Pacific and Atlantic controls of the relationship between Mainland Southeast Asia and East China interannual precipitation variability

Jessica K. Wang · Jin-Yi Yu · Kathleen R. Johnson

Received: 9 January 2020 / Accepted: 1 April 2020 / Published online: 8 April 2020
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

Abstract
The Asian monsoon region is highly dependent on boreal summer rainfall, which directly impacts the socio-economic stability and welfare of billions of people each year. Precipitation variability over East China has been extensively studied and is known to be characterized by meridional tripole and dipole precipitation structures. In contrast, few studies have focused on precipitation variability over Mainland Southeast Asia (MSEA) and the possible relationship with the variability over East China. Here we focus on how interannual precipitation variability across MSEA during 1983–2017 may be associated with the tripole or dipole patterns using an empirical orthogonal function (EOF) analysis. The first EOF shows a meridional tripole pattern in East China summer precipitation and an in-phase relationship between MSEA and South China precipitation. In contrast, the second EOF shows a meridional dipole pattern in East China precipitation and an out-of-phase relationship between MSEA and South China precipitation. We show that the first EOF mode is a delayed precipitation response to the El Niño-Southern Oscillation (ENSO), while the second EOF mode is a simultaneous precipitation response to the remote influence of the North Atlantic Oscillation (NAO). Therefore, the in-phase or out-of-phase variations in precipitation between MSEA and South China may be used to gauge the relative importance of local Pacific and remote Atlantic influences on Asian monsoon climate.

Keywords Precipitation · Asian monsoon · Southeast Asia · ENSO · NAO

1 Introduction

Interannual precipitation variability across East China has been well-characterized by meridional dipole and tripole structures (Hsu and Liu 2003; Hsu et al. 2007; Han and Zhang 2009; Ye and Lu 2012). The tripole pattern illustrates a positive rainfall anomaly center along the Yangtze River region and negative anomaly centers to the north and south or vice versa (Hsu et al. 2007; Huang et al. 2012; Day et al. 2015). Conversely, the dipole rainfall pattern describes out-of-phase variations in precipitation between southeastern and northeastern China (Ding et al. 2008; Qian et al. 2014; Sun and Wang 2015). The spatial heterogeneity in precipitation across East China occurs particularly during boreal summer due to the East Asian summer monsoon (EASM) (Ding et al. 2008).

The EASM exhibits several meridional quasi-stationary stages during its seasonal evolution and distinct transitions of abrupt change (Ding and Chan 2005). The differential heating between the Asian continent and the Pacific Ocean induces a low-level pressure contrast, which causes low-level monsoon flow from the South China Sea to East Asia (Sui et al. 2013). Sea surface temperature (SST) variations in the tropical Pacific and Indian Oceans related to the El Niño-Southern Oscillation (ENSO) exert significant influence on the EASM (Wang et al. 2000; Wu et al. 2003, 2009; Hsu et al. 2007; Feng et al. 2011). Following an El Niño event, cooling over the western Pacific can induce an anticyclonic circulation anomaly through the Gill-Matsuno type response, which can sustain this anomaly to the following summer through local air-sea interactions (Wang et al. 2000). The positive southeasterly wind anomaly on the west side of this anomalous anticyclone can strengthen the EASM and impact precipitation over East China (Wang et al. 2000; Wu et al. 2003). Other studies have suggested that ENSO can also affect the EASM through anomalous warming of Indian Ocean SSTs (Xie et al. 2009, 2016), which can trigger...
a low-level anticyclonic circulation anomaly in the western north Pacific and strengthen the EASM (Du et al. 2009; Xie et al. 2016). Shifts in the strength or zonal extensions of the Western Pacific Subtropical High (WPSH) (Sui et al. 2007; Wu and Zhou 2008) may also impact summer rainfall patterns over East China (Gong and Ho 2002). During periods when the WPSH intensifies, shifts southward, or extends westward, above-normal precipitation is expected along the Yangtze river valley and northward into southern Japan (Mao et al. 2010). These WPSH variations can be driven by SST anomalies over the western tropical Pacific (Sui et al. 2007; He et al. 2015) or the equatorial central Pacific (Wang et al. 2013; He et al. 2015), both of which are linked to ENSO.

In addition to ENSO impacts on East Asian summer precipitation, the remote influence of the North Atlantic Oscillation (NAO) in the preceding winter and spring on the Asian monsoon via modifying the strength and location of the 200-hPa jet stream has been widely documented in studies (Yang et al. 2004; Sung et al. 2006; Zuo et al. 2012). However, recent studies have demonstrated the impact of the concurrent summer NAO (SNAO) on East Asian precipitation patterns (Sun et al. 2008; Folland et al. 2009; Linderholm et al. 2011, 2013; Wang et al. 2018). Linderholm et al. (2011) proposed that North Atlantic storm tracks and transient eddy activity associated with the SNAO led to the observed significant and positive (negative) correlations with rainfall over southeastern China (central East China). Furthermore, thermal forcing over the Tibetan Plateau may provide an intermediate bridge effect in this teleconnection that leads to the dipole pattern in East China summer rainfall. Negative SNAO events were found to be associated with decreased precipitation over southeastern China and wet conditions along the Yangtze River basin and vice versa leading to this Eurasian teleconnection between the SNAO and EASM (Wang et al. 2018).

Despite the current literature on the leading modes of interannual to interdecadal precipitation variability in East China (He et al. 2017; Qiu and Zhou 2019), we stress that few studies have considered precipitation variability over Mainland Southeast Asia (MSEA) in relation to East China precipitation. MSEA encompasses Cambodia, Laos, Myanmar, Thailand, Vietnam, and peninsular Malaysia. Spatial patterns of precipitation vary greatly across the broad Asian Monsoon region and MSEA is geographically-situated at the boundaries among several distinct sub-monsoon systems (including the EASM and the Indian summer monsoon), such that MSEA precipitation patterns may be influenced by the complex dynamic interactions among these systems (Wang et al. 2002). Similar to the reliance in China, the economies of MSEA countries largely depend on the success of the entire agricultural sector, including farming, forestry, and fishing (Mekong River Commision 2005). Therefore, variations in summer rainfall can play a significant role in millions of lives. While a number of studies have focused on MSEA interannual precipitation variability (Misra and DiNapoli 2014; Mie et al. 2015; Tsai et al. 2015; Shrivastava et al. 2017; Ratna et al. 2017), none have investigated how MSEA precipitation patterns may be linked to the observed dipole or tripole precipitation patterns in East China or the dynamic mechanisms responsible for the potential linkage.

