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• **Review** •

Recent Advances in Understanding Multi-scale Climate Variability of the Asian Monsoon※

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ABSTRACT

Studies of the multi-scale climate variability of the Asian monsoon are essential to an advanced understanding of the physical processes of the global climate system. In this paper, the progress achieved in this field is systematically reviewed, with a focus on the past several years. The achievements are summarized into the following topics: (1) the onset of the South China Sea summer monsoon; (2) the East Asian summer monsoon; (3) the East Asian winter monsoon; and (4) the Indian summer monsoon. Specifically, new results are highlighted, including the advanced or delayed local monsoon onset tending to be synchronized over the Arabian Sea, Bay of Bengal, Indochina Peninsula, and South China Sea; the basic features of the record-breaking mei-yu in 2020, which have been extensively investigated with an emphasis on the role of multi-scale processes; the recovery of the East Asian winter monsoon intensity after the early 2000s in the presence of continuing greenhouse gas emissions, which is believed to have been dominated by internal climate variability (mostly the Arctic Oscillation); and the accelerated warming over South Asia, which exceeded the tropical Indian Ocean warming, is considered to be the main driver of the Indian summer monsoon rainfall recovery since 1999. A brief summary is provided in the final section along with some further discussion on future research directions regarding our understanding of the Asian monsoon variability.

Key words: Asian monsoon, multi-scale climate variability, monsoon onset, East Asian summer monsoon, East Asian winter monsoon, Indian summer monsoon

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Article Highlights:

- Advanced or delayed local monsoon onset synchronized over the tropical Asian regions (from the Arabian Sea to South China Sea)
- Different processes on multiple time-scales (from synoptic to decadal) all contributed to the record-breaking mei-yu in 2020
- Recent recovery of the East Asian winter monsoon intensity is possibly attributable to the Arctic Oscillation
- Recent recovery of the Indian summer monsoon rainfall is possibly attributable to the accelerated warming over South Asia

1. Introduction

Monsoon is a phenomenon of the annual cycle involving large differences in both wind and precipitation between summer and winter (e.g., Ramage, 1971; Huang et al., 2003). For example, East Asia features strong southerly winds and abundant rainfall in summer and strong northerly winds and

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little rainfall in winter (Chen et al., 2019). Changes in monsoon intensity are crucial for people living in monsoon regions because water resources, agricultural harvests, transportation, and human lives are often affected by the natural hazards associated with anomalous monsoon activity. Hence, research on monsoon variability and its factors of influence has long been a top priority for Chinese meteorologists, and significant progress has been made over the past several decades (e.g., Tao and Chen, 1987; Ding, 1994; Zhang et al., 1996, 2017; Huang et al., 2004, 2012; He et al., 2007; Chen et al., 2013; Ding et al., 2015; Xue et al., 2015).

The Asian monsoon, which includes the East Asian and South Asian monsoon subsystems, is an important component of the global climate system (e.g., Tao and Chen, 1987). The East Asian summer monsoon (EASM) normally bursts in mid-May over the South China Sea (SCS) and propagates to North China, Korea and Japan in late July, featuring a typical summer rainband elongating zonally from the SCS to the Pacific. The onset of the South China Sea summer monsoon (SCSSM) signifies the start of the rainy season over East Asia. The northern boundary of the EASM is located in the transitional climate belt between the humid tropics and the arid midlatitudes, and this transition area has suffered from frequent meteorological disasters in recent decades due to the extremely fragile ecosystem with high sensitivity to climate change. In addition to research on monsoon intensity, numerous studies have been conducted in recent years on the SCSSM onset and the EASM northern boundary or transitional zone in East Asia. Attention has also been paid to the links between the EASM and the South Asian or Indian summer monsoon (ISM) in terms of both onset and intensity. Regarding the East Asian winter monsoon (EAWM), the work of many meteorologists has contributed to a better understanding of its variations across multiple time scales, including intraseasonal, interannual and interdecadal time scales. Moreover, the Asian summer monsoon (ASM) system is highly complex, with distinct spatial features over tropical South Asia and subtropical East Asia. Many achievements have been made in our understanding of the processes of the ISM variability in recent years, too.

This paper reviews recent advances in our understanding of the multi-scale climate variability of the Asian monsoon, with a main focus on the past several years. The remainder of this paper is organized as follows: Section 2 describes the progress that has been made on the SCSSM onset. Research achievements with respect to the EASM and EAWM are presented in sections 3 and 4, respectively. Section 5 summarizes the advancements in research on the ISM. And finally, section 6 provides a summary along with some suggestions for future research to address the unresolved scientific issues regarding our understanding of the Asian monsoon.

2. South China Sea summer monsoon onset

As the pivot of the entire Asian–Australian monsoon system, the SCSSM imposes substantial ecological and socioeconomic impacts worldwide via atmospheric teleconnections (Wang et al., 2009a; Yang et al., 2021; Chen et al., 2022a). The onset of the SCSSM marks the large-scale adjustment of the atmospheric circulation from the cold- to warm-season type (Chen et al., 2022a; Hu et al., 2022c), accompanied by the beginning of the major wet season (Hu et al., 2020b; Luo et al., 2020) and distinct changes in cloud and radiative features (Huang et al., 2020a). The recent review by Chen et al. (2022a) summarized the multi-scale variations of the SCSSM onset, including the interdecadal, interannual, intraseasonal, and synoptic scales. As a complement to Chen et al. (2022a), this part mainly focuses on research advances in the last few years.

2.1. *Linkages among local monsoon onsets over the tropical ASM region*

Climatologically, the onset of the tropical ASM consists of three different stages: monsoon onset over the Bay of Bengal and Indochina Peninsula in late April to early May; over the SCS and Arabian Sea in mid-May; and over the Indian subcontinent in late May to early June (Xiang and Wang, 2013; Liu et al., 2015; Bombardi et al., 2019, 2020; Hu et al., 2020a, 2021, 2022c). Most previous studies have mainly focused on the local monsoon onset of different sub-systems. However, recent studies have revealed that these local monsoon onsets are not independent, but instead closely connected to each other (Xing et al., 2016; Yang et al., 2021; Zeng et al., 2021; Hu et al., 2022a, c). For example, the monsoon onset over the Bay of Bengal exhibits an in-phase variation with that over the Arabian Sea (Hu et al., 2022a), India (Xing et al., 2016), and the SCS (Zeng et al., 2021), and the local monsoon onset over the Arabian Sea and India are also highly correlated (Hu et al., 2022a). As reviewed by Chen et al. (2022a), many studies have revealed the synchronized advancement of the tropical ASM onset after the mid-to-late 1990s. Based on the monthly mean rainfall and low-level winds in May, Hu et al. (2022c) revealed that the dominant mode of tropical ASM onset is characterized by coherent variations of local monsoon onset, i.e., the local monsoon onset tends to be synchronously advanced or delayed over the Arabian Sea, Bay of Bengal, Indochina Peninsula, and SCS.

The synchronized variation of local monsoon onsets can be attributed to both atmospheric internal processes and external forcings (Fig. 1). For example, accompanying an advanced monsoon onset over the Bay of Bengal, strong convective activity and latent heating appears therein, which is conducive to the breakdown and withdrawal of the subtropical high. As such, the monsoon onset over India and the SCS also tends to be earlier (Xing et al., 2016). Additionally, a synchronized delay of tropical ASM onset is more likely to occur during the easterly phase of the 30–80-day oscillation (Hu et al., 2022c). The spatial scale of the 30–80-day oscillation is greater than that of the ASM sub-systems (i.e., the Arabian Sea, Bay of Bengal, and SCS), and its timescale is longer than that of the local monsoon onset (i.e., in pentads or days). Thus, the 30–80-day oscillation is large enough to act as the background condition for the tropical ASM onset

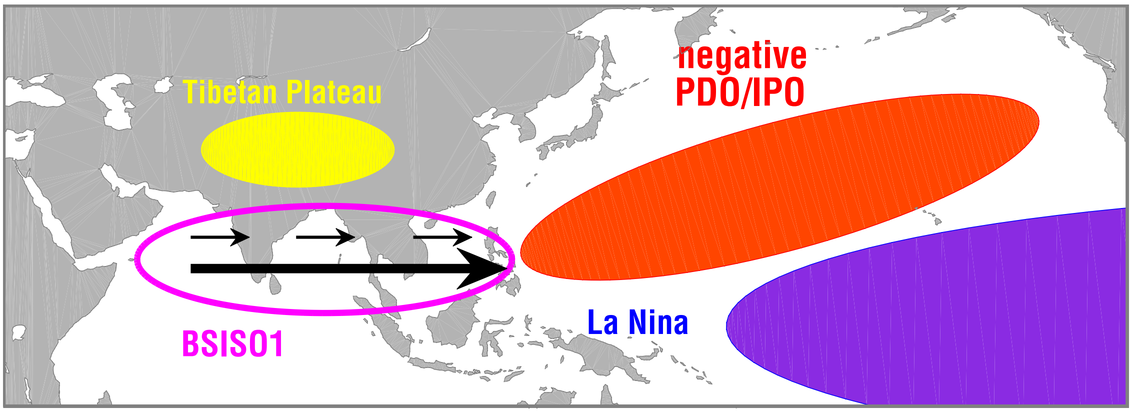

Fig. 1. Schematic of the dominant mode of the tropical ASM onset, featuring coherent variations of local monsoon onset. This mode can be attributed to both atmospheric internal processes (BSISO1) and external forcings (Tibetan Plateau, ENSO, and IPO).

(Hu et al., 2022c).

External forcings like the Tibetan Plateau's thermal condition, the El Niño–Southern Oscillation (ENSO), and the Interdecadal Pacific Oscillation (IPO) also play important roles in the simultaneously delayed or advanced tropical ASM onset. Based on observational datasets and model simulations, Hu et al. (2022a) revealed that the diabatic heating over the Tibetan Plateau leads to a westward movement of the South Asian high, which is favorable for a synchronized advanced monsoon onset over the Arabian Sea and India. ENSO is recognized as the most important interannual factor modulating the tropical ASM onset (Hu et al., 2022b, and references therein), and a preceding winter El Niño event tends to be followed by delayed monsoon onset over the Bay of Bengal (Wu and Mao, 2019), Indochina Peninsula (Hsu et al., 2014), SCS (Martin et al., 2019), and India (Ordoñez et al., 2016). Xiang and Wang (2013) investigated the interdecadal advanced tropical ASM onset after the mid-to-late 1990s. Their results revealed that the equatorial Rossby wave response to the La Niña-like mean state change can explain this advanced ASM onset (Xiang and Wang, 2013), which is associated with the positive-to-negative phase transition of IPO. Hu et al. (2022c) noticed that another interdecadal change in the ASM onset might have occurred after 2013/14. This recent delayed tropical ASM onset may also be attributable to the IPO, which exhibited a negative-to-positive phase transition in the early 2010s. In addition to the equatorial Rossby wave mechanisms mentioned by Xiang and Wang (2013), Hu et al. (2022c) suggested that the IPO may modulate the tropical ASM onset via a midlatitude Rossby wave train.

