°N , 55° – 100°E), in which the variability shorter than 7 yr and associated with global-mean SST has been removed. Their correlations are 0.54 and 0.75, respectively. The results suggest that the interdecadal PJ teleconnection pattern is more tightly associated with the basinwide SSTAs in the tropical Indian Ocean than the IPO.

5. Origin of the EA2 mode

SSTAs associated with the EA2 mode are shown in Fig. 10a. The most significant feature is basinwide warming in the North Atlantic, which resembles the spatial pattern of the AMO (Fig. 2b). Meanwhile, the PC-EA2 time series is generally in phase with the AMO index, except for during the 1960s (Fig. 10b). Their correlation coefficient is 0.66, reaching the 10% significance level. Hence, the EA2 mode is closely associated with the AMO. In this section, we focus on their relationship.

a. CGT pattern on the interdecadal time scale

To explore global large-scale circulation anomalies associated with the EA2 mode, low-pass-filtered geopotential heights at 200, 500, and 700 hPa were separately regressed onto the PC-EA2 time series (Fig. 11). The upper troposphere in the Northern Hemisphere is dominated by strong significant positive height anomalies over the tropical and subtropical North Atlantic and a belt of positive height anomalies along the middle latitudes, with five significant positive nodes located in

eastern North America, Europe, central Asia, the western North Pacific, and the eastern North Pacific, respectively (Fig. 11a). To demonstrate the midlatitude wavelike pattern more clearly, the geopotential height eddy anomalies are also shown, which are defined as the deviation of the height anomalies from the zonal mean (Fig. 12). It is clear that there is a wave train along the climatological jet stream, with a zonal wavenumber-5 structure (Fig. 12a). The corresponding wave activity flux reveals that wave energy propagates from the subtropical North Atlantic northeastward to the midlatitude eastern North Atlantic and then propagates eastward around the globe (Fig. 12b). The circumglobal wavenumber-5 wave train along the jet stream is similar to the summer CGT pattern studied from the meteorological perspective and on interannual time scales (Ding and Wang 2005; Ding et al. 2011). On the other hand, Lee and Hsu (2013) found that, for the annual mean, the upper-troposphere geopotential height in the middle latitudes of the Northern Hemisphere oscillates on the multidecadal time scale, the spatial pattern of which includes a strong zonal symmetric component and a zonal wavenumber-4 or wavenumber-5 eddy component, similar to that shown in Fig. 12a. For simplicity, the midlatitude wave train is referred to as the interdecadal CGT pattern in this study.

The geopotential height anomalies at 200, 500, and 700 hPa (Fig. 11) indicate that the interdecadal CGT has an equivalent barotropic structure. East Asia is dominated by cyclonic circulation anomalies centered over the Bohai Sea and extending southwestward, which is evident in the middle and lower troposphere (Figs. 11b,c; also see Fig. 3b), but less clear in the upper troposphere because of a strong anticyclonic zonal symmetric component (Fig. 11a).

b. Possible mechanisms responsible for the maintenance of the interdecadal CGT

Based on the results presented in Fig. 10a, it is conceivable that the interdecadal CGT pattern could be closely associated with AMO-related forcing. In the North Atlantic, the atmospheric response to the underlying warm SSTAs includes two systems. Atmospheric circulation anomalies in the tropical North Atlantic (south of 20°N) are dominated by a baroclinic mode, with cyclonic (anticyclonic) anomalies in the lower (upper) troposphere (Figs. 11a,c). The baroclinic mode is generated by enhanced deep convective heating (Fig. 13c) associated with underlying warm SSTAs (Fig. 10a). In the extratropical North Atlantic (north of 20°N), atmospheric circulation anomalies exhibit an equivalent barotropic dipole pattern, with cyclonic anomalies to the south of Iceland and anticyclonic

FIG. 10. (a) Low-pass-filtered JJA-mean SST regressed onto the PC-EA2 time series (K). SSTAs exceeding the 10% significance level are white dotted. (b) Normalized summertime AMO index (red line) and PC-EA2 time series (black line).