The motivation for this work stems from not only including MSEA in the analysis of the relationship between precipitation variability and climate phenomena (e.g., ENSO), but also the potential implications for paleoclimate studies and future climate projections. Proxy evidence obtained from climate archives, such as speleothems, tree rings, and lakes, has been widely used to extend the record of EASM precipitation variability beyond the instrumental record, and increasingly suggests significant regional variability in the precipitation response to external forcing and internal climate variations. For instance, a synthesis of high-resolution paleoclimate records interpreted as moisture or precipitation variability from the EASM region revealed spatially distinct precipitation variations (Chen et al. 2015, 2019a) over the last millennium. On centennial timescales, studies have shown various periods during which there were generally drier conditions in southern China, while the northern part was wetter (Chen et al. 2015). This spatial pattern of “south flood-north drought” observed since the late 1970s (Gong and Ho 2002; Ding et al. 2008) has also been observed in historical documents and speleothem records from eastern China (Wang et al. 2001). Increasingly, multi-proxy paleoclimate evidence suggests that Asian Monsoon precipitation also did not respond uniformly to past changes in insolation or Atlantic Meridional Overturning Circulation (AMOC) (Chiang et al. 2015; Zhang et al. 2018; Huang et al. 2018), suggesting that the dipole and/or tripole rainfall patterns may persist across a wide range of timescales. Despite efforts to synthesize multi-proxy records from across East Asia, there are few high-resolution proxy records from MSEA, limiting our understanding of past rainfall patterns (Buckley et al. 2010; Chawchai et al. 2015; Yamoah et al. 2016; Wang et al. 2019). Given the heterogeneous nature of precipitation response to both external forcings and internal climate variability, further analysis of spatial and temporal precipitation variability and the underlying mechanisms in both modern and paleo-data is necessary for improving our understanding of regional precipitation variability across the broad Asian Monsoon region.

The present study aims to investigate the interannual precipitation variability across East China and MSEA, with a focus on identifying how MSEA precipitation variations are linked to the observed East China interannual dipole and tripole precipitation patterns. The main purpose of this study is to analyze the dynamical mechanisms that give rise to these
spatial precipitation patterns between MSEA and East China and to examine the possible relations with atmospheric teleconnections. The implications for this work extend for both paleoclimate studies and future precipitation projections for East China and MSEA. Climate change in response to increasing greenhouse gases (Christensen et al. 2013) have already influenced regions of MSEA, observed through extreme weather events, including droughts, floods, and tropical cyclones (Asian Development Bank 2009). Direct impacts have led to a decline of crop yields in Thailand, Vietnam, and Indonesia, massive flooding in Hanoi, Hue (Vietnam), Jakarta (Indonesia), and Vientiane (Laos), landslides in the Philippines and droughts in many other parts of MSEA (Asian Development Bank 2009). Therefore, an improved understanding of the coupling (or decoupling) of interannual precipitation patterns can aid in improving future projections of precipitation variability across the broader Asian Monsoon region where they continue to remain uncertain over the next century (Christensen et al. 2013).

The organization of the text proceeds as follows. The datasets and methodology are introduced in Sect. 2. Section 3 examines the features of the first two leading EOF modes of July–August precipitation and the associated atmospheric circulation anomalies. In Sect. 4, the teleconnections linked with the EOF modes are examined. A summary and final thoughts are given in Sect. 5.

2 Data and methods

This study uses the multi-satellite, high-resolution Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks - Climate Data Record (PERSIANN-CDR) precipitation product that provides daily precipitation estimates at 0.25° spatial resolution for the period from January 1983 to December 2017 (Ashouri et al. 2015). The primary source of precipitation data is collected from infrared (IR) satellite data of global geostationary satellites, and the model is pre-trained using the National Centers for Environmental prediction stage IV hourly precipitation data to meet calibration requirements. Model parameters are held fixed and the model is run using the historical record GridSat-B1 infrared data (Knapp 2008). Here we focus on the seasonal mean precipitation averaged in July and August over East China and MSEA (100–124°E and 8°–45°N).

Additional datasets used in this study include the following: (1) monthly means reanalyses of zonal and meridional winds at 850-hPa, 200-hPa geopotential heights, vertical velocity (omega) and vertically-integrated zonal and meridional moisture flux and vertically-integrated moisture flux divergence at 0.75° × 0.75° spatial resolution from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5) data; (2) the NOAA Extended Reconstructed SST data at 2.0° × 2.0° provided by the National Oceanic and Atmospheric Administration/National Climate Data Center (Huang et al. 2017). The ERA5 zonal and meridional moisture flux and its divergence are integrated over the full atmospheric column, which consists of 37 levels that extend from 1 to 1000 hPa. All the reanalysis datasets used in this study cover the same 35-year period as the PERSIANN-CDR precipitation dataset.

To identify the dominant modes of East China and MSEA summer precipitation variations, we apply an empirical orthogonal function (EOF) analysis on PERSIANN-CDR precipitation, averaged during the boreal summer months, over the region that is bounded by 100°–124°E and 8°–45°N. The western coastal portion of MSEA (e.g., Myanmar and parts of Thailand) experiences the heaviest rainfall during the summer monsoon season due to the coastal mountain ranges of Myanmar (Shige et al. 2017). Therefore, it was necessary to exclude this western coastal portion of MSEA in order to capture both the observed meridional tripole pattern in East China based on previous studies (Chiang et al. 2015) and the precipitation variability over MSEA. As a result, this study focuses on the region that includes Laos, Vietnam, Cambodia, and parts of Thailand, which has particular paleoclimate significance due to the availability of several published paleoclimate records that span at least the last few hundred years and longer from this area (Buckley et al. 2010; Xu et al. 2011; Sano et al. 2012; Wang et al. 2019). The PERSIANN-CDR dataset was selected over longer-term precipitation datasets because of the higher spatial resolution available. Following previous studies (Chiang et al. 2015; Day et al. 2015; Kong et al. 2017; Zhang et al. 2018), boreal summer is defined as July and August (JA). This monthly averaged period best represents the overlap of two intraseasonal stages of precipitation over East Asia that characterize the dominant mode of East Asia summer rainfall interannual variability (Chiang et al. 2015). In this study, the precipitation variability across East China and MSEA are decomposed into the spatial patterns of the two leading modes (EOF1 and EOF2, hereafter). The corresponding PCs (PC1 and PC2) represent their temporal variations.

