ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 36, SEPTEMBER 2019, 887–901

• Review •

Recent Progress in Studies of the Variabilities and Mechanisms of the East Asian Monsoon in a Changing Climate

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(Received 1 November 2018; revised 15 April 2019; accepted 28 May 2019)

ABSTRACT

Located in a monsoon domain, East Asia suffers devastating natural hazards induced by anomalous monsoon behaviors. East Asian monsoon (EAM) research has traditionally been a high priority for the Chinese climate community and is particularly challenging in a changing climate where the global mean temperature has been rising. Recent advances in studies of the variabilities and mechanisms of the EAM are reviewed in this paper, focusing on the interannual to interdecadal time scales. Some new results have been achieved in understanding the behaviors of the EAM, such as the evolution of the East Asian summer monsoon (EASM), including both its onset and withdrawal over the South China Sea, the changes in the northern boundary activity of the EASM, or the transitional climate zone in East Asia, and the cycle of the EASM and the East Asian winter monsoon and their linkages. In addition, understanding of the mechanism of the EAM variability has improved in several aspects, including the impacts of different types of ENSO on the EAM, the impacts from the Indian Ocean and Atlantic Ocean, and the roles of mid- to high-latitude processes. Finally, some scientific issues regarding our understanding of the EAM are proposed for future investigation.

Key words: East Asian summer monsoon, East Asian winter monsoon, changing climate, monsoon onset and withdrawal, transitional climate zone, different types of ENSO

Citation: Chen, W., L. Wang, J. Feng, Z. P. Wen, T. J, Ma, X. Q. Yang, and C. H. Wang, 2019: Recent progress in studies of the variabilities and mechanisms of the East Asian monsoon in a changing climate. *Adv. Atmos. Sci.*, **36**(9), 887–901, https://doi.org/10.1007/s00376-019-8230-y.

Article Highlights:

- Interdecadal changes of the EAM around the 1990s have been studied extensively, including its evolution and intensity.
- The ENSO–EAM relationship is unstable and can be disturbed by both internal and external factors.
- Further studies on the behaviors of the EAM in a changing climate and the associated mechanisms are needed in the future.

1. Introduction

Monsoon is an important component of Earth's climate system. Its onset, evolution, and variability are crucial for the people that live in monsoon regions, because anomalous behaviors of monsoon often lead to natural hazards such as flooding, droughts, heat waves, and blizzards, which significantly affect society and human lives. The East Asian monsoon (EAM) is driven by the thermal contrast between the largest continent of Eurasia, the surrounding oceans (Pacific and Indian), as well as the elevated heat source of the Tibetan Plateau (Huang et al., 2003). The EAM consists of the East Asian summer monsoon (EASM), which features strong southerly winds and abundant rainfall in summer, and the East Asian winter monsoon (EAWM), which features strong northerly winds and little rainfall in winter (Huang et al., 2012). Strong southerly flow in summer transports water vapor to eastern China, Korea, and Japan, causing continuous and heavy rainfall in East Asia (e.g., Tao and Chen, 1987; Chen et al., 2009). In contrast, cold surges in winter bring cold and dry air southward along the coast of East Asia to the South China Sea (SCS) and the Indochina Peninsula, causing climate disasters such as low temperature and severe snowstorms in East Asia (e.g., Ding, 1994; Chen et al., 2000; Chang et al., 2006). Therefore, monsoon research has tra-

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ditionally been a high priority for the international climate community. It is also an urgent task for the scientific community to gain a better understanding of the variabilities and mechanisms of the monsoons to meet the rising demand of reliable monsoon prediction. This is particularly challenging in a changing climate where the global mean temperature has been rising.

IPCC (2013) indicated that the warming of the climate system is unequivocal. In addition to the robust long-term warming, the global mean surface temperature exhibits substantial decadal and interannual variability. The EAM also has significant interannual and interdecadal variabilities that are driven by both natural and anthropogenic forcing. For example, the interannual variations of the summer monsoon rainfall cause drought or wet conditions in many parts of East Asia, and their persistence on decadal time scales leads to long-term changes. Such changes are important to be understood for regional agriculture, transportation, and economies. The characteristics of the evolution of the EASM, including both its onset and withdrawal over the SCS, and the changes in the northern boundary activity of the EASM or the transitional climate zone (TCZ) in East Asia, have been analyzed further in recent years. Extensive studies on the EAWM have also been conducted.

Since the end of the 20th century, the tropical Pacific Ocean has been undergoing a rapid dynamic change, having experienced a climate regime shift in the Pacific sea surface temperature (SST) pattern (Hong et al., 2014). This climate regime shift has coincided with the slowdown in surface warming in the post-1998 period, often referred to as the global warming hiatus (Trenberth and Fasullo, 2013), in a scenario where the concentrations of greenhouse gases are still increasing (Kosaka and Xie, 2013). This decadal SST change is characterized by a warming over the equatorial western Pacific, midlatitude North and South Pacific, and a cooling in the equatorial central Pacific. Although the tropical Pacific Ocean displays a La Niña-like cooling pattern while SST in the Indian Ocean has continued to increase, this SST pattern differs from the well-known La Niña-induced basin-wide cooling across the Indian Ocean on the interannual time scale. It is well known that on the interdecadal timescale the Pacific basin SST experienced a great climate regime shift around 1976/77 (Miller et al., 1994; Wang, 1995), with a pronounced warming in the tropics and a cooling over the midlatitudes. Many studies have documented that this climate regime shift led to a significant circulation change over various regions of the globe, including Southeast and East Asia (e.g., Chang et al., 2000; Zhang et al., 2004; Kwon et al., 2005; Li et al., 2010; Jia et al., 2015a; Wu and Wang, 2015). In the most recent decade, much research has focused on the climate regime shift around the end of the 1990s and its impacts on both the EASM and EAWM.