anomalies to the west of North Africa (Fig. 11). The dipole pattern resembles the eastern Atlantic pattern (EAP), which is a dominant internal mode of summertime atmospheric variability over the North Atlantic (Msadek and Frankignoul 2009; Msadek et al. 2011). Msadek et al. (2011) proposed that the atmospheric responses on the interdecadal time scale projecting onto the EAP are triggered by anomalous stationary wave activity, which is associated with underlying warm SSTAs, and reinforced by the change in transient eddies in the storm tracks. Figure 12b shows that the EAP-related perturbation propagates eastward around the globe along the climatological jet stream and forms the interdecadal CGT pattern. It is worth noting that the interdecadal CGT pattern has a strong zonal symmetric component, especially in the upper troposphere (Fig. 11a). The zonally elongated cyclonic anomalies are also associated with the SSTAs in the North Atlantic (Msadek et al. 2011; Lee and Hsu 2013).

c. Comparisons between the 20CR and other datasets

As noted by Ding et al. (2011), the GCT pattern tends to give rise to SAT and precipitation anomalies along its path. Hence, the robustness of the interdecadal CGT may be verified by comparing the spatial patterns of interdecadal CGT-related SAT and precipitation anomalies from 20CR with the corresponding

observational results (Fig. 13). Since our focus is on the similarity in spatial patterns rather than magnitudes, we show the correlation coefficients rather than regression coefficients.

In the 20CR dataset, the locations of warm and cold centers over the midlatitude land areas generally correspond to those of the anticyclone and cyclone centers of the interdecadal CGT pattern (Fig. 13a). The warm centers over North America, Europe, and in the vicinity of Lake Baikal reach the 10% significance level. These warm centers are also seen in the SAT anomalies from the CRUTEM3 records, though only very sporadic areas reach the 10% significance level (Fig. 13b). A clear difference between 20CR and CRUTEM3 is seen in eastern China; that is, the former is covered by cold anomalies, while the latter is covered by warm anomalies. The difference is discussed in section 6b.

Compared with SAT, the precipitation anomalies show a more complicated spatial pattern. In 20CR (Fig. 13c), the suppressed (enhanced) precipitation anomalies in the middle latitudes reaching the 10% significance level are seen over Europe and to the east of Lake Baikal (north of Lake Baikal and the vicinity of Japan). These precipitation anomalies over land areas are also seen in the corresponding results from the CRU precipitation records, though most of them do not pass the significance test (Fig. 13d).

FIG. 11. (a) Low-pass-filtered JJA-mean 200-hPa geopotential height regressed onto the PC-EA2 time series (m). (b),(c) As in (a), but for 500 and 700 hPa, respectively. Anomalies exceeding the 10% significance level are white dotted.

The similarities in the SAT and precipitation anomalies between the 20CR and observational datasets suggest that the interdecadal CGT pattern may exist in the interdecadal fluctuations of midlatitude atmospheric circulation in the Northern Hemisphere and modulate the SAT and precipitation along its path. However, there are uncertainties regarding its impacts on the SAT over the East Asian continent.

To further check the robustness of the interdecadal CGT pattern, we compare the circulation anomalies from 20CR with those from the JRA-55 and ERA-20C reanalysis datasets. For comparison with JRA-55, we focus on the period 1958–2012. Composites were produced in terms of the AMO index, with positive phase minus negative phase, because of the shorter data lengths (Fig. 14). For 20CR, a circumglobal wavelike

anomalous height belt with five positive nodes is seen in the upper troposphere along the middle latitudes of the Northern Hemisphere (Fig. 14a). The wavelike pattern has equivalent barotropic structure (Figs. 14a–c). The height anomalies over the North Atlantic exhibit a barotropic dipole pattern, with a cyclonic center to the south of Iceland and an anticyclonic center over the midlatitude North Atlantic (Figs. 14a–c). These patterns greatly resemble the EA2-related circulation anomalies for the period of 1920–2012. The equivalent barotropic wave pattern with five positive nodes in the middle latitudes of the Northern Hemisphere and the barotropic dipole pattern over the North Atlantic are also seen in the JRA-55 results, with high pattern similarities with those from 20CR (Figs. 14d–f). However, it is worth noting that eastern China is covered by strong cyclonic

FIG. 12. (a) The 200-hPa geopotential height eddy anomalies associated with the EA2 mode (shading, m). The eddy is defined as the deviation of the 200-hPa geopotential height anomalies in Fig. 11a from their zonal mean. Contours show the climatological 200-hPa zonal wind (m s^{-1}). (b) As in (a), but with vectors of the corresponding wave activity flux ($\text{m}^2 \text{s}^{-2}$).

anomalies in the middle and lower troposphere in the EA2 mode (Figs. 11b,c), while this feature is not seen in the composite results from either 20CR (Figs. 14b,c) or JRA-55 for the period 1958–2012 (Figs. 14e,f).