Statistical significance of correlation coefficients and anomalies based on linear regression are determined by Student’s t test at the 90% confidence interval. Anomalies are defined as the deviations from the seasonal mean after removing the linear trend. All the time series and data presented in this study are unfiltered and detrended.

3 Results

3.1 Leading precipitation modes and associated circulation anomalies

The climatology of mean JA climate during the period 1983–2017 is characterized by prevailing westerly and
southwesterly winds that transport warm, moist air from the Indian and tropical Pacific Oceans and cause heavy precipitation along the coastal regions of MSEA and the Philippines (Fig. 1). Precipitation over MSEA is also somewhat influenced by local orographic effects, which can lead to heterogeneous rainfall patterns among neighboring countries (Chang et al. 2005; Wang et al. 2012b). Additionally, southerly winds from the South China Sea transport moisture-laden air into East China and towards the Yangtze River valley. The presence of a dominant anticyclonic wind pattern off East Asia is also shown in the JA climatology.

We focus on the first two leading modes from the EOF analysis to examine the interannual precipitation variability across East China and MSEA. These two EOF modes are distinguished from the rest of the EOF modes based on their eigenvalues (not shown) and together explain 36% of the precipitation variability in the study region. The first EOF mode (EOF1; accounting for 23% variance) clearly illustrates a meridional tripole pattern. Positive loading values are centered just north of the Yangtze River region and negative loading values are present to the north and south (Fig. 2a). This meridional tripole pattern over East China is broadly consistent with other studies, though these studies have referred to this first EOF mode as the dipole mode (Han and Zhang 2009). The time series of PC1 (Fig. 2b) exhibits interannual and interdecadal variability. In addition to the meridional tripole pattern observed in the EOF1, we distinguish that precipitation variations in MSEA are broadly in-phase with those over South China, which we describe as the region just northwest of the Pearl River Valley region.

The second EOF mode (EOF2; accounting for 14% variance) mainly describes the relatively uniform negative loading pattern across East China, which is contrasted by a positive loading region extending from coastal southeastern China to MSEA (Fig. 2c). Unlike the EOF1 mode, the EOF2 mode is distinguished by the out-of-phase precipitation variations between MSEA and most of south China (excluding the coastal regions). Given these analyses, we confirm that the EOF1 and EOF2 patterns represent two different relationships between MSEA and East China (particularly the South China) precipitation variability. It is noted that, in the EOF2 mode, the precipitation anomaly along coastal southeastern China is in-phase with that in MSEA. This in-phase relationship may be associated with tropical cyclones; however, additional work on the extent of tropical cyclone-induced rainfall is beyond the scope of this study.

To investigate the dynamic mechanisms associated with these two EOF modes, we first regress precipitation and 850-hPa wind anomalies onto PC1 across the broad Asian monsoon region (Fig. 3). The tripole pattern revealed in EOF1 is consistent with a rainbelt centered just north of the Yangtze River region and reduced rainfall to its north and south. The regression of 850-hPa winds reveals an anomalous low-level anticyclone centered around 20° N and 115° E, suggesting a strengthening and westward extension of a western Pacific anomalous anticyclone (Fig. 3a). Dynamically, the anomalous anticyclone can induce descending motion and contribute to the drier conditions over both South China and MSEA regions. Additionally, water vapor transport and supply play important roles in this precipitation pattern. The regression of vertically-integrated moisture flux onto PC1 shows near-identical circulation patterns as the regression of 850-hPa winds onto PC1 (Fig. 3b). The anomalous anticyclone induces divergent water vapor flux out of MSEA and South China, while there is convergent motion north of Yangtze River region. In addition, the easterly anomalies to the south of 20° N transport moisture out of MSEA and towards the Bay of Bengal and Indian Ocean, which can contribute to the decreased precipitation pattern observed over MSEA. These patterns of moisture transport provide additional evidence for the tripole pattern observed in the EOF1 pattern and the in-phase precipitation variations between South China and MSEA. These results indicate that the strengthening and westward extension of an anomalous anticyclone can be a key contributor to the first mode of precipitation variability and the in-phase relationship between MSEA and South China precipitation.

We repeat the same analyses for PC2 and compare how anomalous wind and moisture circulation patterns impact the observed dipole pattern in EOF2. Regression of 850-hPa wind anomalies onto PC2 is characterized by anomalous easterly winds centered around 30° N and is accompanied by anomalous cyclonic circulation to the south and anomalous anticyclonic circulation to the north (Fig. 3c). The anomalous anticyclone centered around Japan is weaker and the vectors are not all statistically significant at the 90% confidence level. However, the significant, stronger anomalous

Fig. 1 Summer (July–August) precipitation [shading, mm] and 850-hPa winds [vector, m s−1] climatology derived from PERSIANN-CDR data (Ashouri et al. 2015) and ERA5 reanalysis dataset for the period 1983–2017. The area outlined by the black box was used in the EOF analysis.
cyclone extends from the coast of South China on the western edge to the central western Pacific on the eastern edge (Fig. 3c). The regressions of moisture transport and divergence show water vapor transport and convergence over the Philippine Sea, South China coast, and MSEA, whereas anomalous moisture divergence and moisture flux from the western Pacific contributes to the observed decreased precipitation over South China (Fig. 3d).