2.2. *Interdecadal changes in SCSSM onset*

In a recent review paper, Chen et al. (2022a) summarized the interdecadal change in the SCSSM onset around the mid-to-late 1990s. The mean SCSSM onset date has advanced by about half a month, which is not a local phenomenon but an integral part of the interdecadal advancement of the large-scale tropical ASM onset (Chen et al., 2022a; Hu et al., 2022c). The interdecadal advancement of SCSSM onset is directly related to northwestward-propagating tropical disturbances, including vigorous tropical cyclone activities and enhanced intraseasonal oscillations (Hu et al., 2018; Chen et al., 2022a). Meanwhile, the primary source of this interdecadal shift is speculated to be the warm sea surface temperature (SST) anomalies in the western North Pacific (WNP; Yuan and Chen, 2013; Wang and Kajikawa, 2015; Chen et al., 2022a). However, some recent studies have provided other additional perspectives. For example, based on model simulations, Yu et al. (2016) suggested that the interdecadal advancement of SCSSM onset can be partly attributed to the urbanization of eastern China. Compared to previous studies focusing on the WNP, Lin and Zhang (2020) emphasized the important role of low-level zonal wind anomalies around Kalimantan Island, which is a response to the warm SST anomalies in the equatorial western Pacific. Apart from the tropical pathways like westward-propagating equatorial Rossby waves (Wang and Kajikawa, 2015; Chen et al., 2022a), the Pacific Ocean can also modulate the tropical ASM onset via the eastward-propagating Rossby wave train (Hu et al., 2022c). In addition to the tropical atmosphere and oceans, You et al. (2021) revealed that the warming in the mid-upper troposphere over subtropical East Asia can enhance the meridional temperature gradient, which was favorable for the interdecadal advancement of SCSSM onset in the mid-1990s. Moreover, some recent studies have suggested that the average date of SCSSM onset may have been delayed again in the early 2010s (Jiang and Zhu, 2021; Ai et al., 2022; Hu et al., 2022c). This recently delayed SCSSM onset may be attributable to the negative-to-positive phase transition of the IPO (Hu et al., 2022c) and the interdecadal warming of the tropical Indian Ocean (Ai et al., 2022). However, due to the relatively short time period, the robustness and mechanisms of the early-2010s interdecadal change in SCSSM onset still need further investigation.

In addition to the interdecadal changes in the mean monsoon onset date, recent studies have also investigated the interdecadal change in the relationship between ENSO and

SCSSM onset. Traditionally, ENSO is considered to be the most important factor controlling the SCSSM onset, and a preceding El Niño (La Niña) tends to be followed by a delayed (advanced) SCSSM onset (Zhu and Li, 2017; Martin et al., 2019). However, this relationship has broken down in recent years. For example, after the 2017/18 La Niña event, the SCSSM onset in 2018 was extremely late (Liu and Zhu, 2019; Deng et al., 2020); and after the 2018/19 El Niño event, the SCSSM onset in 2020 was extremely early (Hu et al., 2020a; Liu and Zhu, 2020). Several perspectives have been put forward to explain the recently weakened relationship between ENSO and SCSSM onset, including the interdecadal background changes (Hu et al., 2022c; Xu et al., 2022), ENSO diversity (Jiang and Zhu, 2021; Hu et al., 2022b), interference of other types of interannual variabilities (Ai et al., 2022; Cen et al., 2022; Hu et al., 2022b), and impacts of intraseasonal oscillations (Liu and Zhu, 2021; Hu et al., 2022b). Some studies have noted that the ENSO–SCSSM onset relationship is related to the background conditions, like the IPO or PDO (Pacific Decadal Oscillation; Hu et al., 2022c; Xu et al., 2022). Namely, the impacts of ENSO on the SCSSM onset are strong only during positive PDO phases (Xu et al., 2022). The modulation effects of the PDO on the ENSO–SCSSM onset linkage take place through affecting the anomalous WNP anticyclone (Xu et al., 2022). Jiang and Zhu (2021) suggested that the frequent occurrence of "cold tongue" La Niña is vital, but this perspective cannot explain the extremely early monsoon onset in 2019 following an El Niño event. Hu et al. (2022b) revealed that the anomalous Walker circulation associated with ENSO has been much weaker in recent years, and has thus been unable to deliver ENSO signals to the SCSSM onset. The changes in Walker circulation are closely related to the diversity of ENSO; namely, the frequent occurrence of central Pacific ENSO in recent years (Hu et al., 2022b). In addition, in recent years, the SCSSM onset has become more dominated by other SST signals, like the Northwest Indian Ocean (Ai et al., 2022) and the Victoria mode of North Pacific (Hu et al., 2022b). The Northwest Indian Ocean may modulate the SCSSM onset via suppressing the seasonal convection over the SCS and inducing eastward-propagating convective activities (Ai et al., 2022). The Victoria mode is the second empirical orthogonal function (EOF) mode of the extratropical Pacific Ocean SST (Ding et al., 2015), and can modulate the SCSSM onset via the large-scale divergent circulation (Hu et al., 2022b). Lastly, the influences of ENSO on the SCSSM onset may be contaminated by intraseasonal oscillation. For example, the vigorous quasi-biweekly oscillation in recent years may have disrupted the SCSSM onset from the slow-varying seasonal march modulated by ENSO (Liu and Zhu, 2021; Hu et al., 2022b), which may also have resulted in the weakened relationship between ENSO and SCSSM onset.

2.3. *The connections between SCSSM onset and rainfall anomalies*

The onset of the SCSSM is not only characterized by steady changes in low-level zonal winds (from easterly to westerly), but also by sudden bursts of monsoonal convection (Chen et al., 2022a). One important application of the SCSSM onset is that it can be used to predict summertime rainfall anomalies. For example, corresponding to a late SCSSM onset, the total summer rainfall over subtropical East Asia (lower reaches of the Yangtze River valley and southern Japan) tends to increase (Huang et al., 2006; He and Zhu, 2015). This connection can be understood through two perspectives: the water vapor transport associated with the WNP anticyclone and the Pacific–Japan (PJ) pattern (Chen et al., 2022a). However, SCSSM onset mainly occurs in May (Hu et al., 2020a, 2022c; Chen et al., 2022a), and thus it has a much greater impact on the climate anomalies in early summer than in peak summer. Jiang et al. (2018) noticed that, accompanying a late SCSSM onset, there appears to be increased rainfall in the middle and lower reaches of the Yangtze River basin in May. However, these previous studies on the connections between SCSSM onset and rainfall anomalies mainly focused on the monthly or seasonal mean rainfall (He and Zhu, 2015; Jiang et al., 2018), and little attention was paid to extreme rainfall. In comparison, some recent studies have investigated the relationship between SCSSM onset and extreme rainfall over southern China and Southeast Asia.

Rainfall over southern China exhibits a typical double-peak evolution, with a major peak in mid-June and a second peak in mid-August (Sun et al., 2019; Hu et al., 2020b; Luo et al., 2020). As such, the rainy seasons in southern China can be classified into two distinct parts: the rainy season from April to June, known as the first rainy season or pre-summer flooding season; and the rainy season from July to September, known as the second rainy season or post-flooding season (Gu et al., 2018; Hu et al., 2020b; Luo et al., 2020). Recent studies have revealed that the SCSSM onset can greatly affect the rainfall properties of the first rainy season. Wu et al. (2020) revealed that the frequency of warm-sector heavy rainfall increases markedly from April to June, which is closely related to SCSSM onset. In contrast, the occurrence of frontal heavy rainfall exhibits less monthly variation during the first rainy season (Wu et al., 2020). In addition to the occurrence frequency, Li et al. (2020) reported that rainfall intensifies over southern China after the SCSSM onset, irrespective of the duration, which results from the favorable thermodynamic environment. Further details of related studies can be found in the recent review paper by Luo et al. (2020) and are therefore not repeated here.

In addition to the heavy rainfall over southern China, a recent study by Hu et al. (2022d) investigated the close linkage between the SCSSM onset and extreme rainfall over Southeast Asia in May. Usually, an early SCSSM onset is accompanied by a higher chance of extreme rainfall over Southeast Asia. The intensity of tropical synoptic-scale systems is thought to play an important role in this linkage (Hu et al. 2022d). Accompanying an advanced SCSSM onset, the anomalous low-level cyclone over the SCS and the Philippine Sea increases the mid-troposphere humidity via moisture transport and the Ekman pumping effect. Besides, the barotropic energy conversion associated with this anomalous cyclone promotes the development of tropical synoptic-scale systems (Huangfu et al., 2017; Hu et al., 2022d). The combined effects of increased moisture and enhanced tropical disturbances can result in an increase in the occurrence of extreme rainfall in Southeast Asia.

3. East Asian summer monsoon

The EASM can affect not only the East Asian countries of China, Japan and Korea, but also other parts of the globe including India and North America through teleconnections (Srinivas et al., 2018; Zhou et al., 2020; Kosaka, 2021). In this section, we review several important issues, including the contributions of multi-scale factors to the super mei-yu in 2020, the close linkage between the summer monsoon rainfall in South Asia and East Asia, the climate variations over the EASM transitional zone, and the impacts of the Tibetan Plateau on the EASM.

3.1. *The record-breaking mei-yu in 2020: basic features and multi-scale processes*

In early summer (from mid-June to mid-July), the convergence of monsoonal warm–humid airmass and cold airmass from mid and high latitudes creates a quasi-stationary front over East Asia (extending from central-eastern China to Japan), which is known as mei-yu in China, baiu in Japan, and changma in Korea (Ding, 2007; Ding et al., 2020). The variabilities of this planetary-scale mei-yu front can affect not only local regions including the Yangtze River valley and Japan (Ding et al., 2020), but also the global climate through teleconnections such as the PJ pattern (Nitta, 1987; Lu and Lin, 2009; Xu et al., 2019) and the circumglobal teleconnection pattern (Ding and Wang, 2005; Zhou et al., 2020). The recent review by Ding et al. (2020) summarizes the multi-scale variabilities of the mei-yu and the related factors of influence.