The recent decade-long hiatus period is characterized by a La Niña-like pattern with warm SST anomalies over the tropical western Pacific, which facilitated enhanced precipitation and strengthened the Pacific Walker circulation. Meanwhile, it also featured frequent central-Pacific (CP) El Niño events after the 1990s (Lee and McPhaden, 2010; Pascolini-Campbell et al., 2015). CP El Niño features maximum SST warming in the equatorial central Pacific, which is different to the conventional eastern-Pacific (EP) El Niño whose maximum SST warming is located in the equatorial eastern Pacific (Ashok et al., 2007; Kao and Yu, 2009; Jia et al., 2016). As the major air–sea coupling phenomenon in the tropical Pacific, El Niño–Southern Oscillation (ENSO) is one of the most important factors influencing the EAM variability (e.g., Zhang et al., 1996, 1999, 2017b; Huang et al., 2004; Chan and Zhou, 2005). On the one hand, ENSO exerts different impacts on the EASM during its different stages. In the summer before the peak of El Niño, droughts often occur over northern and southern China, while in the summer following the peak of El Niño, the rainfall anomalies show a completely different pattern with excessive rainfall over the Yangtze–Huaihe River Valley (e.g., Huang and Wu, 1989; Liu and Ding, 1992; Chen, 2002). On the other hand, the ENSO–EAM relationship depends not only on complex ENSO properties, such as CP and EP ENSO, but also on the modulation effects from other factors. Hence, the ENSO–EAM relationship is unstable on the interannual time scale, and experiences evident interdecadal change. In recent years, Chinese scientists have conducted extensive and in-depth research on these issues.

Since the EAM is a highly complicated system with an extremely large meridional extent stretching from the high latitudes to the tropics, as well as significant spatial variability, it is hard to comprehensively review the field of EAM research in just one paper. Hence, in this paper, recent progress in studies on the variabilities and mechanisms of the EAM in a changing climate are reviewed with a focus on the interannual to interdecadal time scales. Particular attention is given to the interdecadal changes of the EAM around the 1990s, including both monsoon evolution and intensity, and the impacts of different types of ENSO. The review focuses mostly on research progress in China in the 2010s. At the end of the paper, some scientific issues regarding our understanding of the EAM are suggested for future investigations.

2. Interdecadal changes in the EAM and associated processes

2.1. *Interdecadal changes of SCS summer monsoon onset and withdrawal*

The SCS summer monsoon onset (SCSSMO) is regarded as the commencement of the rainy season in East Asia and has a significant influence on the EASM circulation (e.g., Huang et al., 2006). Considering that the EAM is a complex monsoon system with strong interactions between the tropical and midlatitude systems (Lau et al., 2000), Wen et al. (2016) presented a conceptual picture of the possible mechanisms leading to the SCSSMO involving both tropical and extratropical processes. The related weather system configuration includes southward movement of the subtropical jet in the upper troposphere, deepening of the East Asian trough and withdrawal of the subtropical high from the SCS in the middle troposphere, southward invasion of cold air, northward propulsion of tropical monsoon, and their anomalous convergence in the central and northern part of the SCS in the lower troposphere. An interdecadal change in the SCSSMO date can be observed around 1993/94, at about half a month earlier, which is believed to be associated with changes in the Pacific Ocean SST (Kajikawa and Wang, 2012; Kajikawa et al., 2012; Yuan and Liu, 2013; Yuan and Chen, 2013). In addition, an interdecadal advancement of summer monsoon onset can be observed around 1998/99 for the Arabian Sea and Bay of Bengal (Xiang and Wang, 2013). The difference in occurrence time of the interdecadal change has been addressed, and the period around the mid-1990s has been suggested to be a transition (Huangfu et al., 2015).

The development of the SCS cross equatorial flow (SCSCEF) is one of the key features of the SCSSMO (Chen et al., 1991). Previous studies have indicated that a strong SCSCEF tends to favor an early SCSSMO (e.g., Gao and Xue, 2006; Lin et al., 2017). In view of the significant interdecadal change in the SCSSMO, Hu et al. (2018) further investigated the relationship between the SCSSMO and the SCSCEF in May. An interdecadal change in the SCSSMO–SCSCEF relationship was observed around the late 1990s. It is noteworthy that this interdecadal change is largely independent of ENSO, which can affect both the CEF (Li et al., 2014) and SCSSMO (Zhou and Chan, 2007; Ding et al., 2016). Possible causes for this interdecadal change are suggested to be the different driving factors for the SCSSMO, which are the northward march of the ITCZ in the period before the late 1990s and more tropical cyclones and disturbances during May in the period after the late 1990s. Hence, the SCSSMO–SCSCEF relationship becomes weaker after the late 1990s.