These results indicate that the influence of an anomalous anticyclone is important for both the meteorological and water budget aspects of the EOF1 pattern, such that dry conditions persist in both South China and MSEA. However, the anomalous easterly flow associated with the EOF2 pattern produces drying in south-central China, but the cyclonic circulation anomaly to the south over the South China Sea produces wet anomalies over MSEA. In the next section, we investigate potential mechanisms that may have produced these anomalous circulation centers and subsequently anomalous precipitation patterns.

### 3.2 Surface to upper-atmosphere structures

We analyze the 200-hPa geopotential height (Z200) anomalies to determine whether the observed precipitation patterns are linked to perturbations in the upper troposphere (i.e., the Asian westerly jet stream or barotropic wave trains). To highlight the wave components of upper-air structure, zonal means are subtracted from the anomalies prior to the regression analysis. The regression onto PC1 shows a positive Z200 anomaly over South China and a negative Z200 anomaly north of the Yangtze River valley (Fig. 4a). These two anomalies respectively lead to anomalous descending motions over South China and MSEA and ascending motions over North China and contribute to the tripole precipitation pattern of EOF1. Figure 4b shows the vertical cross sections of the regression of omega velocity anomalies onto PC1. The zonal averages in these plots were taken over the longitudinal region of 100° to 124° E (box in Fig. 1). Anomalous ascending motion is clearly shown to occur north of ~30° N where the negative Z200 anomaly is located, while anomalous descending motion is present over the region between 15° N and 30° N where the positive Z200 anomaly appears (Fig. 4b). These latitudinal rain bands correspond to the respective loading patterns and precipitation anomalies associated with EOF1 (see Fig. 2a), which suggest that the Z200-induced descending motion also contribute to the in-phase precipitation variations between MSEA and South China. Figure 4a shows that these two Z200 anomaly centers may...
Fig. 3 The regression maps of JA precipitation [mm] and 850-hPa winds [m s$^{-1}$] onto a PC1 and c PC2 for 1983–2017. The linear regression of the vertical integral of water vapor transport [vectors, kg (ms)$^{-1}$] and vertically integrated moisture divergence [shading, kg m$^{-2}$] onto b PC1 and d PC2 shows similar patterns. The black vectors and black stippled regions in a-d denote significance at the 90% confidence level.

Fig. 4 The regression maps of Z200 minus the zonal mean and vertical velocity [Pa s$^{-1}$] onto a, b PC1 and c, d PC2, respectively. The solid (dashed) contours present positive (negative) values. The black stippled regions in a, c and the black contours in b, d denote significance at the 90% confidence level.
be associated with that of a wave train-like pattern, which originates around the northern flank of the Tibetan Plateau. Taken together, variations in the low-level anticyclone may affect the water vapor transport, whereas the wave train in the upper atmosphere may lead to anomalous descending and ascending motion that could contribute to the EOF1 pattern of precipitation variability.

The Z200 regression onto PC2 is dominated by a zonal wave train pattern that extends from the tropical Atlantic to the western Pacific via Eurasia (Fig. 4c). Over East Asia, the regression pattern is characterized by an anomalous cyclone over Mongolia and Russia, an anomalous anticyclone off the coast of Central China that extends into Japan, and weak cyclonic anomalies over the Bay of Bengal and MSEA regions. The anticyclone anomaly is consistent with 850 hPa anticyclonic wind anomalies over Japan and South Korea (see Fig. 3c). Therefore, the surface circulation anomalies associated with EOF2 are observed in both the lower and upper atmospheres, which suggests the barotropic circulation anomalies associated with a zonally-extended wave train from the Atlantic produce the out-of-phase precipitation pattern between South China and MSEA. This wave train weakens the band of zonal winds centered at 30°N and off East China (see Figs. 3c and 4c), which can then induce anomalous ascending to the north and anomalous ascending to the south due to geostrophic adjustments. It is noted that the observed regression pattern bears some resemblance to the regression onto PC1 (Fig. 4a), though opposite in sign, which could suggest that SST anomalies over the Atlantic or NAO-related circulations may influence both EOF1 and EOF2 modes. However, the distinct precipitation patterns and anomalous vertical motions confirmed by Fig. 4d where vertical velocity (omega) anomalies are regressed onto PC2 suggest alternative mechanisms. Anomalous ascending motion is positioned between ~10° and 20°N (i.e., the MSEA region), whereas descending motion is centered between 25° and 30°N (Fig. 4d). Therefore, the zonally-extended wave train in the upper troposphere induce surface anomalous circulation to affect moisture transport and anomalous vertical motions to give rise to the EOF2 precipitation pattern and the out-of-phase relationship between MSEA and South China.

4 Linked teleconnections with precipitation modes

Given the above results, the tripole precipitation pattern in EOF1 may indicate that the anomalous anticyclone in the western Pacific is an important circulation system of precipitation in East China and MSEA. We further explore whether ENSO plays a key role in precipitation variability across South China through its delayed impacts on the WPSH as observed in previous studies (Wang et al. 2000; Xie et al. 2009). The correlation coefficient between PC1 and previous December–January–February (DJF) Niño3.4 index, which is defined as the average SST anomaly over 5°S–5°N 170°–120°W, is calculated as \( r = 0.29 \) and is statistically significant at the 90% level. The year-to-year comparison between the Niño3.4 index and the PC1 shows coherence in which the preceding winter eastern tropical SSTs align with shifts in the PC1, though some significant ENSO events including the 2015–2016 event do not appear as a large shift in the PC1 (not shown).

To examine the possible connection between ENSO and the EOF1 mode, we regress SST anomalies onto PC1 from the preceding autumn to the concurrent summer of the EOF analysis.