In June–July 2020, a record-breaking mei-yu hit East Asia, which was characterized by a one-week-earlier onset, a half-month-later withdrawal, an extremely long duration, the strongest mean rainfall intensity, and frequent heavy rainstorm processes (Ding et al., 2021c; Niu et al., 2021). For example, the mei-yu season in 2020 lasted for 62 days, which was twice the climatological length. The accumulated rainfall reached 759.2 mm, which broke the record stretching back to the 1960s, and 18 national meteorological stations in China broke their historical records for daily rainfall (Ding et al., 2021c; Niu et al., 2021). More than 63 million people were affected by the floods, landslides and urban waterlogging associated with this super mei-yu, with 142 people reported dead or missing. The direct economic cost was estimated to be more than 178 billion RMB (Wei et al., 2020a; Ding et al., 2021c; Ge et al., 2022; Lu et al., 2022; Ma et al., 2022c). This super mei-yu was directly linked to anomalous circulation in the tropical and extratropical regions. On the one hand, an anomalous anticyclone was evident over the WNP during June–July, which transported abundant moisture to subtropical East Asia (Ding et al., 2021c; Wang et al., 2021b; Chen et al., 2022b) and excited the PJ pattern, thus affecting the mei-yu rainfall (Ding et al., 2021c; Qiao et al., 2021). On the other hand, the mid- and high-latitude circulation featured a "two ridge–one trough" pattern, and the excessive atmospheric blockings brought cold airmasses into the mei-yu region (Ding et al., 2021c; Qiao et al., 2021; Wang et al., 2021a). The above circulation anomalies can be attributed to the combined effects of the atmosphere, ocean, and sea ice. Figure 2 summarizes in detail the contributions of these factors to the super mei-yu, which we discuss in depth in the next two paragraphs, including climate

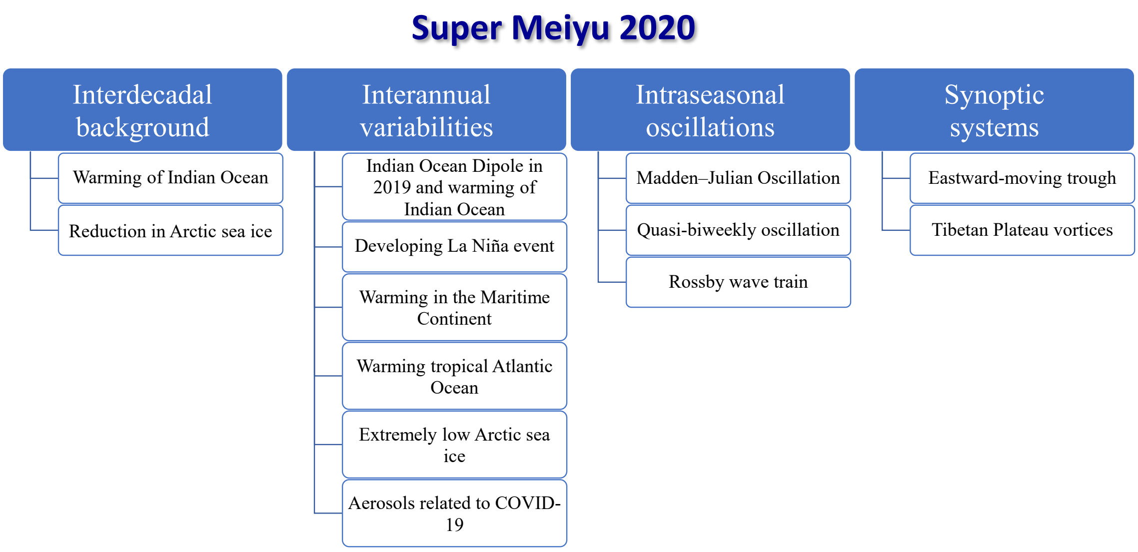

Fig. 2. Schematic of the multi-timescale (from interdecadal to synoptic) factors influencing the super mei-yu in 2020.

variabilities on the interannual–interdecadal timescales (e.g., SST and sea ice) and subseasonal timescales [e.g., the Madden–Julian Oscillation (MJO) and synoptic disturbances].

Unlike the extreme mei-yu in 1998, the super mei-yu in 2020 was not preceded by a strong El Niño event (Chen et al., 2021b; Cai et al., 2022). However, a very strong Indian Ocean dipole (IOD) was observed in the preceding autumn of 2019 (Takaya et al., 2020; Zhou et al., 2021). The combination of the 2019 IOD event and the decadal warming trend of the Indian Ocean resulted in a strong Indian Ocean warming in the early summer of 2020 (Guo et al., 2021; Tang et al., 2021; Chen et al., 2022b). The warming Indian Ocean excited equatorial Kelvin waves to the east, which is regarded as the major contributor to the anomalous cyclone over the WNP (Takaya et al., 2020; Chen et al., 2021b, 2022b; Ding et al., 2021b; Tang et al., 2021; Zhou et al., 2021; Cai et al., 2022). In addition, several studies have suggested that the developing La Niña in the equatorial central-eastern Pacific (Ding et al., 2021c; Chu et al., 2022), warming in the Maritime Continent (Tang et al., 2021; Zhao et al., 2022b), and the warm SST anomalies in the tropical Atlantic Ocean (Feng and Chen, 2021, 2022; Tang et al., 2021; Wang et al., 2021b; Zheng and Wang, 2021) also contributed to the anomalous WNP anticyclone. Specifically, the cold SST anomalies in the central-eastern Pacific excited an equatorial Rossby wave response and reinforced the WNP anticyclone (Pan et al., 2021; Tang et al., 2021), the active convections over the Maritime Continent promoted the WNP anticyclone via the local meridional circulation (Chu et al., 2022; Zhao et al., 2022b), and the Atlantic Ocean modulated the WNP anticyclone through an equatorial Kelvin wave response and the mass flow (Wang et al., 2021b). Note that the warm SST anomalies in the WNP seem to be a consequence of the anomalous anticyclone rather than its cause. In addition to the tropical oceans, Chen et al. (2021a) and Chen et al. (2022b) mainly emphasized the role of extremely low Arctic sea ice in the late spring and early summer, which mainly affected the super mei-yu via modulation of the atmospheric blockings and related cold-air activity. Interestingly, several studies have also revealed the impacts of reduced aerosols in the COVID-19 pandemic on the super mei-yu (Kripalani et al., 2022; Yang et al., 2022).

Apart from the above interannual variabilities and interdecadal backgrounds, some studies have also emphasized the prominent roles of high-frequency variabilities, including intraseasonal oscillations, synoptic-scale disturbances, mesoscale vortices, and the diurnal cycle. For example, Liang et al. (2021) and Zhang et al. (2021) noticed that an active phase of the MJO persisted in the Indian Ocean throughout June and July, and that the teleconnection associated with this MJO facilitated the super mei-yu in 2020. Ding et al. (2021a, c) revealed that the super mei-yu in 2020 exhibited remarkable quasi-biweekly oscillation, which may have been linked to the atmospheric blockings (Chen et al., 2021a, 2022b) and intraseasonal WNP anticyclone (Wang et al., 2021b). The midlatitude Rossby wave train associated with the phase transition of the North Atlantic Oscillation is also believed to have been important, which is also on the intraseasonal timescale (Liu et al., 2020; Qiao et al., 2021). As for the synoptic- and mesoscale, the eastward movement of troughs (Ding et al., 2021a) and Tibetan Plateau vortices (Li et al., 2021a; Fu et al., 2022; Ma et al., 2022c) are regarded as prominent rainfall producers of this super mei-yu. Zeng et al. (2022) and Xia et al. (2021) investigated the diurnal cycles of the super mei-yu.

3.2. *Linkage between the summer monsoon rainfall over South Asia and East Asia*

The ASM system includes two separate yet closely related subsystems: the EASM and the South Asian summer monsoon (SASM). The EASM and SASM are different in many aspects (Roxy et al., 2015; Huang et al., 2017; Wu, 2017). For example, the SASM is related to the meridional land–sea thermal contrast, while the EASM is mainly associated with the zonal land–sea thermal contrast. As such, the SASM circulation is characterized by strong vertical easterly shear (i.e., easterly winds above westerly winds), while the EASM circulation features obvious vertical westerly shear (i.e., westerly winds throughout the troposphere). This may partly explain why the SASM region is dominated by cumulus clouds while the EASM region is a mix of cumulus and stratiform clouds (Huang et al., 2017). Despite the above differences, the SASM and EASM are also closely linked to each other. Many studies have shown that the summer monsoon rainfall over South Asia is positively correlated with that over northern China and negatively correlated with that over the Yangtze River basin and southern Japan (Wei et al., 2014b, 2015, 2019; Wu, 2017; Wu and Jiao, 2017; Stephan et al., 2019; Xue et al., 2022). In a previous review paper, Wu (2017) summarized two pathways of the linkage between the SASM and EASM on the interannual timescale. The "south pathway" is via the moisture transport over the low latitudes that involves the East Asia–Pacific (EAP) pattern (Huang and Sun, 1992; Huang, 2004) or PJ pattern (Nitta, 1987; Xu et al., 2019) and the movement of the western North Pacific subtropical high. Meanwhile, the "north pathway" is through the extratropical Silk Road pattern (SRP; Enomoto et al., 2003; Wang et al., 2017b, 2021c; Chowdary et al., 2019; Hu et al., 2020d) or the circumglobal teleconnection (CGT) pattern (Ding and Wang, 2005; Zhou et al., 2020) along the subtropical westerly jet, which is associated with the displacement of the South Asian high (Wei et al., 2014b, 2015, 2019; Xue and Chen, 2019; Xue et al., 2021). At the end of the review paper, Wu (2017) raised several important issues that were not well understood at that time. Subsequent works have further investigated these issues of the SASM–EASM linkage, including the impacts of ENSO and regional SST anomalies (Wu and Jiao, 2017; Ha et al., 2018; Liu and Huang, 2019), climate model performances (Preethi et al., 2017; Wu and Jiao, 2017; Woo et al., 2019), the linkage on the intraseasonal timescale (Wei et al., 2019), and the non-stationarity of the linkage (Lin et al., 2017; Wu and Jiao, 2017; Wu et al., 2018; Sun and Ming, 2019; Stephan et al., 2019; Cen et al., 2022).