Although there have been many studies that have focused on the SCSSMO (e.g., Ding et al., 2015; Xue et al., 2015a), fewer studies have addressed the monsoon withdrawal, which is also a very important issue. Also, the limited number of previous studies on the EASM withdrawal mainly focused on mainland China (Ding and Chan, 2005; Zhan et al., 2016; Ding et al., 2018b). In fact, the autumn rainfall in western China is traditionally viewed as the last rainy season of the year (Wang and Ding, 2008; Yuan and Liu, 2013). However, Wang and LinHo (2002) documented that the retreat of rainfall is much later in the SCS than in the subtropical East Asian region, and that the SCS summer monsoon withdrawal (SCSSMW) should be regarded as the final stage in the withdrawal of the EASM. In contrast to the SCSSMO, previous studies have found that the SCSSMW is more gradual and lasts much longer compared to the abruptness of the monsoon onset across the entire SCS, and that the withdrawal of rainfall is much later than the withdrawal of wind, as compared to the simultaneous onset of westerly winds and convection (Fong et al., 2007; Li and Zhang, 2009; Wang et al., 2009a; Huang and Zhang, 2010). Hu et al. (2018) further analyzed the climatological characteristics of the synoptic features and changes during the SCSSMW. Luo and Lin (2017) indicated that El Niño can advance the SCSSMW and thus shorten the length of the summer monsoon season. In the future, the dynamic mechanisms for the SCSSMW and the linkage between the monsoon withdrawal in subtropical East Asia and the tropical SCS need further investigation. Interestingly, recent work by Hu et al. (2019) found a significant interdecadal change in the SCSSMW around the mid-2000s. The SCSSMW occurred much later (about two weeks) after the mid-2000s, with the increased number and more frequent visits to the SCS by tropical cyclones and enhanced quasi-biweekly oscillation activities suggested as two possible contributors for this delayed SCSSMW. Although it was mentioned that the decadal SST warming in the Philippine Sea in September may be a crucial external forcing for the delayed SCSSMW, the detailed physical mechanisms need to be further pursued in the future. Furthermore, the interdecadal advancement of the SCSSMO and the delay of the SCSSMW did not occur concurrently. Specifically, the advancement of the SCSSMO occurred in the mid-1990s while the delay to the SCSSMW occurred in the mid-2000s. Nonetheless, it seems that the advanced onset and delayed withdrawal may both have resulted from tropical systems, including tropical cyclones and intraseasonal oscillations. Thus, the linkage and similarities between the SCSSMO and SCSSMW may be hidden in their trigger mechanisms.

2.2. *Changes of the northern boundary activity of the EASM and the monsoon transitional zone in China*

After the SCSSMO, the monsoon moves northward over East Asia reaching the northern margin of the summer monsoon, and then retreats southward until the SCSSMW. Lots of research has been devoted to identifying an index that adequately represents the EASM intensity. However, although studies on EASM indices have made great progress (e.g., Wang et al., 2008a), consensus has not yet been reached regarding the definition of an index that adequately represents the intensity and northernmost location of the EASM (Mei et al., 2015). In addition, the northern margin of the EASM exhibits significant interannual fluctuations owing to the variation of the EASM northward march, resulting in the formation of the monsoon transitional zone (MTZ) (e.g., Qian et al., 2012; Chen et al., 2018). The MTZ is the transitional belt between monsoon and non-monsoon regions, as well as between humid and arid regions, which is characterized by a northeast–southwest oriented belt in China (Qian et al., 2012; Zhang et al., 2016; Wang et al., 2017a). Owing to sharp climate and biome gradients, the MTZ has a fragile ecosystem and is more sensitive to climate changes and vulnerable to natural disasters. Any deficiency or excess in precipitation during the rainy season has large impacts on irrigation, animal husbandry, and socioeconomics. Recently, Piao et al. (2017) found an interdecadal change of the MTZ around 1998/99, involving a summer rainfall decrease of about 18% of the climatological amount in the MTZ of East Asia. Since rainfall plays a crucial role in drought conditions, this abrupt rainfall decrease significantly influenced the regional drought situation. The time series of three drought indices all shift from positive to negative in 1999, indicating an exacerbation of the drought conditions. The driving factor for this interdecadal change is suggested to be a quasi-zonal wave-like atmospheric teleconnection pattern over the Eurasian continent. This teleconnection pattern, together with the anticyclonic circulation over the MTZ, was responsible for the decrease in summer rainfall over the East Asian MTZ. Further studies suggest that the warming SST anomalies over the North Atlantic could excite the quasi-zonal wave-like teleconnection pattern over the Eurasia, resulting in the rainfall decrease over the MTZ and worsening the drought conditions there (Piao et al., 2017; Wang et al., 2017b).

Considering both the precipitation and potential evaporation, Wang et al. (2017a) further investigated the TCZ variation in East Asia, which is closely related to the MTZ changes, by using observations and CMIP5 model outputs. In the historical period, both the front and rear edges of the TCZ exhibit wide year-to-year excursions and have experienced coastward migration with increasing aridity throughout the TCZ. In addition, the front edge exhibits a higher amplitude of deviation than the rear one, indicating an important influence of the EASM. Models are capable of largely reproducing the climatological shape and orientation of the TCZ, although a northwestward bias is apparent. In the global warming scenario period, there is continuing southeastward displacement for the front edge, but an opposite northwestward movement is projected for the rear one, as a consequence of significant drying trends in the humid zone together with regime shifts towards humid conditions in the arid zone. Despite the expanded TCZ sector, however, the available water resources inside it suffer small magnitude changes without preferential tendency towards either drier or wetter conditions, implying neither deleterious nor beneficial effects on the TCZ environment. Moreover, the interannual variability of the TCZ is expected to become stronger, resulting in more frequent occurrences of extreme swings. Finally, it is noted that uncertainty arising from climate models dominates in the TCZ under various emission scenarios, in contrast to the situation in humid and arid zones.

2.3. *Summer SLP change over the Mongolian region after the early 1990s and the possible mechanisms*

The EASM is strongly affected by tropical and subtropical systems such as the western North Pacific subtropical high (WNPSH), the East Asian mei-yu front, tropical cyclones, and intraseasonal oscillations (Tong et al., 2009; Lu et al., 2014). Meanwhile, it is also influenced by synoptic processes in the mid–high latitudes (Yuan et al., 2012a; Zhou et al., 2012), among which one dominant feature is migratory cyclone systems and associated fronts. Compared with studies on the tropical and subtropical influences on the EASM, fewer studies have been conducted about the impacts of extratropical synoptic systems on the seasonal mean changes of the EASM.