These results indicate that the interdecadal CGT pattern does exist and is associated with AMO forcing. However, it is worth noting that, although the existence of the interdecadal CGT is robust, its impacts on the EASM are not. At present, we do not know what causes the differences between 20CR and JRA-55, but we can speculate two possible reasons. The first is that the atmospheric responses in the area to the AMO-related forcing are not completely separated from the responses to the external forcing during this short time span. The second is that the atmospheric responses in the area to the AMO-related forcing are unstable.

The 200-, 500-, and 700-hPa geopotential height anomalies associated with the second EOF mode derived from ERA-20C are also checked (Fig. S4 in the supplementary material). The middle latitudes are also dominated by a barotropic wave train in the EOF mode. However, the wave train only has four nodes and the nodes over the Asia and Pacific are shifted relative to those in the EA2 from 20CR (Fig. 11 and Fig. S4a). In 20CR, East Asia is controlled by low pressure anomalies centered over the Bohai Sea (Fig. 11), while in ERA-20C, it is controlled by high pressure anomalies extending from the north (Fig. S4). On the other hand, the PC time series of the EOF2 from ERA-20C is highly correlated with the AMO index ($r = 0.71$), just like the

PC-EA2. As a result, the spatial pattern of the EOF2 from ERA-20C is quite different from that of the EA2 from 20CR (Fig. 3b and Fig. S1b), while their PCs are highly correlated (Fig. 3e). Considering the similarities between 20CR and JRA-55 (Fig. 14), we believe that 20CR should be more reliable than ERA-20C in the large-scale circulation anomalies associated with the AMO.

6. Conclusions and discussion

a. Conclusions

This study attempts to investigate the leading modes of the interdecadal variability of the EASM by using the 20CR dataset over the past 93 yr (1920–2012). The interdecadal variability of the EASM is linked to the dominant interdecadal fluctuation modes of the global climate system through global-scale atmospheric teleconnection patterns. The major findings are summarized as follows:

- 1) An MV-EOF analysis was applied to the June–August (JJA) mean 850-hPa wind vector field over the EASM region, in which variability shorter than 7 yr and associated with global-mean SST was removed. The first two dominant modes account for 22.1% and 17.8% of the total variance, respectively.
- 2) The first mode (EA1) is characterized by an anomalous anticyclone centered over the Bohai Sea and an anomalous cyclone centered over Taiwan. The circulation anomalies are part of a meridional

FIG. 13. Spatial distributions of the correlations between the PC-EA2 time series and low-pass-filtered JJA-mean surface air temperature anomalies from (a) 20CR and (b) CRUTEM3 (K). Anomalies exceeding the 10% significance level are white dotted. Gray shading on land areas denotes missing observations. (c),(d) As in (a),(b), but for precipitation anomalies (mm day^{-1}).

wave-like teleconnection pattern propagating poleward from the southern tropical WNP. The dynamical properties of the teleconnection pattern are similar to those of the PJ pattern defined conventionally on the interannual and intraseasonal time scales, such as the vertical structure with the combined baroclinic and barotropic modes and the poleward

energy propagation confined to the lower troposphere. Therefore, the teleconnection pattern is referred to as the interdecadal PJ pattern. The interdecadal PJ pattern is maintained by suppressed convection over the southern tropical WNP.

- 3) The second MV-EOF mode (EA2) is characterized by cyclone anomalies extending from northeastern

FIG. 14. Composites of JJA-mean geopotential height (m) at (a) 200, (b) 500, and (c) 700 hPa from 20CR. The composites are calculated in terms of the AMO index with the positive phase (1958–67 and 1995–2012) minus the negative phase (1968–94). (d)–(f) As in (a)–(c), but for JRA-55.