The connection between the SASM and EASM is not stationary, undergoing significant interdecadal changes. For example, the correlation between the summer rainfall in South Asia and northern China is rather strong before the 1970s but very weak in recent years (Wu, 2017; Wu and Jiao, 2017). Several hypotheses have been proposed to explain this interdecadal weakening relationship, which include external forcing such as SST, atmospheric internal variabilities, and stochastic processes. After removing the ENSO signal by partial correlation analysis, the interdecadal changes between summer rainfall over South Asia and northern China are still evident. As such, ENSO may make little contribution to the long-term change in this relationship (Wu, 2017; Wu and Jiao, 2017; Wu et al., 2018). This speculation was partly supported by an AGCM simulation forced by climatological SST and sea ice. The correlation between the SASM and northern China rainfall also exhibited remarkable interdecadal changes in the absence of ENSO (Wu et al., 2018). As such, the atmospheric internal variabilities may play important roles in the connection between the SASM and EASM. The forcing and the basic states are the two most important factors in determining atmospheric teleconnection. Regarding the forcing over South Asia, Wu and Jiao (2017) suggested that a combination of larger South Asian rainfall anomalies and more positive South Asian rainfall anomaly years may contribute to a stronger linkage between the SASM and northern China. This is because a higher mean rainfall background is favorable for a stronger dynamic response (Wu and Jiao, 2017). In addition to the forcing applied by heating, the atmospheric basic state is also very prominent. Lin et al. (2017) revealed that, after the 1970s, the subtropical westerly jet over East Asia shifted northward, which led to an increase in the wavelength of the stationary Rossby wave train (i.e., SRP/CGT). As such, the portion of the wave train over East Asia shifted eastward, and the anomalous anticyclone in the upper level also displaced eastward. This resulted in the eastward movement of rainfall anomalies from northern China to the Yellow Sea, and thus a weakening relationship between the SASM and northern China rainfall anomalies. A recent study by Xue et al. (2022) also indicated the movements of the westerly jet and the South Asian high are vital for the linkage between the SASM and northern China. In addition, Sun and Ming (2019) reported that mid- and high-latitude disturbances can also disrupt the connection between the SASM and the EASM. The summer North Atlantic Oscillation can affect the atmospheric circulation south of Lake Baikal, which is closely linked to central East Asian summer rainfall in recent years. When the signals of the circulation anomalies south of the Lake Baikal are removed, the linkage between the SASM and EASM becomes significant again after the 1970s. Last but not least, Monte Carlo simulations (Wu and Jiao, 2017; Wu et al., 2018) suggest the possibility that the interdecadal changes in the SASM and EASM linkage being due to stochastic processes cannot be excluded.

In the review paper by Wu (2017), the SASM was considered a more active influencing factor, while the EASM was regarded as a passive recipient of influences. However, some recent studies have revealed the impacts and feedbacks of the EASM on the SASM. The EAP/PJ pattern is a dominant mode of the EASM variability (Nitta, 1987; Huang and Sun, 1992; Huang, 2004; Xu et al., 2019), which describes the out-of-phase variations of rainfall anomalies over the subtropical region (i.e., mei-yu) and tropical region (i.e., the monsoon trough). Based on observational analysis and model simulations, Srinivas et al. (2018) and Kosaka (2021) revealed the impacts of the PJ pattern on the SASM rainfall. These impacts include the atmospheric pathway and the oceanic pathway. When the PJ pattern is characterized by an anomalous anticyclone in the subtropics (e.g., Japan) and a cyclone over the tropics (e.g., WNP), the westward-extending anomalous cyclone and westerly winds can modulate the vertical motion via Ekman pumping effects. As such, the rainfall increases in central-eastern India but decreases in southern India (Srinivas et al., 2018; Kosaka, 2021). Such rainfall and circulation patterns resemble the first coupled mode between the vertically integrated water vapor transport over the SASM and EASM regions extracted by singular value decomposition (Liu and Huang, 2019). Apart from the atmospheric pathway, the anomalous westerly winds associated with the PJ pattern can reinforce the monsoonal southwesterly winds, thereby cooling the SST in the northern Indian Ocean. These cold SST anomalies can in turn change the evaporation and atmospheric circulation, which is the oceanic pathway of the PJ pattern affecting the SASM (Srinivas et al., 2018; Kosaka, 2021). In addition to the low-level circulation mentioned above, the South Asian high in the upper level is also vital for the linkage between the SASM and EASM. While previous studies mainly emphasized the impacts of latent heating over the SASM region on the displacement of the South Asian high (Wei et al., 2014b; Wu, 2017), some recent studies have revealed that the latent heating over the EASM region (e.g., Yangtze River valley and south of Japan) can also affect the location of the South Asian high (Wei et al., 2015, 2019; Zhou et al., 2020; Wang et al., 2021a), thus creating feedback to the rainfall over the SASM region. The displacement of the South Asian high is closely linked to the CGT pattern, which is a zonal wavenumber-5 teleconnection pattern in the upper troposphere. There are close interactions between the SASM and the CGT pattern (Ding and Wang, 2005, 2007). On the one hand, the SASM rainfall may excite a downstream Rossby wave train extending to East Asia and North America. On the other hand, the wave train excited in the jet exit region of the North Atlantic may affect the intensity and rainfall of the SASM (Ding and Wang, 2005, 2007). Recently, Zhou et al. (2020) revealed that the latent heating associated with the EASM can stimulate an upper-tropospheric teleconnection that resembles the CGT pattern. As such, the impacts and feedbacks of the EASM on the SASM may also be

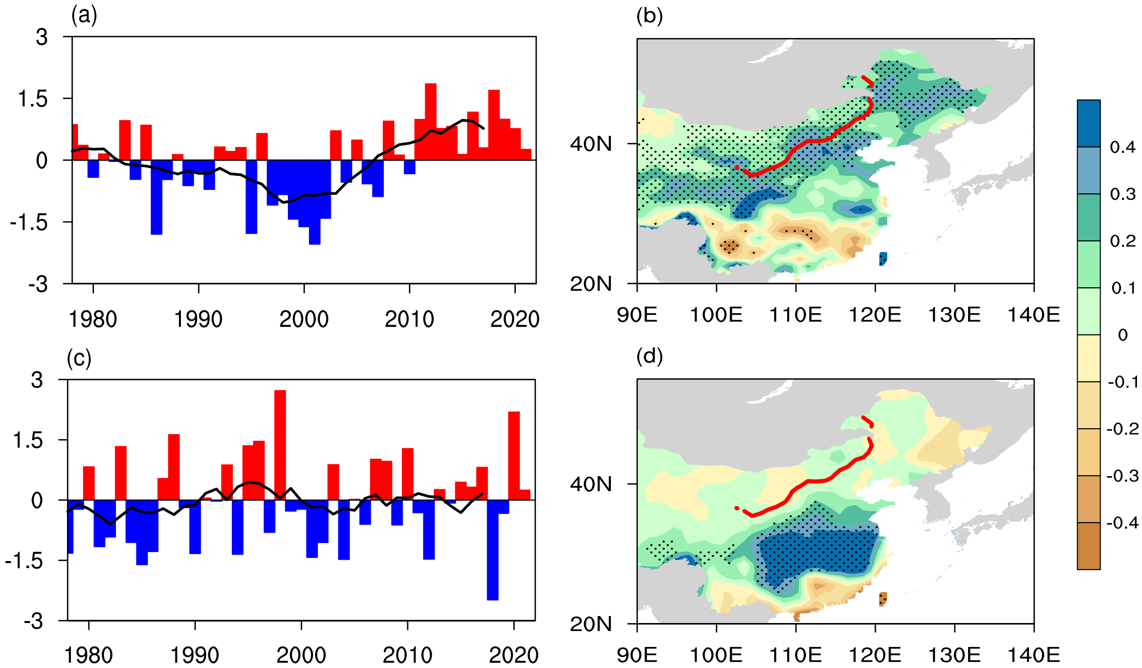

Fig. 3. Time series of the (a) EASM northern boundary index (bars) from 1979–2021 with the corresponding 9-yr running mean (black line), and (b) its regressed summer (June–August) precipitation pattern (units: mm d^{-1}). (c, d) As in (a, b) but for the EASM intensity index. The dotted areas in (b, d) denote where the regressed anomalies are significant at the 95% confidence level, and the red lines represent the climatological mean position of the EASM northern boundary. The northern boundary index and intensity index of the EASM were calculated based on the definitions proposed by Chen et al. (2018) and Wang and Fan (1999), respectively.

achieved by the CGT pattern.

3.3. *Dry–wet climate variations over the EASM transitional zone*

In addition to intensity changes, the advancement of the EASM system can also exert a substantial influence on dry–wet conditions over a vast area of East Asia (Fig. 3). The EASM usually begins in southern China in May, and then marches northward in two stages before reaching its northernmost position in late July (Wang and LinHo, 2002; Ding and Chan, 2005; Chen et al., 2009; Yuan et al., 2012). The northernmost position of the EASM exhibits significant spatial fluctuations from year to year, thus forming a southwest–northeast-oriented belt between the arid and humid climate zone—the monsoon transitional zone (MTZ; Wang et al., 2017a, 2021e; Piao et al., 2021c; Zhao et al., 2021; Piao et al., 2022). The MTZ extends from the east of the Tibetan Plateau to Northeast China, and mainly covers semi-arid climate zones with rather low annual total precipitation amounts. Due to the scarcity of water resources, the MTZ is extremely sensitive and vulnerable to climate variability, especially to precipitation changes. Far from oceanic moisture sources, the formation of precipitation here is closely related local land processes, with the available water vapor contributed greatly by evaporation, according to methods under both Eulerian (Piao et al., 2018a, 2020) and Lagrangian frameworks (Wang et al., 2023).