Section 2.2 mentioned that an anomalous anticyclonic center can be observed near Mongolia over the MTZ of East Asia (Piao et al., 2017; Wang et al., 2017b). This anticyclonic center has an equivalent barotropic structure and indicates the interdecadal change of the EASM (Zhang et al., 2017b). Its formation has been attributed to the increase in Tibetan Plateau snow cover in the preceding winter–spring (Wu et al., 2010), the increased surface air temperature around Lake Baikal (Zhu et al., 2012; Du et al., 2016), and the quasi-stationary atmospheric wave train induced by anomalous warming of the North Atlantic SST (Piao et al., 2017; Wang et al., 2017b). In contrast, the possible role of extratropical cyclones has not been discussed.

Zhang et al. (2019) indicated that the summer SLP over the Mongolian region tends to be below-normal in years when there are more and stronger Mongolian cyclones, and vice versa. A clear interdecadal increase in the summer SLP is apparent after the early 1990s, accompanied by less and weaker Mongolian cyclone activity. Zhang et al. (2019) further suggested that both the regional meridionally and vertically inhomogeneous warming induced the changes in vertical wind shear and static stability, which were responsible for the reduced cyclone activity.

2.4. *Interdecadal changes in the intensities of the EAM*

2.4.1. *Interdecadal change of the EASM intensity*

Many previous studies have been devoted to the interdecadal change of the EASM around the late 1970s (e.g., Ding et al., 2008, 2009; Zhu et al., 2011). Mainly, the tropical SST anomalies have been suggested to be responsible for the interdecadal weakening of the EASM (Ding et al., 2009; Li et al., 2010; Fu and Li, 2013), with a possible impact from the abrupt increase in the winter and spring snow over the Tibetan Plateau (Ding et al., 2009). Recent studies indicate a significant interdecadal change of the EASM since the early 1990s to 2000, which is associated with a northward shift of the precipitation belt to the Huaihe River valley (HRV). Thus, there is a marked rainfall increase in the HRV and South China and a decrease in the Yangtze River valley (e.g., Kwon et al., 2007; Liu et al., 2011; Zhu et al., 2014; Zhang et al., 2015; Ding et al., 2016; Wang et al., 2018). This interdecadal change of the EASM also corresponds to an eastward retreat and northward movement of the WNPSH (Liu et al., 2012), a weakening of the subtropical westerly jet (Kwon et al., 2007), and a reduced temperature meridional gradient in the upper troposphere (Zhang and Zhou, 2015). It should be noted that the strength of the EASM is still weaker than that during 1965–80 (Tang and Wu, 2012; Ding et al., 2013).

Distinct controlling mechanisms have been proposed to explain this interdecadal change in summer rainfall in the 1990s (e.g., Wu et al., 2010; Yim et al., 2014). Zhang et al. (2017a) further compared these two interdecadal changes in the EASM between the 1970s and the 1990s and some common features of these two changes were observed. Both the changes in the 1970s and 1990s are associated with a wave train over mid-high latitudes, with a similar spatial pattern but opposite phases. In addition, the weakening of the EASM induced by global warming may regulate these two interdecadal changes (Lei et al., 2011). However, differences between these two changes are apparent, especially in terms of the roles played by intraseasonal oscillation and synoptic-scale disturbance (Kwon et al., 2007; Chen et al., 2015). Influences of SST forcing on the interdecadal changes of the EASM have also been addressed extensively, including the Interdecadal Pacific Oscillation and the western North Pacific (WNP) and Indian Ocean SST anomalies (Wu et al., 2010; Liu et al., 2012; Wang et al., 2012; Zhu et al., 2011, 2014; Yuan and Chen, 2013; Zuo et al., 2013; Han et al., 2014; Zhang et al., 2017a). In addition, possible impacts from the changes of spring Arctic sea-ice concentration, spring Eurasian snow cover, and winter snow cover over the Tibetan Plateau have been documented (Tang et al., 2013; Si and Ding, 2013).

2.4.2. *Interdecadal change of EAWM intensity*

It is well known that the EAWM experienced decadal weakening in the late 1980s (e.g., Jhun and Lee, 2004; Wang et al., 2009b; Chen et al., 2013a; Jia et al., 2015a). Although the global mean temperature keeps rising, frequent severe winters have been observed over East Asia during the past decade, indicating a decadal strengthening of the EAWM after the early 2000s (Ding et al., 2014; Wang and Chen, 2014; Wang and Lu, 2017). By comparing two strong epochs of the EAWM, Wang and Chen (2014) revealed that the strong epoch of the EAWM before the mid-1980s features a center of negative surface air temperature anomalies mainly over the coast of East Asia with large meridional scale. The associated atmospheric circulation anomalies resemble those associated with the Northern Annular Mode (Thompson and Wallace, 2001). In contrast, the strong epoch of the EAWM after the early 2000s features a center of negative surface air temperature anomalies over the Siberian region, implying that the strong EAWM is mainly confined over the northern part of East Asia. The meridional scale of this anomalous cold center is much smaller than that observed in the strong EAWM epoch before the mid-1980s, whereas the zonal scale is much larger (Wang and Chen, 2014). The associated atmospheric circulation is characterized by a quasi-zonal Rossby wave train over Eurasia with an anomalous anticyclonic center being located near the Ural Mountains. It suggests that the positive phase of the Eurasian teleconnection pattern (Liu et al., 2014) and the enhanced blocking frequency near the Ural Mountains (Wang and Chen, 2014) are the direct atmospheric factors that account for the recent strong EAWM epoch.