In the preceding autumn (Fig. 5a), positive SST anomalies over the tropical eastern Pacific indicate developing El Niño conditions. The typical Indian Ocean warming induced by the developing El Niño is also evident in the regression pattern. Atmospheric teleconnections and ocean dynamics associated with El Niño induce a basin-wide surface warming over the tropical Indian Ocean (Nigam and Shen 1993; Masumoto and Meyers 1998; Klein et al. 1999; Lau and Nath 2000; Xie et al. 2002; Yang et al. 2007). Meanwhile, negative SST anomalies are present over the western tropical Pacific. The warm SST anomalies expand westward towards the tropical central Pacific by winter (Fig. 5b). In the following spring (Fig. 5c), SST anomalies decrease in the tropical eastern Pacific as the El Niño decays. The positive SST anomalies induced by the El Niño-like conditions are still present in the tropical Indian Ocean and act as a capacitor to produce delayed impacts on the atmosphere over the western North Pacific (Lau et al. 2003; Xie et al. 2009; Du et al. 2009; Wu et al. 2010). The developing El Niño should also excite an anomalous anticyclonic circulation over the western North Pacific (Wang et al. 2000) through the Gill-type response, which can also be maintained through local atmosphere–ocean coupling during the decaying summer.

A weakened Walker circulation initiated by the El Niño-like conditions induces anomalous divergence and downward motion over the Maritime continent and an anticyclone over the Philippines also prolongs the impact of ENSO (Wang et al. 2000). Through these three mechanisms, the preceding El Niño event can produce a delayed intensification impact on the WPSH in the following summer (Chen et al. 2019b). Finally, in the concurrent summer, the central tropical Pacific SST anomalies transition to negative anomalies (Fig. 5d). The regression shown in Fig. 5 confirms that the EOF1 mode of precipitation variability is linked to an ENSO forcing, which results in in-phase precipitation variations between MSEA and South China precipitation variations.
We repeat the regression analysis that we conducted onto PC1, but onto the DJF Niño3.4 index. Near-identical circulation anomalies are present in the regression maps. There is the presence of an anomalous anticyclone at 850-hPa (Fig. 6a), the associated moisture fluxes that diverge out of MSEA and South China and converge into Yangtze River region (Fig. 6b), and a wave train at 200-hPa emanating from the northern flank of Tibetan Plateau toward South China (Fig. 6c). Given these similar circulation anomalies and patterns, the regression of precipitation does show the in-phase precipitation variations between South China and MSEA (Fig. 6a). Lastly, we examined precipitation anomalies in JA following all major El Niño and La Niña events since 1982. Here, El Niño (La Niña) events were selected based on NOAA’s criterion that the Ocean Niño Index (ONI) be greater or equal to (less than or equal to) 0.5 °C for a period of at least five, consecutive and overlapping three-month seasons. Five El Niño events (1982, 1987, 1991, 1997, and 2015) were classified as either strong or very strong, with a 3-month Niño 3.4 average greater than 1.50 and 2.0, respectively (Fig. 7a). The analyzed La Niña years were the following: 1988, 1998, 1999, 2007, and 2010. Qualitatively speaking, the composites of these events suggests that El Niño likely plays a role in producing the meridional precipitation pattern and the in-phase relationship between South China and MSEA, as noted in previous studies (Jin et al. 2016). However, precipitation anomalies during La Niña events do not appear to be robust (Fig. 7b). Possible explanations may be that (1) La Niña events are typically weaker than El Niño events due to nonlinear dynamic processes (Burgers and Stephenson 1999), (2) interdecadal modulations of La Niña events in response to Pacific climate shifts over the last several decades that may have muddled the precipitation signals (Wang et al. 2012a), or (3) a combination of others factors influencing East China and MSEA precipitation as well as ENSO, such as the Indian Ocean (Watanabe and Jun, 2002) or North Atlantic SST (Wang et al. 2011).

We then evaluated the dynamic mechanisms influencing the EOF2 mode of precipitation variability and the out-of-phase variations between South China and MSEA precipitation. As previously mentioned, upper-tropospheric anomalies are dominated by a zonally-extended wave train structure that originates from the North Atlantic Ocean and extends towards the Japan Sea. We explore the possible relationship between EOF2 and the NAO, which is the leading variability mode in the atmosphere over the North Atlantic (Hurrell 1995). We find the highest correlation between PC2 and the average of May–June–July (MJJ) values of the NAO index from the Climate Prediction Center with a correlation coefficient of $r = 0.43$ that is statistically significant at 99% confidence level. Previous studies have found that the EASM and the preceding spring (April–May) NAO are well-correlated. Gu et al. (2009) showed that the March NAO is closely related to a leading precipitation mode, which exhibits out-of-phase variation between the Yangtze river valley and southeast China. Although the EOF analysis did not include MSEA, the spatial pattern in southeast China and the Yangtze River region is similar to the spatial pattern seen in EOF2 of our study (Fig. 2b and their Fig. 1b).

We repeat the regression analyses onto the NAO index as was done for PC2 to assess whether the MJJ NAO may induce similar anomalies. The regression maps of precipitation anomalies and low-level winds onto the NAO index (Fig. 8a) show qualitatively similar results as the regression maps onto PC2. Some differences do exist, for example, the cyclonic circulation pattern centered over the South China Sea that likely induces more precipitation over South China compared to that of the regression map onto PC2 (Fig. 3c). The low-level cyclonic pattern is mostly concentrated over the South China Sea (Fig. 8a) as opposed to an elongated anticyclonic pattern (Fig. 3c). However, the patterns of vertically-integrated moisture flux patterns, such as the
Fig. 6 As in Fig. 3, but for the a, b regression maps onto DJF Niño3.4 index for 1983–2017. The regression map of Z200 minus the zonal mean and vertical velocity [Pa s⁻¹] onto c DJF Niño 3.4 index also shown. The black vectors in a, b and black stippled regions in a–c denote significance at the 90% confidence level. The solid (dashed) contours present positive (negative) values.

Fig. 7 Composite precipitation anomalies (mm) for a strong/very strong El Niño events b strong La Niña events and strong c positive and d negative NAO events. The black stippled regions represent significance at 90% confidence level. The n values present the number of years that are composited in each panel.
moisture divergence over parts of South China that extends into the Yangtze River region, remain consistent (Fig. 8b). The regression map onto Z200 also highlights the barotropic pattern observed in the regression map onto PC2 and supports the lower geopotential heights over MSEA and the wave train-like patterns that appear to originate from the North Atlantic through Eurasia and propagate southeastward into South China (Fig. 8c). This wave train between the North Atlantic and East Asia has been observed in other studies (Bao-Qiang and Ke 2012). Lastly, we examined JA precipitation anomalies observed during all major NAO events since 1982. The strong NAO events were selected based on years in the MJJ index that exceeded one standard deviation. We identified four strong positive NAO events (1992, 1994, 2008, 2013) and four strong negative NAO events (1993, 1998, 2008, 2012) events. By compositing the associated precipitation anomalies during these NAO years, it is clear that during strong NAO events, the precipitation anomalies resemble the EOF2 pattern and South China and MSEA show an overall pattern of precipitation variations that are out-of-phase (Fig. 7c, d).