Considering that more than half of the annual total precipitation occurs in the summertime, several studies have mainly focused on summer precipitation variations and revealed their connections with SST anomalies over the tropical Pacific and northern Atlantic (Piao et al., 2017, 2018b; Zhao et al., 2019a, b). For example, it has been suggested that SST anomalies over the tropical central-eastern Pacific (TCEP) and tropical Northern Atlantic (TNA) can exert combined impacts on the interannual variation of summer precipitation via triggering an atmospheric wave train over Eurasia (Zhao et al., 2019b, 2020a, b); and only when opposite-sign SST anomalies appear over the TCEP and TNA are they both significantly correlated with the precipitation variation over the MTZ. This is because in opposite-sign (same-sign) cases, atmospheric anomalies induced by the TCEP SST anomalies are amplified (weakened) by those generated by the TNA SST changes (Zhao et al., 2020b). In addition to interannual variations, summer precipitation over the MTZ underwent remarkable interdecadal decreases in the late 1990s, along with prolonged drought conditions (Piao et al., 2017, 2021a). Observational results and sensitivity experiments show that the SST warming in the North Atlantic played an important role in this interdecadal change via inducing a wave-like teleconnection pattern from western Europe to Asia (Piao et al., 2017; Wang et al., 2017a).

Subsequent studies have projected future changes in precipitation over the MTZ and analyzed the main influencing factors (Piao et al., 2021b, c, 2022). The precipitation amount is expected to increase throughout the year according to both CMIP5 and CMIP6 model simulations, with the most significant changes identified in summer (Piao et al., 2021c, 2022). Moisture budget analysis suggests that changes in vertical moisture advection and evaporation together dominate the precipitation increases, with the former factor playing a more important role. It is worth noting that changes in vertical moisture advection are mainly controlled by dynamic effects associated with atmospheric changes in CMIP6, but thermodynamic components related to humidity increase in CMIP5. This inconsistency between CMIP5 and CMIP6 results might be caused by the stronger warming gradient between the mid- high latitudes and the tropics projected in CMIP6 (Piao et al., 2021c). Based on 40-member ensemble projections of the National Center for Atmospheric Research's Community Climate System Model, version 3, Piao et al. (2021b) further indicated that the projected precipitation increases are under the combined impacts from external forcing and internal atmospheric variability. The internal atmospheric variability mainly holds dominant modes resembling those associated with the Arctic Oscillation (AO) and Polar-Eurasian pattern, causing large model spread via modulating vertical motions and water vapor transport over the MTZ.

3.4. *Impacts of the Tibetan Plateau on the EASM*

The Tibetan Plateau exerts a large impact on the EASM through orographic effects and interactions with the westerlies (e.g., Wu et al., 2007; Chen and Bordoni, 2014; Son et al., 2019, 2020; Kong and Chiang, 2020; Seok and Seo, 2021). As an elevated heat source and sink in the middle troposphere, the anomalous thermal state of the Tibetan Plateau modulates the land–sea thermal contrast and affects the climate over Asia (Duan and Wu, 2005; Wu et al., 2007). Snow anomalies over the Tibetan Plateau can induce anomalous heating or cooling in the atmospheric column through the snow-albedo effect and the snow-hydrological effect (Barnett et al., 1989; Yasunari et al., 1991). Consequently, Tibetan Plateau snow anomalies affect the atmospheric circulation and weather and climate in neighboring and remote regions. There have been numerous studies of the impacts of Tibetan Plateau snow anomalies on the EASM (e.g., Duan et al., 2018). Earlier studies focused mostly on the influence of the cold season (autumn–winter–spring) snow anomalies over the central-eastern Tibetan Plateau based on station snow observations. Utilizing satellite snow data, recent studies have detected the influence of the summer snow over the western Tibetan Plateau on the East Asian summer rainfall (e.g., Xiao and Duan, 2016; Wang et al., 2018).

Wang et al. (2018) summarized two pathways for the impacts of Tibetan Plateau summer snow anomalies on East Asian summer rainfall (Fig. 4). One is through a midlatitude atmospheric wave pattern induced by western Tibetan Plateau snow anomalies. More snow cover over the western Tibetan Plateau excites an upper-level wave pattern that extends to Northeast China (Fig. 4a). The anomalous southwesterlies to the south of an anomalous cyclone bring more moisture from the lower latitudes, leading to a band of excessive rainfall extending from the mid-to-lower Yangtze River to Japan. The other is through the tropical Indo-western Pacific vertical circulation triggered by southern Tibetan Plateau snow anomalies (Fig. 4b). Anomalous cooling accompanying more snow cover over the southern Tibetan Plateau induces more convection through anomalous meridional overturning circulation. Anomalous convection over the Indian Ocean causes anomalous zonal overturning circulation with anomalous upper-level westerlies over the tropical Indian Ocean and anomalous upper-level convergence over the WNP. The suppressed convection over the WNP induces a meridional atmospheric circulation anomaly pattern with an anomalous lower-level cyclone over East Asia, inducing more rainfall extending from the middle-lower Yangtze River to Japan. When the amount of western and southern Tibetan Plateau snow is more than normal, their consistent impacts lead to more precipitation over the middle and lower reaches of the Yangtze River and subtropical WNP, and less precipitation over the northern Indian Ocean and tropical WNP (Wang et al., 2018).

4. The East Asian winter monsoon

The EAWM is an essential component of the global monsoon system in boreal winter and has widespread impacts on the weather and climate in the Asia-Pacific region and beyond (Fig. 5a; e.g., Chen et al., 2000; Chang et al., 2011; Wang and Lu, 2017; Yu et al., 2020; Ma and Chen, 2021). Its variations range from synoptic to interdecadal timescales and beyond, causing cold snaps, snowstorms, and haze in East Asia and strong tropical–extratropical interactions via the transportation of cold airmasses (e.g., Wang et al., 2009b; Zhou et al., 2009; Wang and Chen, 2014; Ding et al., 2014; Abdillah et al., 2017; Yu et al., 2021; Zheng et al., 2022). This section reviews three aspects of recent EAWM studies: its interdecadal, long-term, and subseasonal variations.

4.1. *Variations of the EAWM at the interdecadal timescale and beyond*

The EAWM intensity has been found to have shifted from strong to weak around 1988 (Fig. 5b; Kang et al., 2006; Wang et al., 2009b; Miao et al., 2018; Miao and Wang, 2020; Miao and Jiang, 2021) and experienced significant strengthening after the early 21st century (Fig. 5b; Ding et al., 2014; Wang and Chen, 2014; Xiao et al., 2016). Accompanied by these decadal variations, the surface air temperature (SAT) over East Asia also experienced decadal fluctuations, with a significant warm period from the mid-1980s to the early 2000s and a cold period from the early 2000s to mid-2010s (Fig. 5c; Kang et al., 2006; Xiao et al., 2016). The weakening of the EAWM after the mid-1980s has been attributed to global warming because the East Asian wintertime SAT during this period shows a similar warming trend to the global mean SAT (e.g., Yang and Wu, 2013; Ding et al., 2014). However, the recovery of the EAWM intensity after the early 2000s in the presence of continuing greenhouse gas (GHG) emissions suggests an essential role of internal climate variability in the interdecadal variations of the

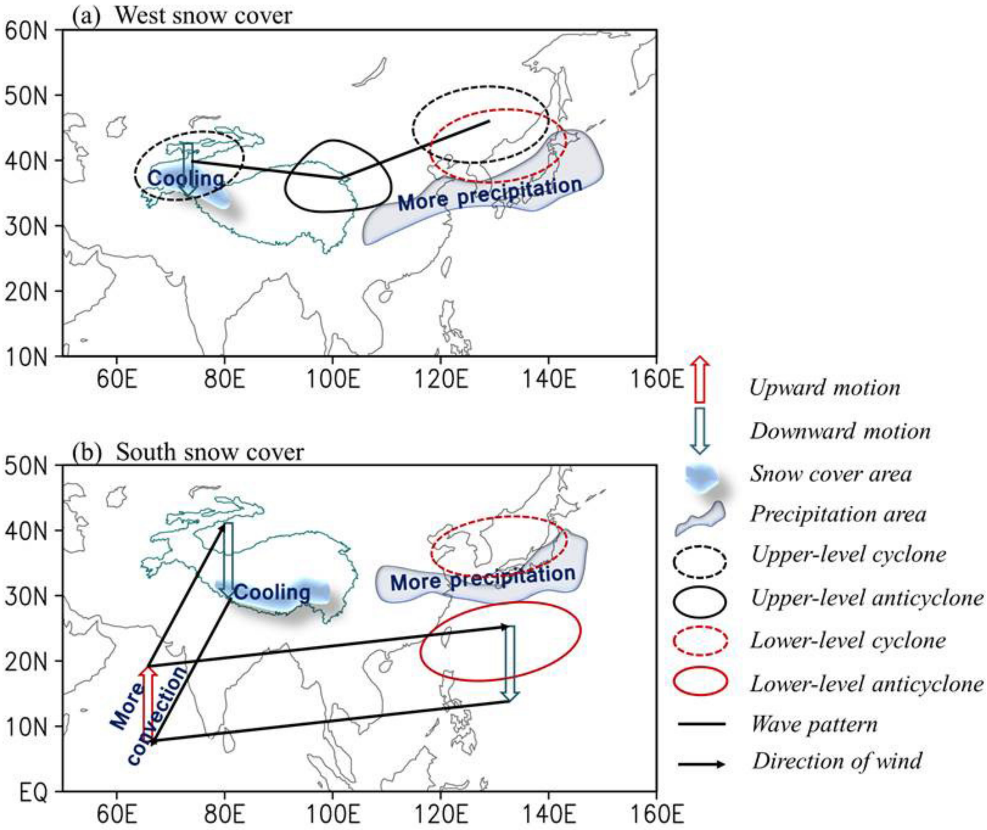

Fig. 4. Two pathways for the impacts of Tibetan Plateau summer snow anomalies on East Asian summer rainfall. One is a midlatitude atmospheric wave pattern associated with western Tibetan Plateau snow anomalies, and the other is tropical Indo-western Pacific vertical circulation triggered by southern Tibetan Plateau snow anomalies.