The mechanism of the decadal weakening of the EAWM in the mid-1980s has been studied extensively, whereas that of the decadal strengthening of the EAWM in the early 2000s remains unanswered. Considering that the recent strong EAWM epoch (Wang and Chen, 2014) and the associated frequent extreme cold events over midlatitude Eurasia (Tang et al., 2013) occurs concurrently with the declining of the Arctic sea ice (Walsh, 2014), the reduction of the sea ice in the Barents–Kara Sea was inferred to play some role (Wang and Chen, 2014). Several mechanisms have been proposed to explain the processes that the Arctic sea ice influences the EAWM (Chen et al., 2014, Wang and Lu, 2017, Zhang et al., 2019), but some issues still remain unclear and uncertain. For example, Mori et al. (2014) performed a series of numerical experiments with 100 ensemble members using an atmospheric general circulation model driven by observation-based sea-ice concentration anomalies. They showed that when the sea ice concentration is reduced in the Barents–Kara Sea, the frequency of severe winters is doubled in central Eurasia and northern East Asia, confirming the influence of Arctic sea ice on the EAWM. However, the magnitudes of the modeled atmospheric circulation and surface air temperature responses are much weaker than the observed anomalies, implying that this influence should not be exaggerated. On the one hand, this result suggests that reduced Arctic sea ice very likely contributed constructively to the decadal strengthening of the EAWM after the early 2000s. On the other hand, it implies that some other atmospheric external forcing or even the atmospheric internal variability may also be important in causing the decadal variations of the EAWM.

In addition to reduced Arctic sea ice, warm SST anomalies in the Atlantic may also have facilitated the recently strong EAWM (Xiao et al., 2016). On the basis of numerical experiments, Sato et al. (2014) suggested that the local response to the reduced sea ice over the Barents Sea cannot produce cold anomalies over midlatitude Eurasia if the forcing outside the Arctic region is not taken into consideration. In this respect, the SST warming in the Gulf Stream extension region can excite a planetary wave train that is important in causing the midlatitude Eurasian cold anomalies (Nakanowatari et al., 2014; Sato et al., 2014; Simmonds and Govekar, 2014; Luo and Lin, 2017). Hence, these results suggest that the atmospheric patterns initiated outside the Arctic region play a crucial role in the response of the EAWM to the Arctic sea ice (Luo et al., 2016b).

2.5. *The ENSO–EASM relationship on the interdecadal time scale*

The interannual ENSO–EASM relationship is unstable, and it shows clear changes on the interdecadal time scale. Previous works have revealed that the ENSO–EASM relationship during the ENSO decaying phase strengthened after the late 1970s (Wang et al., 2008b; Xie et al., 2010). The anomalous lower-tropospheric anticyclone over the WNP, which is a bridge coupling El Niño to the EASM, strongly intensified after the late 1970s, causing severe EASM rainfall anomalies. Wang et al. (2008b) attributed this interdecadal change to the enhanced amplitude and periodicity of ENSO after the late 1970s. However, Xie et al. (2010) reported that the strengthened ENSO–EASM relationship is because of the changes in the Indian Ocean SST response to ENSO. The Indian Ocean anomalous SST warming induced by El Niño through air–sea interaction reaches its peak in the El Niño decaying summer, the season when El Niño's SST anomalies in the tropical Pacific nearly disappear. The Indian Ocean SST warming can excite a Kelvin wave, which propagates eastward and induces easterly wind anomalies in the tropical western Pacific. Near the surface, the friction turns the winds into northeasterlies blowing into the Indian Ocean region where the anomalous pressure is low, thus yielding surface divergence and suppressed convection in the WNP and further leading to an anomalous anticyclone. This anticyclone is further amplified by the convection–circulation feedback over the western Pacific. Therefore, when the Indian Ocean SST response to ENSO intensified after the 1970s, the anomalous anticyclone (cyclone) over the western Pacific became correspondingly much stronger, which tightened the relationship between ENSO and the EASM.

In addition, the ENSO–EASM relationship can also be modulated by some low-frequency fluctuation in the climate system. The Pacific Decadal Oscillation (PDO) is such a phenomenon (Feng et al., 2014). During the PDO positive phase, the El Niño-induced low-level wind anomalies during its decaying summer are characterized by an anomalous anticyclone over the Philippine Sea and a cyclone to its north. Correspondingly, the summer mean rainfall anomalies in China show a tripolar pattern, with more rainfall over central China and less rainfall over southern and northern China. Such a rainfall pattern experiences a weak sub-seasonal variation. In contrast, during the PDO negative phase, the wind anomalies associated with El Niño are characterized by a large-scale anticyclone over the WNP. Therefore, the summer mean rainfall anomalies show a dipole pattern, with more rainfall over southern China and less rainfall over northern China. This anomalous rainfall pattern has a strong sub-seasonal variation, with the positive rainfall band moving northward. The distinct ENSO–EASM relationship under different PDO phases can be attributed to the impacts of the PDO on the El Niño decaying speed.

In addition to the modulation effect on the ENSO-related EASM rainfall anomalies, the PDO can also modulate the relationship between ENSO and the South Asian high (SAH), which is another important component in the EASM system (Xue et al., 2018). It was shown that when ENSO is in phase with the PDO (i.e., El Niño/positive PDO or La Niña/negative PDO), ENSO has a significant impact on the SAH activity (Xue et al., 2018). The SAH is located further south (north) and usually strengthened (weakened) for the El Nino/positive PDO (La Nina/negative PDO). When ENSO is out of phase with the PDO, the SAH activity is close to climatological status. This difference is because ENSO has a strong anchor in the Indian Ocean SST anomalies when the PDO and ENSO are in phase, which influences the tropospheric temperature by moisture adjustment and thus results in anomalous SAH activity (Xue et al., 2018).

In addition to the PDO, another low-frequency fluctuation in the climate system, the Atlantic thermohaline circulation (THC), can also modulate the El Niño–EASM relationship. Chen et al. (2014) found by conducting a water-hosting experiment that the anomalous anticyclone over the WNP during the El Niño decaying summer is intensified under the condition of a weakened THC. The weakened THC is accompanied by an increased amplitude and frequency of El Niño on the one hand, but increased climatological humidity over the western-central North Pacific on the other hand. Both of these two factors favor the formation of a strong anomalous anticyclone associated with El Niño (Chen et al., 2014).