These analyses support our findings that the EOF1 and EOF2 modes of precipitation variability likely represent responses of East China and MSEA precipitation to ENSO and NAO forcings, respectively. We emphasize that the dominant precipitation patterns across East China vary between these two modes, but also the relationship between MSEA and South China also changes. We hypothesize that precipitation anomalies in these two regions should reflect an in-phase relationship during strong ENSO events and potential out-of-phase precipitation variations in response to a remote Atlantic forcing.

5 Conclusions

Precipitation across East China and MSEA is characterized by strong interannual variability. The features of the interannual variations of JA mean rainfall for East China and MSEA were assessed using satellite precipitation data. The spatial structure of summer rainfall over East China and MSEA were analyzed using the EOF method for the period of 1983–2017. Results showed that the leading mode of interannual precipitation variability over the last few decades is characterized by a meridional tripole pattern and in-phase precipitation variations between South China and MSEA. We conclude that this precipitation mode is likely driven by anomalous anticyclone variations over the western Pacific in response to ENSO. Conversely, the second leading mode of interannual precipitation variability is characterized by a meridional dipole pattern and an out-of-phase relation between South China and MSEA precipitation. This mode is primarily driven by a zonally-extend wave train from the North Atlantic sector and associated with the summer
NAO. Therefore, the in-phase and out-of-phase relationship between MSEA and South China precipitation manifest the relative controls of the local Pacific ENSO forcing and the remote Atlantic NAO forcing.

This study discusses the interannual variability across East China and MSEA, but it should be mentioned here that precipitation over these regions experiences significant interdecadal variations as well (Huang et al. 2013; Sun and Wang 2015). Previous studies have revealed a variety of other factors contributing towards the interdecadal variability of East Asian climate, such as the Pacific Decadal Oscillation (Wang et al. 2008; Feng et al. 2014). A 10-year high-pass Butterworth filter was initially applied to the PERSIANN-CDR precipitation dataset similar to the methods in other studies (Hsu et al. 2007; Jin et al. 2016; He et al. 2017). However, both the EOF modes and the regression analyses yielded similar results to the final results presented here, highlighting a potential caveat of the PERSIANN-CDR dataset, which cannot capture the interdecadal variations given the 35-yearlong dataset. Moreover, it will be intriguing to further analyze how the response from ENSO and/or NAO forcings on the relationships between South China and MSEA evolve in the future due to climate change. The present study focuses on a small set of strong ENSO and NAO events given the temporal limitation of the precipitation data set and calls for additional studies to evaluate how the ENSO and NAO remote forcings may influence the interdecadal precipitation variations between South China and MSEA.

In addition to investigating these relationships on interdecadal timescales, other studies have analyzed past changes in the EASM climate over glacial-interglacial timescales through paleoclimate proxy records and paleoclimate model simulations. These studies have found that meridional precipitation patterns in East China are present on longer timescales (Chiang et al. 2015; Kong et al. 2017; Zhang et al. 2018), though the forcing is likely different than for the modern interannual variability. For instance, the tripole pattern of precipitation variability has been shown to be driven by the timing and duration of distinct stages of the EASM related to insolation-forced shifts in the position of the westerlies relative to the Tibetan Plateau (Kong et al. 2017) during the Holocene. While the present study does not find a strong argument towards a shift in the westerly jet in influencing East China precipitation patterns, it does provide additional insight on the mechanisms influencing precipitation variability in both East China and MSEA. Our findings can have significant implications for paleoclimate studies that utilize precipitation proxies from the Asian Monsoon region, specifically MSEA and South China (Wang et al. 2019) to infer the relative Pacific and Atlantic teleconnections on past East Asian climate. By identifying the dominant controls on interannual precipitation patterns across MSEA and East China, our results can help improve paleoclimate proxy comparisons among sites situated within these two regions. While additional studies are needed to clarify whether the ENSO and NAO forcings on the relationships between South China and MSEA are stationary on longer timescales, our results combined with additional paleoclimate records from MSEA and South China can provide a more comprehensive and broad view of the EASM system during both the instrumental and paleoclimate periods. Future studies that combine climate proxies, observational data, and output from global circulation models are necessary to further investigate the spatial and temporal patterns of precipitation variability across East China and MSEA.

Acknowledgements We thank Zachary M. Labe, Dillon J. Amaya, and Michael L. Griffiths for valuable discussions and suggestions. PERSIANN-CDR data were obtained from https://chrsdata.eng.uci.edu. We acknowledge the ERA5 reanalysis data is from the Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalysis of the global climate. The data were downloaded from Copernicus Climate Change Service Data Store (CDS), March 2019. https://cds.climate.copernicus.eu/cdsapp#!/home. Monthly ONI data obtained by the NOAA/PSD through https://www.esrl.noaa.gov/psd/data/correlation/oni.data. NOAA_ERSSST_V5 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/. This work was supported by the National Science Foundation Graduate Research Fellowship Grant DGE-1321846 to J.K. Wang, National Science Foundation grants AGS-1505145 and AGS-1833075 to J.-Y. Yu, and National Science Foundation grant AGS-1603056 to K.R. Johnson.

Compliance with ethical standards
Conflict of interest The authors declare no competing financial interests.