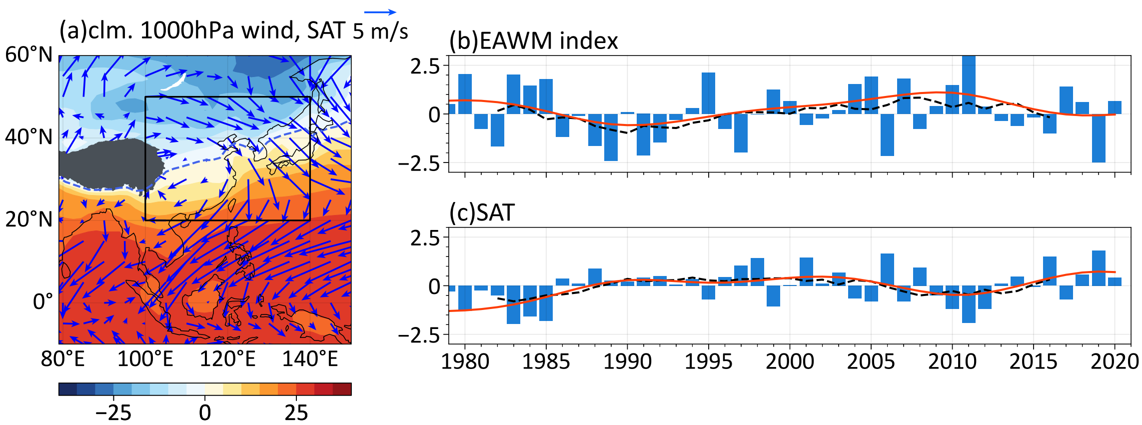

Fig. 5. (a) Climatological winter (December–January–February, DJF) mean 1000-hPa horizontal winds (vectors; units: m s^{-1}) and SAT (color shading; units: °C). The blue dashed line indicates the 0°C isotherm. (b) Standardized DJF-mean EAWM index [bars; defined by Chen et al. (2000)] during 1979–2021. The black dashed line is the nine-point running average of the EAWM index. The red solid line is the low-frequency component of the EAWM index filtered by ensemble empirical mode decomposition (Wu and Huang, 2009). (c) As in (b) but for the area-mean SAT anomaly within 20°–50°N and 100°–140°E [box in (a)]. The data used in this figure are from NCEP–DOE Reanalysis II for the period 1979–2021.

EAWM intensity (e.g., Gong et al., 2019a, b, 2021; Wang et al., 2021b). The latter is highly consistent with that of the AO, the dominant mode of internal atmospheric variability over the extratropical Northern Hemisphere for approximately 100 years (Wang et al., 2021b). An interdecadal change in the AO from a positive to a negative phase can induce widespread cooling in northern East Asia, which offsets the forced warming by more than 70% in northern East

Asia during 1979–2018 (Gong et al., 2019a). This effect largely weakens the warming trend and even induces a cooling trend in some parts of northern East Asia, and is preceded by the multidecadal fluctuation of the internal component of autumn Arctic sea ice (Gong et al., 2021). The correlation coefficient between the AO and the internally induced winter SAT anomalies in northern East Asia is 0.9 when the variability shorter than 7 years is filtered out from the data. This means that the AO accounts for 81% of the total variance of the interdecadal change in internally induced SAT over northern East Asia (Gong et al., 2019a). Therefore, the AO is the most crucial internal climate variability determining the interdecadal fluctuation of the EAWM, especially for the northern part of East Asia. Although the AO is an atmospheric internal variability, external forcings can also exert an important influence on its long-term variations or trends. For example, some studies have revealed that an increase in GHGs can force a positive AO trend by strengthening the meridional temperature gradient (e.g., Shindell et al., 1999). It has also been suggested that the Arctic sea-ice loss or the increase in snow cover in the Eurasian continent may have contributed to the negative trend of the AO during 1980–2010 (e.g., Allen and Zender, 2011; Yang et al., 2016). In addition, the Indian Ocean warming has been documented as having played an important role in the positive trend of the AO from the late 1950s to the present day (Jeong et al., 2022). The external forcing of the long-term variations of the AO described above may be an important source of the interdecadal variations of the EAWM, which needs further investigation.

In addition to the EAWM intensity, the EAWM amplitude of interannual variability has also experienced multidecadal changes, such as a weakening after the 1980s. This timing is roughly consistent with that of the interdecadal weakening of the EAWM intensity because the large-scale warming after the mid-1980s was favorable to a reduction in the land–sea thermal contrast and a weakening of the intensity of the EAWM on the interannual time scale (He, 2013). Nevertheless, the amplitude of the interannual variability of the Siberian high's intensity in winter (December–February) did not weaken between 1958 and the present day. It was weak from the 1950s to the mid-1990s and became strong at the beginning of the 21st century, consistent with the interdecadal amplification of the EAWM intensity in the past two decades (e.g., Wang and Chen, 2014; Ding et al., 2014; Chen et al., 2021a). Also, the interdecadal enhancement of the interannual variability of the EAWM can be found not only in the Siberian high but also in other components of the EAWM. The underlying mechanism may involve the change in large-scale land–sea thermal contrast over East Asia since the mid-1990s. In fact, the phase changes of the interannual variability amplitudes of the land–sea thermal contrast index in the East Asian region are basically consistent with those of the Siberian high, which was weak from 1980 to the mid-1990s and strong afterward (Chen et al., 2021a). The land–sea thermal contrast is one of the most fundamental and direct reasons for the formation of the EAWM. Due to the large ocean heat capacity, the temperature increase in the Northwest Pacific SST was smaller than that of the land in East Asia against the background of global warming from 1980 to the mid-1990s. Therefore, the thermal gradient between the sea and the land was reduced and this led to the weakening of the amplitude of the EAWM interannual variability. However, the global temperature entered a warming stagnation phase that lasted for more than 10 years after the late-1990s (Kosaka and Xie, 2013). During this period, the warming over land in East Asia slowed but the tropical eastern Pacific cooled on an interdecadal scale. The strengthening of the trade winds caused by the anomaly made Pacific surface seawater accumulate in the western Pacific, which in turn caused a significant acceleration in the warming of the upper ocean in the Northwest Pacific, thereby enhancing the sea–land thermal contrast in East Asia. This effect may have led to an increase in the EAWM amplitude of its interannual variability. If the internal variability of the climate system and the global warming caused by GHGs are superimposed in-phase in the next 10 to 20 years, and the warming re-enters an accelerating stage, the EAWM intensity of the interannual variability will likely increase again in the future.

4.2. *Subseasonal variations of the EAWM*

Subseasonal variation of the EAWM largely manifests as an occurrence of cold events or the development of cold anomalies over East Asia associated with wind anomalies (e.g., Wang et al., 2021d). Many studies have shown that changes in the mid–high-latitude circulation systems contribute to temperature anomalies over East Asia (Ding and Krishnamurti, 1987; Jeong and Ho, 2005; Song and Wu, 2017). The intraseasonal variability of the EAWM is dominated by two Rossby wave trains over North Atlantic–Eurasia, with one propagating along the polar front jet and the other along the subtropical westerly jet (Jiao et al., 2019; An et al., 2022). Both of these wave trains can generate an anomalous anticyclone/cyclone over Japan and thereby impact the low-level winds and air temperature over East Asia. Further studies have indicated that the air pollution over the North China Plain in winter is closely related to the anomalous anticyclone over Northeast Asia, and thus is influenced by the two Rossby wave trains (An et al., 2020; Song et al., 2022). A case study showed that the formation of severe haze over the North China Plain during November–December 2015 can be attributed to the combined effect of the two Rossby wave trains over Eurasia (An et al., 2020).

Precursory signals have been detected in the stratosphere before the occurrence of cold events over East Asia. Song and Wu (2019d) found that changes in the stratospheric planetary wavenumber-1 are closely linked to cold anomalies over East Asia. The reflection of the planetary wavenumber-1 pattern leads to the downward propagation of stratospheric signals, which contributes to the development of the tropospheric Rossby wave train over Eurasia and thus leads to an enhancement of the Siberian high and cold anomalies over

East Asia. Moreover, Rossby wave breaking, which is characterized by an irreversible overturning of the potential temperature contours on the tropopause (McIntyre and Palmer, 1983), has also been found to be associated with cold anomalies over East Asia. Song and Wu (2021) indicated that anticyclonic wave breaking over western Siberia accompanied by a positive AO phase contributes to the development of the Rossby wave train over Eurasia and thus a strengthening of the Siberian high, which then leads to cold anomalies over East Asia. Cyclonic wave breaking over the North Pacific is connected with a westward retrogression of North Pacific blocking, during which the Siberian high is intensified, also causing cold anomalies over East Asia.

The EAWM has been shown to be influenced by tropical large-scale air–sea interaction. For example, it has been documented that the MJO can induce a poleward Rossby wave train and have an impact on the EAWM (Jeong et al., 2005; He et al., 2011). A previous study (Song and Wu, 2018) also indicated that both positive and negative phases of the AO can lead to cold events over East Asia but with differences in the location and extent of the cold anomalies. Another study found that the MJO-induced poleward Rossby wave train influencing East Asia can be modulated by the AO (Song and Wu, 2019a). The wave source over the Arabian Sea induced by the MJO convection is intensified by positive AO–related southeastward dispersion of wave energy, causing an enhancement of the poleward wave train triggered by phases 2 and 3 of the MJO, which leads to the development of an anomalous cyclone over midlatitude East Asia and cold anomalies there. The cooperative relationship of the MJO and the AO in influencing cold events over East Asia weakens in late winter in association with the weakened connection between the MJO and the AO, which is caused by the decrease in meridional heat fluxes and thus the weakened constructive interference with climatological stationary waves and decreasing of the poleward tropospheric eddy momentum and heat fluxes over the western Pacific (Song and Wu, 2019b). Moreover, the Quasi-Biennial Oscillation (QBO) in the tropical stratosphere can modulate the MJO during boreal winter, meaning the MJO-related temperature anomalies over East Asia are different in easterly and westerly QBO phases (Song and Wu, 2020).

Recent studies have also found that the intraseasonal variations of the EAWM show a close connection with tropical rainfall/convection over the western Pacific, which includes areas such as the SCS, the Maritime Continent, and the Philippine Sea (Jiao and Wu, 2019; Ma and Chen, 2021; Ma et al., 2022b). Statistical results show that the tropical convection over the western Pacific is enhanced for about six to eight days after the peak of strong intraseasonal EAWM events (Ma et al., 2022b). The anomalous convective heating over the Maritime Continent and the tropical Indian Ocean can also lead to the occurrence of cold events over East Asia (Song and Wu, 2019c). The anomalous tropical heating generates an anomalous overturning circulation cell, with ascending motion and convergence over the tropics and descending motion over Siberia, which contributes to radiative cooling over Siberia and a southeastward intrusion of the Siberian high, resulting in cold anomalies over East Asia. This can also generate a Rossby wave train that propagates toward North America, where it induces temperature changes (Dong and Wang, 2022).