3. Impacts of two types of ENSO on the EAM and the possible mechanisms

3.1. *Different impacts of CP and EP ENSO on the EASM*

A broad consensus has been reached that two types of El Niño have a completely different influence on the EASM during their developing and decaying summers (Weng et al., 2007; Feng et al., 2011; Karori et al., 2013; Li et al., 2014). In the summer of CP El Niño developing stages, a Rossby wave train named the Pacific–Japan (PJ) pattern is seen with an anomalous anticyclone around Japan and an anomalous cyclone to its north and south (Weng et al., 2007). This PJ pattern brings droughts to central China and southern Japan, leading to a weakened EASM. In the summer of EP El Niño developing stages, however, the PJ pattern is weak and located in a region far from East Asia. Therefore, there are no evident rainfall anomalies in East Asia, leading to an approximately normal EASM. The difference in the PJ pattern between CP and EP El Niño can be attributed to the westward location of the anomalous diabatic heating associated with CP El Niño SST warming, by which a Rossby wave train is emanated from the tropics to extratropics (Weng et al., 2007).

An important issue in studies of the EASM is why the impacts of CP and EP El Niño on the EASM can be prolonged into the summer when CP and EP El Niño decays (Xie et al., 2016; Li et al., 2017; Zhang et al., 2017b). This prolonged impact is often explained by the capacitor effect from the Indian Ocean and Atlantic SST warming (Xie et al., 2009; Rong et al., 2010), or the transition from El Niño to La Niña. In the case of CP El Niño, the anomalous EASM is characterized by enhanced rainfall over the Huaihe River extending to the Yellow River and suppressed rainfall over southern China (Feng et al., 2010). Bao and Han (2009) found an analogous rainfall anomaly pattern in the summers of 2003 and 2007, which were the decaying periods of two CP El Niño cases with maximum SST anomalies over the central Pacific in the previous winters. By contrast, EP El Niño causes an anomalous EASM, with above-normal rainfall anomalies over the Yangtze River valley and southern part of China (Feng et al., 2010). Hence, the evident difference is that the positive anomalous rainfall band is located southward for EP El Niño compared with that for CP El Niño, which is caused by the different location of an anomalous low-level anticyclone over the WNP associated with the two types of El Niño. For CP El Niño, the anomalous anticyclone extends from the tropics to midlatitudes, bringing abundant moisture to the midlatitudes and thus causing more rainfall there, while for EP El Niño this anticyclone is located southward, transporting moisture only to southern China (Feng et al., 2011). The distinct evolution of this anticyclone between CP and EP El Niño was also disclosed by Yuan et al. (2012b). Feng et al. (2018) further examined the asymmetric impacts of ENSO on this anticyclone, and found that the CP El Niño-induced anticyclone and La Niña-induced cyclone bear a resemblance in their intensity and spatial pattern, implying a much weaker asymmetry compared with that for EP ENSO. Moreover, CMIP5 models have large biases in simulating the impacts of CP El Niño on the EASM with a slow decay of El Niño in most simulations (Feng et al., 2019).

In addition to the EASM rainfall, the two types of El Niño also exert different impacts on the outbreak of Asian summer monsoon (Wang et al., 2013; Ding et al., 2016). The date of Asian summer monsoon outbreak is generally normal for CP El Niño decaying phases, whereas it is late for EP El Niño decaying phases. This is possibly caused by stronger impacts of EP El Niño on the Indian Ocean SST anomalies than CP El Niño (Wang et al., 2013).

3.2. *Different impacts of the CP and EP ENSO on the SAH*

The SAH is an important component of the EASM system, and can exert substantial influences on the variability of weather and climate around Asia (e.g., Tao and Chen, 1987; Wei et al., 2012, 2014; Xue et al., 2015b, c). Previous studies have shown that ENSO events play an important role in the interannual variability of the SAH (Zhang et al., 2000; Xue et al., 2015b). Xue (2016) further investigated the different influences of the two types of tropical Pacific warming events on the variability of the SAH in boreal summer. The findings indicated that the summer SAH is more strongly influenced by the preceding winter's EP El Niño than CP El Niño. During the following summer of EP El Niño events, the composite SAH anomaly is stronger and located further south than for CP El Niño. The distinct SAH variation is mainly attributable to the difference between the charge effect over the tropical Indian Ocean (TIO) associated with EP and CP El Niño events. For EP El Niño, the inversed Walker circulation associated with El Niño with descending motion in the western tropical Pacific and the Maritime Continent, and rising motion in the eastern tropical Pacific, is stronger and lasts for a longer time. Stronger descending motion over the Maritime Continent and easterly winds over the eastern TIO will exert crucial impacts on the surface heat fluxes and subsurface dynamical heating process over the TIO. The stronger surface and subsurface heating process during EP El Niño leads to warmer SST over the TIO during the following summer. As a result, significantly warmer SST anomalies over the TIO will exert a stronger influence on tropospheric temperature via the moisture adjustment, and subsequently lead to significant influences on the SAH variations.