References
Ashouri H, Hsu K-L, Sorooshian S et al (2015) PERSIANN-CDR: daily precipitation climate data record from multisatellite observations for hydrological and climate studies. Bull Am Meteorol Soc 96:69–83. https://doi.org/10.1175/BAMS-D-13-00068.1
Asian Development Bank (2009) The economics of climate change in Southeast Asia: a regional review. Asian Development Bank, Mandaluyong
Bao-Qiang T, Ke F (2012) Relationship between the Late Spring NAO and summer extreme precipitation frequency in the middle and lower reaches of the Yangtze River. Atmos Ocean Sci Lett 5:455–460. https://doi.org/10.1080/16742834.2012.11447038
Buckley BM, Anchukaitis KJ, Penny D et al (2010) Climate as a contributing factor in the demise of Angkor, Cambodia. Proc Natl Acad Sci USA 107:6748–6752. https://doi.org/10.1073/pnas.0910827107
Burgers G, Stephenson DB (1999) The “normality” of El Niño. Geophys Res Lett 26:1027–1030. https://doi.org/10.1029/1999GL900161
Chang C-P, Wang Z, McBride J et al (2005) Annual cycle of Southeast Asia—maritime continental rainfall and the asymmetric monsoon transition. J Clim 18:287–301. https://doi.org/10.1175/JCLI-3257.1
Hydroclimatic changes in China by Chen J, Chen F, Feng S et al (2015)

The summer North Atlantic Oscillation by Folland CK, Knight J, Linderholm HW et al (2009)

Different impacts of El Niño by Feng J, Chen W, Tam C-Y, Zhou W (2011)

West Asian and monsoon Asia: spatiotemporal differences in climate change and possible mechanisms on decadal to sub-orbital timescales by Chen F, Chen J, Huang W et al (2019a)

The key oceanic regions responsible for long persistence of El Niño-induced north Indian Ocean warmings by He C, Zhou T, Wu B (2015)

Interdecadal change of summer precipitation over Eastern China around the late-1990s and associated circulation anomalies, internal dynamical causes by Huang R, Liu Y, Feng T (2013)

The changing impact mechanisms of a diverse El Niño on the Western Pacific Subtropical High by Chen M, Yu J-Y, Wang X, Jiang W (2019b)

Role of air–sea interaction in the summer North Pacific by Du Y, Xie S-P, Huang G et al (2009)

The dipole mode of the summer rainfall over East China during 1958–2001 by Han J, Zhang R (2009)

Interdecadal variation of the summer rainfall over India by Ding Y, Chan JCL (2005)

The East Asian summer monsoon: an overview by Christensen JH, Kumar KK, Aldrian E et al (2013)

Impact of ENSO on the variability of the Asian-Australian Monsoons as simulated in GCM experiments by Jin D, Hameed SN, Huo L et al (2016)

The meridional triple and dipole modes by Chen F, Chen J, Huang W et al (2019a)

The interannual variability of the western North Pacific subtropical high and associated mechanisms by Han J, Zhang R (2009)

Interannual variability of Eastern China Summer Rainfall: the origins of the meridional triple and dipole modes by He C, Lin A, Gu D et al (2017)

Relationship between the Tibetan Plateau heating and East Asian summer monsoon rainfall by Hsu H-H, Liu X (2003)

The spatio-temporal variabilities of the East Asian monsoon system by Huang R, Chen J, Wang L, Lin Z (2012)

Recent changes in ENSO teleconnection over the Western Pacific impacts the Eastern China Precipitation dipole by Huang R, Li Y, Feng T (2013)

Interannual teleconnection over the Western Pacific by Linderholm HW, Ou T, Jeong J-H et al (2011)

Asian-Australian Monsoons as simulated in GCM experiments by Jin D, Hameed SN, Huo L et al (2016)

J. K. Wang et al.
Mie Z, Sein M, Ogwang BA et al (2015) Inter-annual variability of
summer monsoon rainfall over Myanmar in relation to
ENSO. J Environ Agric Sci 4:28–36
Misra V, DiNapoli S (2014) The variability of the Southeast Asian
summer monsoon. Int J Climatol 34:893–901. https://doi.
org/10.1002/joc.3735
Nigam S, Shen H-S (1993) Structure of oceanic and atmospheric low-
frequency variability over the Tropical Pacific and Indian Oceans.
Part I: COADS Observations. J Clim 6:657–676
Qian C, Yu J-Y, Chen G (2014) Decadal summer drought frequency
in China: the increasing influence of the Atlantic Multidecadal
Oscillation. Environ Res Lett 9:124004. https://doi.
org/10.1088/1748-9326/9/12/124004
Qiu S, Zhou W (2019) Variation in summer rainfall over the Yangtze
River region during warming and Hiatus periods. Atmosphere
(Basel) 10:173. https://doi.org/10.3390/atmos10040173
Ratna S, Ratnam J, Behera S et al (2017) Validation of the WRF
Pacific and Atlantic controls of the relationship between Mainland
Southeast Asia and East...