In addition, the ENSO–EAWM relationship has been found to be stronger during early winter (November–December) than late winter (January–February). This leads to a higher prediction skill for the EAWM in early winter than in late winter (Tian and Fan, 2020). The distinct ENSO–EAWM relationships between early and late winter have been suggested to be related to subseasonal changes in the teleconnections of ENSO over East Asia (Kim et al., 2018; Ma et al., 2022a). In early winter, El Niño is closely related to an anomalous anticyclone over Japan, which causes deceleration of the EAWM and a warmer East Asia (Fig. 6), with La Niña generally having opposite effects. In late winter, however, El Niño (La Niña) cannot induce a clear anticyclonic (cyclonic) anomaly over Japan, leading to weak impacts on the EAWM. Moreover, the early winter anomalous anticyclone/cyclone over Japan supports a strong impact of ENSO on haze pollution over the Beijing–Tianjin–Hebei region (Zhao et al., 2022a). The formation of the anomalous anticyclone/cyclone over Japan in early winter is related to two Rossby wave trains induced by ENSO. One propagates from the tropical Indian Ocean toward East Asia, and the other travels across the North Atlantic and Eurasia (An et al., 2022; Ma et al., 2022a). Numerical experiments suggest that the tropical Indian Ocean–East Asia wave train is mainly generated by precipitation heating in the tropical eastern Indian Ocean/western Pacific region (Fig. 6; Ma et al., 2022a).

Zhong and Wu (2022) investigated the subseasonal variations of the winter SAT over Eurasia using a seasonal-reliant EOF analysis. The first EOF mode was characterized by a persistent SAT anomaly throughout winter, while the second mode was characterized by a reversal of the SAT anomaly from early winter (November–December) to late winter (January–February). Their results were consistent with previous studies that applied the same approach to the SAT from station observations in China (Wei et al., 2014a, 2020b). The underlying mechanism involves internal dynamic processes within the atmosphere that resemble the Scandinavian teleconnection, which is maintained by both dynamic and thermal forcing effects of transient waves and the dispersion of stationary waves from the North Atlantic to Eurasia (Wei et al., 2020b). In contrast, it is loosely related to atmospheric external forcing and implies relatively low predictability of the two modes.

4.3. *Interannual variations of the EAWM*

The interannual variations of the EAWM have been studied extensively (e.g., Chen et al., 2019). Recent progress includes the impacts of Arctic sea ice (Ding et al., 2021b), the stratospheric QBO (Ma et al., 2021), and the COVID-19 pandemic on the winter climate. Arctic warming in the

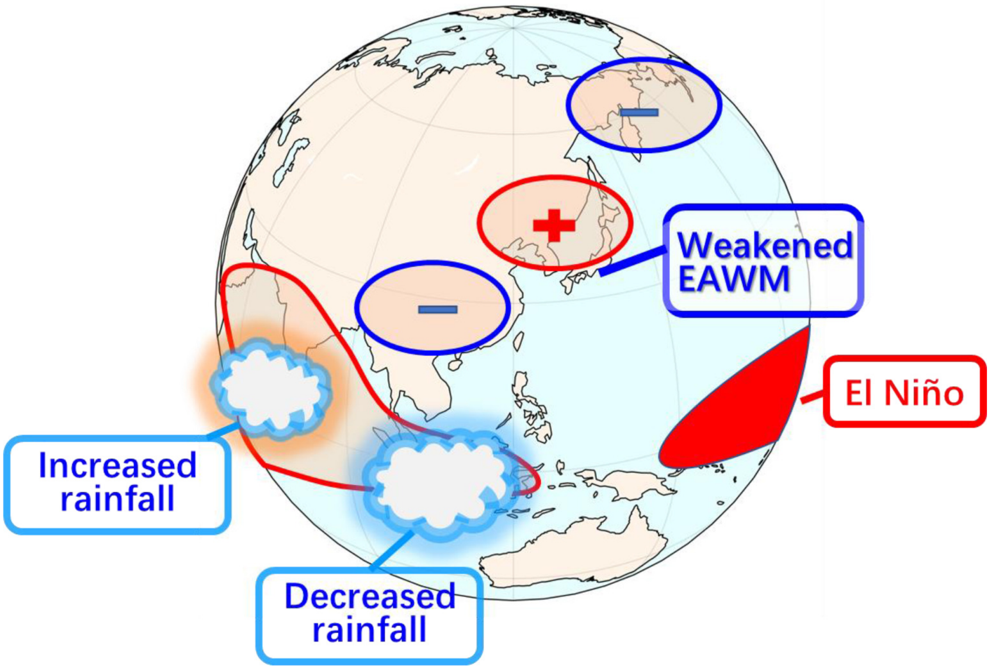

Fig. 6. Schematic of the possible roles of tropical Indian Ocean precipitation anomalies in the effects of ENSO on the EAWM. El Niño is typically accompanied by positive and negative precipitation anomalies in the tropical eastern and western Indian Ocean during early winter. This dipole precipitation anomaly, especially the eastern part, forces a Rossby wave train that propagates toward the pole. This Rossby wave train has an anomalous positive height center over Japan, leading to a weakening of the East Asian trough and hence a weakening of the EAWM.

Barents–Kara Sea (BKS) region is closely connected to cold winters over East Asia (e.g., Kug et al., 2015; Jang et al., 2019). This warm BKS and cold East Asia SAT anomaly pattern is one of the dominant modes—namely, the third mode—of the winter SAT variability over the whole Northern Hemisphere extratropics (Park et al., 2021). The possible mechanism by which BKS warming is related to cooling in East Asia is suggested to take place through large-scale circulation patterns. BKS warming is accompanied by local development of an anomalous anticyclone and downstream development of an East Asian trough, which result in northerly flow and cold anomalies over East Asia (Kug et al., 2015). Jang et al. (2019) further showed that most current climate models can reasonably capture the above-mentioned warm BKS and cold East Asia relationship and the related physical processes. However, the causes of the close relationship remain controversial, with some suggesting it may be forced by Arctic sea-ice and SST anomalies, and others stating that it is contributed by internal atmospheric circulation (e.g., Wang et al., 2020; Dai and Deng, 2022; Wang and Chen, 2022).

Autumn sea-ice variability in the East Siberian–Chukchi–Beaufort Sea has been found to have strengthened in the past two decades, with its loss favoring a colder winter, including in central-western Eurasia and northeastern China, via a persistent Arctic anticyclonic anomaly and enhanced winter monsoon. Reduced sea-ice loss is believed to promote enhanced upward propagation of quasi-stationary planetary waves and generate Eliassen–Palm flux convergence anomalies in both the upper troposphere and stratosphere, contributing to positive geopotential height anomalies in the Arctic (Ding et al., 2021b). In addition, previous studies have proposed that the QBO in the tropical stratosphere can affect tropospheric climate anomalies via three possible pathways—namely, the polar, subtropical, or tropical pathway. A recent study by Ma et al. (2021) showed that, during neutral ENSO winters (without El Niño or La Niña), the easterly phase of the QBO tends to be associated with a weakening of the EAWM through its effect on the subtropical westerly jet stream.

In addition, the short-term reduction in anthropogenic aerosol emissions during the COVID-19 pandemic may have affected the local East Asian atmospheric circulation and climate (Lee et al., 2021). CESM simulations also suggest that the reduction in aerosols in eastern China may have led to surface warming there, albeit the simulated warming is much weaker than the observed one. It is suggested that the direct radiative effect of aerosol, i.e., an increase in downward shortwave radiation, plays a key role in surface warming. Moreover, the initial surface warming can further drive an anomalous cyclone that advects warm and moist air to eastern China (Lee et al., 2021).

5. The Indian summer monsoon

Anomalies of the ISM greatly affect the Indian subcontinent and neighboring regions. In this section, we review the long-term changes in the ISM rainfall and factors, the influences of the Pacific, Indian and Atlantic SST anomalies on the interannual and interdecadal variations of the ISM rainfall. The interdecadal changes in the ISM-SST relationship are also covered.

5.1. *Long-term changes in ISM rainfall*

Changes in ISM rainfall have long been a concern in climatic studies. Research has shown that the ISM rainfall declined from 1950 to 1999 and recovered from 1999 to 2013 (e.g., Roxy et al., 2015; Jin and Wang, 2017; Roxy, 2017). The decline has been attributed to global warming, aerosol effects, deforestation, and a negative-to-positive phase transition of the IPO (Li et al., 2015; Paul et al., 2016; Chou et al., 2018). The accelerated warming over South Asia, which exceeded the tropical Indian Ocean warming, is considered to be the main driver of the ISM revival (Jin and Wang, 2017; Roxy, 2017).

The changes in ISM rainfall display spatial features. Varikoden et al. (2019) found an increasing (decreasing) trend in summer monsoon rainfall in the northern (southern) Western Ghats. They attributed this contrasting trend to a shift in the low-level westerlies over the region. Varikoden and Revadekar (2020) identified an increase in high-intensity rain events and a decrease in low-intensity rain events in the northeast regions of India. Maharana et al. (2021) linked the ISM rainfall changes to the spatial distribution of temperature and moisture changes over the Indian subcontinent. The recent weakening of the southwesterly flow was followed by a reduced northward moisture transport, leading to reduced rainfall over the Indo-Gangetic Plain and northeastern India, while the strengthening of the southwesterly flow was followed by enhanced northward moisture transport and hence increased rainfall over northwestern India.

The factors involved in these long-term ISM rainfall changes have been explored through observational analysis and numerical model experiments. Kumar and Singh (2021) suggested that the decadal trends in ISM rainfall over northeastern India and central India were controlled by long-term variations in the strength of El Niño events. Numerical experiments by Sandeep et al. (2020) showed that a weakening South Asian monsoon circulation is associated with a decline in the Atlantic Multidecadal Overturning Circulation, while precipitation exhibits contrasting responses that are dominated by a thermodynamic response. Through model simulations, Huang et al. (2020b) showed that the IPO contributed to the recent decline and recovery of ISM rainfall through moisture convergence anomalies associated with anomalous Walker circulation and meridional tropospheric temperature gradients along with the induced anomalous convection and zonal moisture advection. A positive-phase IPO appears to be related to decreased ISM rainfall through weakened Walker and Hadley circulations induced by warm SST anomalies over the TCEP, with the opposite occurring during negative phases of the IPO (Krishnamurthy and Krishnamurthy, 2014; Joshi and Kucharski, 2017).