3.3. *Modulation factors from the tropics and extratropics on the ENSO–EASM relationship*

3.3.1. *Indian Ocean Dipole*

The El Niño–EASM relationship can be modulated by SST anomalies from remote oceans. The Indian Ocean Dipole (IOD) serves as one such modulation factor. The IOD is an important air–sea coupling mode in the TIO, with anomalous SST warming in the western Indian Ocean and SST cooling in the eastern Indian Ocean during its positive phase (Saji et al., 1999). By analyzing two cases (1994 and 1983), Weng et al. (2011) reported that different phase combinations of El Niño Modoki and IOD exert different influences on the EASM rainfall. Feng and Chen (2014a) suggested that positive IOD is capable of modulating the El Niño Modoki–EASM relationship. They separated El Niño Modoki into two groups: pure El Niño Modoki and El Niño Modoki with positive IOD. For the pure El Niño Modoki cases, composite low-level wind anomalies were characterized by a large and significant cyclone over the WNP, which caused excessive rainfall in the western Pacific and deficient mei-yu rainfall. By contrast, when positive IOD and El Nino Modoki coexisted, the low-level cyclonic anomalies associated with El Nino Modoki were strongly weakened by the IOD and the EASM behaved almost normally. Further studies have demonstrated that positive IOD can strengthen the Asian summer monsoon heating, which further produces easterly wind anomalies over the western Pacific through inducing a large east–west circulation (Chang and Li, 2000; Li et al., 2003; Gu et al., 2010). The IOD-induced easterly wind anomalies favor the anticyclonic vorticity over the western Pacific, which causes the weakening of the El Niño Modoki-induced cyclone.

3.3.2. *EAWM*

The ENSO–EASM relationship can be modified by the EAWM. Although there is a close correlation between ENSO and the EAWM, the independent part of the EAWM (i.e., ENSO-unrelated EAWM) explains a large variation of the total EAWM (Chen et al., 2013b). It is the ENSO-unrelated EAWM (denoted as EAWMres) that can modulate the ENSO–EASM relationship during the ENSO decaying phase (Feng and Chen, 2014b). When the anomalous EAWMres is weak (strong), the anomalous southerly (northerly) winds on the western side of the anticyclone (cyclone) associated with El Niño (La Niña) are significantly enhanced and extend to high latitudes from the ENSO mature winter to the decaying summer. As a result, the EASM is extremely strengthened (weakened), with more rainfall anomalies over northern China (southern China). In contrast, strong (weak) EAWMres has an opposite modulation effect on the El Niño (La Niña)-related EASM during the El Niño (La Niña) decaying summer. The physical mechanism responsible for this EAWMres modulation effect is still unclear. Feng and Chen (2014b) discussed that EAWMres may exert an influence on the extratropical SST anomalies that persist into the following summer, which may modify the ENSO–EASM relationship. However, how such extratropical SST anomalies interfere with ENSO impacts needs further study.

3.4. *Interaction between ENSO and the EAWM*

When an El Niño happens, increased rainfall and intensified convection dominates the tropical central–eastern Pacific, while the opposite condition prevails in the tropical western Pacific. The resulting anomalous diabatic forcing of the atmosphere can affect atmospheric circulation anomalies in the mid–high latitudes via atmospheric teleconnections (e.g., Jia et al., 2014; Zhang et al., 2015; Ding et al., 2018a;

Ma et al., 2018a). CP and EP ENSO events are found to induce different extratropical teleconnection patterns (Weng et al., 2009; Graf and Zanchettin, 2012; Yu et al., 2015). Actually, climate responses to ENSO are not simply opposite, but show a nonlinear SST–convection relation (Wu and Kirtman, 2007). However, most previous research has focused on the linear influences of ENSO on the EAM, or the different impacts between CP and EP warming events, ignoring the cooling ones. Recently, Feng et al. (2017) investigated the asymmetric atmospheric responses to ENSO. They found that the EP ENSO triggers two obvious asymmetric atmospheric teleconnections: a Pacific–North America-like teleconnection and an Atlantic–Eurasian teleconnection. In contrast, CP ENSO triggers an Arctic Oscillation (AO)-like teleconnection with an appreciable asymmetry in the subtropical amplitudes that are stronger during CP El Niño than during CP La Niña. As a matter of fact, an AO-like atmospheric pattern has been defined by Jia and Lin (2011), considering the importance of the air–sea interaction for seasonal forecasting. Observational analysis and numerical model experiments have demonstrated that this AO-like pattern, excited by a western tropical Pacific SST-related forcing, propagates along the coastal area of East Asia and can significantly impact the winter climate through modulating the mid- to high-latitude atmospheric circulation over the Asian–North Pacific region (Jia et al., 2014, 2015b). Moreover, directly focused on the influence of tropical convection (or convective heating) anomalies instead of SST anomaly patterns, Ding et al. (2018a) identified five major types of tropical convection anomalies by utilizing outgoing longwave radiation datasets and investigated the corresponding extratropical teleconnection patterns in the Northern Hemisphere. The comparison between these five categories and the corresponding SST anomaly patterns further highlighted a nonlinear relationship between convection and SST.

On the other hand, the EAWM can cause deep convection over the Maritime Continent, due to the intrusion of cold air into the tropics (Chang et al., 2011). As a consequence, the East Asian Hadley circulation and the Walker circulation are intensified by the enhanced convective activity associated with the cold air outbreak events (Chang and Lau, 1980; Compo et al., 1999). Hence, the EAWM provides a link from the mid–high latitudes to the tropical western Pacific Ocean, which is one of the key heating centers driving the tropical atmospheric circulations. So far, almost all studies have paid attention to the influence of ENSO on the EAWM, whereas the influence of the EAWM on ENSO at an interannual time scale has received much less attention. Recent work by Ma et al. (2018b) separated the variability of the EAWM into two parts—the $\mathrm{EAWM_{EN}}$ and the $\mathrm{EAWM_{res}}$—and investigated the modulation of the EAWM in the impacts of El Niño on the wintertime rainfall anomalies in southeastern China. Their results showed that strong $\mathrm{EAWM_{res}}$ weakens the positive rainfall anomalies in southeastern China induced by El Niño, because anomalous downward motion over the WNP associated with El Niño is weakened by strong $\mathrm{EAWM_{res}}$. Likewise, weak $\mathrm{EAWM_{res}}$ does the opposite. The modulated convective activity over the WNP on the one hand changes the anomalous local Hadley circulation associated with El Niño, whilst on the other hand the modulated WNP convective activity induces different low-level atmospheric responses to El Niño. Further work has also found that the winter climate anomalies over North America for the same phase of ENSO are significantly different for strong and weak EAWM (Ma et al., 2018a). By increasing the convective heating over the western Pacific, strong EAWM strengthens the Pacific Walker circulation, and weakens (strengthens) the El Niño (La Niña) related effects on the extratropics via a modulation of the Pacific–North America teleconnection pattern. These results suggest that, along with ENSO, the variability of the EAWM should be taken into account for seasonal prediction over extratropical regions.