Sui C-H, Chung P-H, Li T (2007) Interannual and interdecadal vari-
bility of summer monsoon rainfall over Myanmar. Int J Climatol
37:802–820. https://doi.org/10.1002/joc.4741
Sui C-H, Chung P-H, Li T (2007) Interannual and interdecadal vari-
bility of the summertime western North Pacific subtropical high.
Geophys Res Lett 34:L11701. https://doi.org/10.1029/2006GL029204
Sun J, Wang H, Yuan W (2008) Decadal variations of the relationship
between the summer North Atlantic Oscillation and middle East
Asian air temperature. J Geophys Res 113:D15107. https://doi.
org/10.1029/2007JD009626
Sung M-K, Kwon W-T, Baek H-J et al (2006) A possible impact of
the North Atlantic Oscillation on the east Asian summer monsoon
precipitation. Geophys Res Lett 33:L121713. https://doi.
org/10.1029/2006GL027253
Sun B, Wang H (2015) Inter-decadal transition of the leading mode of
inter-annual variability of summer rainfall in East China and its
associated atmospheric water vapor transport. Clim Dyn 44:2703–
2722. https://doi.org/10.1007/s00382-014-2251-0
Tsai C, Behera SK, Waseda T, Yamagata T (2015) Indo-China Mon-
soon Indices. Sci Rep 5:8107. https://doi.org/10.1038/srep08107
Wang B, LinHo WB (2002) Rainy Season of the Asian-Pacific Sum-
mer Monsoon*. J Clim 15:386–398. https://doi.org/10.1175/1520-
0442(2002)015<0386:RATESO>2.0.CO;2
Wang B, Wu R, Fu X et al (2000) Pacific-East Asian teleconnection: how
does ENSO affect East Asian Climate? J Clim 13:1517–1536.
https://doi.org/10.1175/1520-0442(2000)013<1517:PEATHD>2.0.CO;2
Wang B, Wu R, Lau K-M et al (2001) Interannual variability of the
Asian Summer Monsoon: contrasts between the Indian and the
Western North Pacific-East Asian Monsoons*. J Clim 14:4073–
4090. https://doi.org/10.1175/1520-0442(2001)014<4073:IVOTAS>2.0.CO;2
Wang L, Chen W, Huang R (2008) Interdecadal modulation of PDO on
the impact of ENSO on the east Asian winter monsoon. Geophys
Res Lett 35:L20702. https://doi.org/10.1029/2008GL035287
Wang X, Wang C, Zhou W et al (2011) Teleconnected influence of
North Atlantic sea surface temperature on the El Niño onset. Clim
Dyn 37:663–676. https://doi.org/10.1007/s00382-010-0833-z
Wang X, Wang D, Zhou W, Li C (2012a) Interdecadal modulation of
the influence of La Niña events on mei-yu rainfall over the
Yangtze River valley. Adv Atmos Sci 29:157–168. https://doi.
org/10.1007/s00376-011-1012-8
Wang Z, Chang C-P, Wang Z, Chang C-P (2012b) A numerical study of
the interaction between the large-scale monsoon circulation and
orographic precipitation over south and Southeast Asia. J Clim
25:2440–2455. https://doi.org/10.1175/JCLI-D-11-00136.1
Wang B, Xiang B, Lee J-Y (2013) Subtropical high predictability
establishes a promising way for monsoon and tropical storm pre-
dictions. Proc Natl Acad Sci USA 110:2718–2722. https://doi.
org/10.1073/pnas.1214626110
Wang Z, Yang S, Lau N-C et al (2018) Teleconnection between sum-
mer NAO and East China rainfall variations: a bridge effect of the
Tibetan Plateau. J Clim 31:6433–6444. https://doi.org/10.1175/
JCLI-D-17-0413.1
Wang JK, Johnson KR, Borsaet A et al (2019) Hydroclimatic variabil-
ity in Southeast Asia over the past two millennia. Earth Planet
Sci Lett. https://doi.org/10.1016/j.epsl.2019.115737
Wu B, Zhou T (2008) Oceanic origin of the interannual and interdeca-
dal variability of the summertime western Pacific subtropical high.
Geophys Res Lett 35:L13701. https://doi.org/10.1029/2008GL034584
Wu R, Hu Z-Z, Kirtman BP et al (2003) Evolution of ENSO-related
rainfall anomalies in East Asia. J Clim 16:3742–3758. https:
//doi.org/10.1175/1520-0442(2003)016<3742:EORERA>
Wu B, Zhou T, Li T et al (2009) Seasonally evolving dominant interan-
dal variability modes of East Asian Climate*. J Clim 22:2992–
3005. https://doi.org/10.1175/2008JCLI2710.1
Wu B, Li T, Zhou W et al (2010) Relative contributions of the Indian
Ocean and Local SST anomalies to the maintenance of the West-
ern North Pacific anomalous anticyclone during the El Niño Decay-
ing Summer*. J Clim 23:2974–2986. https://doi.
org/10.1175/2010JCLI3300.1
Xie S-P, Annamalai H, Schott FA, McCreary JP (2002) Structure and
mechanisms of South Indian Ocean climate variability*. J Clim
15:864–878. https://doi.org/10.1175/1520-0442(2002)015<864:
SAMOSI>2.0.CO;2
Xie S-P, Hu K, Hafner J et al (2009) Indian Ocean capacitor effect on
Indo-Western Pacific Climate during the Summer following El
Niño. J Clim 22:730–747. https://doi.org/10.1175/2008JCLI244.1
Xie S-P, Kosaka Y, Du Y et al (2016) Indo-western Pacific ocean
capacitor and coherent climate anomalies in post-ENSO summer: a
review. Adv Atmos Sci 33:411–432. https://doi.org/10.1007/
s00376-015-5192-6
Xu C, Sano M, Nakatsuoka T (2011) Tree ring cellulose δ18O of Fokie-
nia hodginsii in northern Laos: a promising proxy to reconstruct
ENSO? J Geophys Res Atmos. https://doi.org/10.1029/2011J
D016694
Yamoono KKA, Chabangborn A, Chawchai S et al (2016) Large vari-
ability in n-alkane δ13C values in Lake Pa Kho (Thailand) driven
by wetland wetness and aquatic productivity. Org Geochem
97:53–60. https://doi.org/10.1016/j.orggeochem.2016.04.008
Yang S, Lau K-M, Yoo S-H et al (2004) Upstream subtropical sig-
als preceding the Asian Summer Monsoon circulation. J Clim
17:4213–4229. https://doi.org/10.1175/1520-0442(2004)017<4213:
USSPAS>2.0.CO;2
Yang J, Liu Q, Xie S-P et al (2007) Impact of the Indian Ocean SST basin mode on the Asian summer monsoon. Geophys Res Lett 34:L02708. https://doi.org/10.1029/2006GL028571
Ye H, Lu R (2012) Dominant patterns of summer rainfall anomalies in East China during 1951–2006. Adv Atmos Sci 29:695–704. https://doi.org/10.1007/s00376-012-1153-5
Zhang H, Griffiths ML, Chiang JCH et al (2018) East Asian hydroclimate modulated by the position of the westerlies during termination I. Science 362:580–583. https://doi.org/10.1126/science.aat9393

Zuo J-Q, Wei-Jing L, Ren H-L, Chen L-J (2012) Change of the relationship between the spring NAO and East Asian Summer Monsoon and its possible mechanism. Chin J Geophys 55:23–34. https://doi.org/10.1002/cjg2.1697

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.