China to Japan. The circulation anomalies are part of a circumglobal wave train along the Northern Hemisphere jet stream. The wave train has barotropic and zonal wavenumber-5 structures, similar to the summertime CGT pattern studied from the meteorological perspective and on interannual time scales. Hence, it is referred to as the interdecadal CGT pattern. The interdecadal CGT pattern is maintained by the forcing of the AMO.

b. Discussion

1) UNCERTAINTY IN THE IMPACTS OF THE INTERDECADAL CGT PATTERN ON THE EASM

The existence of the interdecadal CGT pattern is supported by the observational precipitation and SAT datasets and JRA-55 reanalysis. However, there are uncertainties about how the interdecadal CGT pattern influences the EASM. The EA2-related SAT anomalies in eastern China from 20CR are opposite to those from the CRUTEM3 records (Figs. 13a,b). However, the EA2-related precipitation anomalies in the region from 20CR are generally consistent with those from the CRU records, except for those in northeastern China (Figs. 13c,d). At present, we do not know what causes

this contradiction, which deserves further study in the future.

2) DIFFERENCES BETWEEN INTERDECADAL PJ AND CGT PATTERNS AND THEIR INTERANNUAL COUNTERPARTS

The PJ and CGT patterns on the interdecadal scale are quite different from their counterparts on the interannual time scale. The PJ pattern is driven by anomalous convective heating over the tropical WNP. On the interannual time scale, the anomalous heating is largely contributed by underlying SSTAs in the preceding month (Kosaka and Nakamura 2006). In contrast, on the interdecadal time scale, the anomalous convective heating is not caused by local forcing because of the opposite signs between the precipitation and SST anomalies (Figs. 8a,b). On the other hand, the interdecadal PJ pattern is shifted westward relative to the interannual PJ pattern in both the upper and lower troposphere (Figs. 6a,b, and Figs. 4a,b in Kosaka and Nakamura 2006). What causes the differences deserves further study.

On the interannual time scale, the CGT pattern is maintained by the Indian monsoon precipitation anomalies. Hence, one of the CGT centers located to the north of the Indian monsoon region exhibits baroclinic

FIG. 15. (a) Spatial patterns of the IPO for the period of 1920–67 derived from the second EOF mode of 7-yr low-pass-filtered JJA-mean near-global SST (40°S – 60°N) from 1920 to 1967 (K). (b) As in (a), but for the period of 1968–2012.

structure (Ding et al. 2011). In contrast, on the interdecadal time scale, all the centers of the CGT pattern exhibit barotropic structure (Fig. 11). Based on the study by Msadek et al. (2011), we propose that the interdecadal CGT pattern is triggered by the AMO-related SSTAs in the midlatitude North Atlantic and is reinforced by the change of synoptic-scale eddy activities in the storm track. These mechanisms regarding the maintenance of the interdecadal CGT pattern require further study in the future.

3) WHY DOES THE AMPLITUDE OF THE EA1 DECLINE AFTER THE 1960S?

The reduction in the amplitude after the 1960s is also seen in the EOF modes derived from the ERA-20C (Fig. 3e) and CRU land precipitation (Fig. S2), suggesting that the EA1 derived from the 20CR is reliable. In addition, there is other evidence supporting the reliability of the 20CR and the reduction in EA1 amplitude (which is given in the supplementary material).

As noted in section 4b, the EA1 mode is highly correlated with the interdecadal IOBM. The amplitude of the interdecadal IOBM index during 1967–2012 decreases by more than 50% relative to 1920–67, consistent with the weakening of the EA1 mode, while the amplitude of the IPO shows little change (Fig. 9).

When EOF analysis is conducted for the period of 1920–2012, the IOBM is a part of the spatial pattern of

the IPO (Fig. 2a). However, the relationship between the IPO and the interdecadal IOBM is unstable (Han et al. 2014). We applied EOF analysis to the summertime low-pass-filtered near-global SST for the two periods of 1920–67 and 1968–2012. For both periods, the second EOF mode corresponds to the IPO, with positive SSTAs in the tropical central-eastern Pacific and negative SSTAs in the midlatitude North Pacific (Fig. 15). However, the SSTAs in the tropical Indian Ocean are quite different. For the former period, the tropical Indian Ocean is dominated by basinwide warming (Fig. 15a), while for the latter period, the equatorial and northern Indian Ocean is covered by very weak cold SSTAs and the southern Indian Ocean by weak warm SSTAs (Fig. 15b). These results suggest that the SSTAs in the tropical Indian Ocean are less modulated by the IPO-related forcing during the last 40 yr. Meanwhile, the amplitude of the interdecadal IOBM decreases remarkably.

We speculate that the reduction in the amplitude of EA1 could be associated with the change in the spatial pattern of the IPO and the reduction in the amplitude of the interdecadal IOBM. This issue deserves further study in the future.

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