4. Conclusions and remarks for future studies

During the past several years, significant advances have been achieved in studies of the EAM variabilities on interannual to interdecadal time scales and their mechanisms. Interdecadal variations of the EAM often exert significant influences on society and human lives. In addition, they are an important background of interannual variations of the EAM and a crucial source of disturbance superimposed on a more long-term anthropogenic climate change trend. Hence, interdecadal variations of the EAM have become a hot topic in the scientific community of China. Particularly, the interdecadal changes of the EAM around the 1990s have been studied extensively. These include the SCSSMO and SCSSMW, the northern boundary activity of the EASM and the MTZ in China, summer SLP over the Mongolian region, the intensity of both the EASM and EAWM, and the relationship between the EAM and ENSO.

Recent studies suggest that regime shifts of the Pacific basin SST are accompanied by a change in El Niño behavior from a dominant EP-type warming to a dominant CP-type warming (Chung and Li, 2013; Xiang et al., 2013). ENSO is a dominant interannual mode of climate variability that originates from ocean–atmosphere interactions in the tropical Pacific and is the most dominant source of weather and climate variability worldwide. Since ENSO is one of the most important factors influencing the EAM variability, studies on the impacts and processes of different types of ENSO have been conducted extensively in recent years. ENSO indeed exerts a crucial impact on the EAM; however, the ENSO–EAM relationship is unstable and can be disturbed by both internal and external factors. The internal factors include the distinct properties of an ENSO event, such as the spatial pattern, intensity and decaying speed, all of which can interfere with the ENSO–EAM relationship. The external factors, such as the SST anomalies in the Pacific, Indian and Atlantic oceans, also play an important role in modulating the relationship between ENSO and the EAM. In addition, the ENSO–EAM relationship also experiences evident interdecadal change due to low-frequency phenomena.

Although studies on the behaviors of the EAM in a changing climate and the associated mechanisms have made progress in the past decade, further investigations for understanding the variabilities of the EAM are still needed in the future, especially those that can address the following issues:

(1) So far, most studies have attributed the cause of interdecadal change in the EAM around the 1990s to the regime shift of the Pacific basin SST. It is noteworthy that the recent interdecadal abrupt warming of the western Pacific was identified to have occurred around late 1998/99. However, the EAM also underwent a major shift around 1993. Was the shift of the EAM in the mid-1990s only a regional phenomenon, or was it also induced by some other external forcing, such as the change in North Atlantic SST? Taking the SCSSMO and SCSSMW as an example, the interdecadal advancement of the SCSSMO and the delay in the SCSSMW did not occur concurrently. The same is true for the EASM and EAWM, which show different regime shift features. Moreover, the increasing concentrations of greenhouse gases released by human activities may also contribute to interdecadal changes in the EAM. The relative contributions of the internal variability and external forcing to the different regime shifts in the EAM remain to be explored.

(2) Although the global mean temperature rise has exhibited a slowdown in recent decades, the Arctic surface air temperature has risen by twice as much as the global average. This is termed as polar or Arctic amplification. Arctic amplification occurs in all seasons, but is strongest in autumn and winter. Due to the Arctic warming and reduction of sea ice, Europe, East Asia and North America have experienced anomalously cold conditions, with record snowfall during recent years. Since Gao et al. (2015) already reviewed the progress on the impact of Arctic sea ice on the Eurasian climate, we have not gone into details in this paper. However, the key mechanism (natural and/or anthropogenic forcing) driving the Arctic amplification and sea-ice loss in response to the anomalies from the tropical central Pacific (interdecadal time scale) need to be investigated. Meanwhile, the mechanisms responsible for the possible impact of Arctic amplification (warming and Barents/Bering sea-ice loss) on the interdecadal changes in extreme cold weather, snowfall and precipitation over Eurasia and East Asia need to be studied in the future.

(3) Although many significant advances have been achieved in recent years, we face great challenges in successfully forecasting anomalies of the EAM because of the complex relationship between it and ENSO. Many problems regarding the basic physical processes of the influences of the different flavors of ENSO on the EAM and climatic disasters in China still remain unclear. These problems include: the associations of the onset, intensity and withdrawal of the EAM, as well as the summer and winter monsoon cycle processes, with the different ENSO types; the interactions among different time-scale variabilities of the EAM and the associated physical processes; the combined effect of mid–high latitude processes and ENSO on the EAM; and the possible changes in the ENSO–EAM relationship against the background of global warming. Moreover, several mechanisms have been proposed to be responsible for the appearance of the anticyclone over the WNP. However, which mechanism is applicable to EP El Niño and which is applicable to CP El Niño is not fully clear. Remote ocean thermal conditions can modify the ENSO–EAM relationship. The physical mechanisms behind this modulation have not been fully revealed. All in all, the ENSO–EAM relationship is a complicated issue and needs further and in-depth investigation in the future.

Acknowledgements. We thank the two anonymous reviewers for their valuable comments and suggestions, which led to significant improvements in the manuscript. This work was supported jointly by the National Key Research and Development Program (Grant No. 2016YFA0600604), the National Natural Science Foundation of China (Grant No. 41721004), the Chinese Academy of Sciences Key Research Program of Frontier Sciences (Grant No. QYZDY-SSW-DQC024), and the Jiangsu Collaborative Innovation Center for Climate Change.

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