Numerical model simulations have been conducted to understand the changes in the ISM and the roles of anthropogenic forcing. Li et al. (2021b) investigated the changes in ISM circulation and precipitation based on a large-ensemble simulation of the Canadian Earth System Model, version 2. It was found that the increase in global mean surface temperature weakened the large-ensemble mean ISM circulation but enhanced the precipitation and precipitable water. The decreased upper-level land–sea thermal contrast, which altered the meridional pressure gradient and consequently the upper-level winds, was found to be the main thermal driver of the weakening of the ISM circulation. The increase in ISM precipitation was mainly due to the positive contribution of the thermodynamic component. Ayantika et al. (2021) conducted numerical experiments with the IITM Earth System Model, version 2, to examine the individual and combined effects of GHGs and anthropogenic aerosol forcing on the response of ISM precipitation. The GHG forcing simulation showed an intensification of ISM precipitation, whereas a decrease in ISM precipitation and weakening of monsoon circulation was simulated in response anthropogenic aerosol forcing. Wang et al. (2019) investigated the physical mechanisms of anthropogenic aerosol–induced monsoon changes by decomposing the atmospheric change into a direct atmospheric response to radiative forcing and an SST-mediated change. They showed that the SST-mediated change dominated the aerosol-induced ISM response, with contributions from both the north–south interhemispheric SST gradient and the local SST cooling pattern over the tropical Indian Ocean.

5.2. *Influences of Pacific Ocean SST anomalies on the ISM*

ENSO is an important driver of the ISM variability (e.g., Yun and Timmermann, 2018; Hu et al., 2022e). ENSO influences the ISM through the Walker circulation and Hadley circulation. Kumar and Singh (2021) found significant spatiotemporal variation in the response of the ISM to El Niño. They identified a strengthening of the ISM over northeastern India during El Niño events. Schulte et al. (2021) found that the ENSO–ISM rainfall relationship is influenced by the SST anomaly gradient across the Niño-3 region. Roy et al. (2019) analyzed the ENSO–ISM rainfall connection in CMIP5 model simulations and found that practically no influence can be detected in any parts of India for pure Modoki ENSO events. Dandi et al. (2020) found that rainfall anomalies are negative over the southern Indian Peninsula and positive over the central parts of India during El Niño Modoki years. The atmospheric circulation over the WNP acts as a factor in determining the ISM rainfall anomaly pattern during El Niño Modoki years.

The ENSO–ISM relationship has experienced interdecadal changes in the past (Torrence and Webster, 1999; Krishnamurthy and Goswami, 2000; Kumar et al., 1999, 2006; Hu et al., 2022e), which, along with the plausible reasons why, continue to be a subject of recent studies (Feba et al., 2019; Roy et al., 2019; Dandi et al., 2020; Hrudya et al., 2020, 2021; Pandey et al., 2020; Samanta et al., 2020; Seetha et al., 2020; Schulte et al., 2021; Srivastava et al., 2020; Fan et al., 2021; Kumar and Singh, 2021; Mahendra et al., 2021; Varikoden et al., 2022; Hu et al., 2022e). Pandey et al. (2020) separated the ENSO–ISM rainfall relationship into a "long-term" component and a "short-term" component. They found that the change in the ENSO–ISM rainfall relationship is mainly in the "long-term" component, which changes with an increase in GHG forcing, whereas the "short-term" component does not change appreciably.

The changes in the ENSO–ISM rainfall teleconnections display regional features. Mahendra et al. (2021) found that the ENSO teleconnection to rainfall over northern central India and the southern Indian Peninsula is stronger and more stable in all epochs, whereas the ENSO teleconnection to rainfall over central India and eastern central India has experienced large epochal changes. Seetha et al. (2020) found that the changes in the ENSO–ISM rainfall relationship are mostly pronounced in the ISM core zone. During 1931–1960, the effect of La Niña was more dominant owing to more La Niña events and larger Niño-3.4 SST anomalies. The rainfall during 1961–1990 and 1991–2015 was below normal because of strong El Niño events. These changes were associated with changes in the equatorial Walker and regional Hadley circulations, which modify the low-level monsoon winds and hence the moisture supply to the Indian subcontinent.

The impacts of ENSO on ISM rainfall and their interdecadal changes display subseasonal dependence. Hrudya et al. (2020) compared the impacts of ENSO on ISM rainfall during the onset (June), peak (July–August) and withdrawal (September) phases for the period 1951–2015 and explored the changes in the ENSO–monsoon relationship from earlier decades (1951–1980) to more recent decades (1986–2015). They identified noticeable changes in the ENSO–ISM relationship from the earlier to more recent decades during all three phases. During El Niño events, rainfall increased over most of India in the more recent decades during the onset phase, but decreased during the peak and withdrawal phases. During La Niña events, rainfall decreased over the monsoon core zone of India during all three phases. Srivastava et al. (2020) investigated the impact of ENSO on ISM rainfall during July and August and detected significant changes at multidecadal timescales in the relationship between ENSO and ISM rainfall during July and August. While the impact of ENSO was strong in August and weak in July during 1948–1980, August rainfall showed a weaker relationship to ENSO than July rainfall during the post-1980s.

The impacts of ENSO on the ISM appear to depend upon the equatorial Pacific SST anomaly pattern. Fan et al. (2021) found that the roles of the eastern Pacific (EP) and central Pacific (CP) types of ENSO on the ISM experienced notable multidecadal modulation in the late 1970s. They showed that CP-type ENSO plays a far more prominent role in producing anomalous ISM rainfall after the late 1970s, when the inverse relationship between EP-type ENSO and the ISM weakened dramatically. Samanta et al. (2020) showed that half of the reduction in ISM rainfall during post-1980 La Niña events can be attributed to changes in the spatial pattern and intensity of those events.

5.3. *Influences of Indian Ocean SST anomalies on the ISM*

Another important factor of the ISM variability is the Indian Ocean SST anomalies (e.g., Ashok et al., 2001; Ummenhofer et al., 2011; Chowdary et al., 2015). Crétat et al (2017) studied the impact of the Indian Ocean on ISM rainfall by removing the influences of the Pacific Ocean in model simulations. They found that the ISM rainfall variability was barely modified by the Indian Ocean, and the Indian Ocean did not force the monsoon circulation in the absence of ENSO. Vibhute et al. (2020) explored the decadal variability of tropical Indian Ocean SST and its association with ISM rainfall variability. They found a two-year lag correlation between the decadal-scale tropical Indian Ocean SST and Indian rainfall over the monsoon core zone.

The IOD is an important modulator of the variability of ISM rainfall (Ashok et al. 2004). Krishnaswamy et al. (2015) studied recent shifts in the impact of the IOD on ISM rainfall and found a strengthened impact of the IOD during the period 1942–2011. Then, in a subsequent study, Krishnaswamy et al. (2015) found that the influence of the IOD on mean ISM rainfall and extreme rainfall events has been strengthening in recent decades, but that of ENSO has been weakening. Hrudya et al. (2021) explored the changes in the IOD–ISM rainfall relationship from earlier (1951–1980) to more recent (1986–2015) decades during different phases of the ISM. Their analyses indicated that the IOD–ISM rainfall relationship strengthened during the withdrawal phase (September) over most of India in the more recent decades, but weakened during the onset phase (June). During the peak phase (July–August), the relationship changed from being out-of-phase (negative correlation) to in-phase (positive correlation) over most of the Indian subcontinent. During positive IOD events, an increase in rainfall over the Indian region was observed during all three phases in the more recent decades. During negative IOD events, a decrease in rainfall over the Indian subcontinent was observed during the peak and withdrawal phases.

The relationship between ISM rainfall and the IOD depends upon the distribution of IOD SST anomalies. Jiang et al. (2022) identified differences in the relationship between the ISM and IOD events according to their SST anomaly pattern: Type-W IOD events, with stronger SST anomalies in the western pole, are associated with a weak ISM from May to summer; Type-E IOD events, with stronger SST anomalies in the eastern pole, are associated with a strong ISM; and Type-C events, with comparable SST anomalies in both poles, are synchronous with weak ISM anomalies.

The role of the Indian Ocean in ISM rainfall may take place through its influence on the cycle of ENSO events. Through decoupled model experiments, Terray et al. (2021)

found that the Indian Ocean feedback to ENSO accelerated El Niño shifting to La Niña and modulated the length of ENSO events. This Indian Ocean feedback was mostly active during the decaying phase of El Niño, which was accompanied by a basin-wide warming in the Indian Ocean.

5.4. *Influences of Atlantic SST anomalies on the ISM*

Studies have demonstrated the influence of the Atlantic Niño or Atlantic zonal mode (AZM) on the ISM (Kucharski et al. 2007, 2008, 2009; Nair et al., 2018; Sabeerali et al., 2019). The SST anomalies associated with the AZM modify the low-level convergence over India and thereby the ISM rainfall. Pottapinjara et al. (2014) showed that a warm (cold) AZM event leads to a decrease (an increase) in the number of monsoon depressions over the Bay of Bengal and thereby reduces (enhances) rainfall over India. The AZM induces a Kelvin wave–like response in tropospheric temperature that propagates to the east to reach the Indian Ocean and modulates the mid-tropospheric land–sea thermal gradient and thereby the ISM (Pottapinjara et al., 2014). Pottapinjara et al. (2021) used the Coupled Forecast System, version 2, to examine how well the model simulates this AZM–ISM link. The model simulations showed a Matsuno–Gill-type response to a warm AZM SST anomaly, with anomalous descending motion and reduced rainfall over India. Sabeerali et al. (2019) identified a strengthening in the relationship between ISM rainfall and the AZM in recent decades, which they attributed to the increase in the eastern equatorial Atlantic Ocean SST anomalies.

Recent studies have revealed an association between ISM rainfall and the Atlantic Multidecadal Oscillation (AMO) on multi-decadal timescales (Goswami et al., 2006; Zhang and Delworth, 2006; Wang et al., 2009c; Luo et al., 2011, 2018a, b; Krishnamurthy and Krishnamurthy, 2016). The AMO modulates the subseasonal change in the influences of North Atlantic SST anomalies on ISM rainfall (Borah et al., 2019; Rajesh and Goswami, 2020). The relationship between the ISM and the AMO is not stable over time (Malik et al., 2017). Luo et al. (2018c) detected a weakening of the ISM rainfall–AMO connection since the mid-1990s. Ahmad et al. (2022) investigated the AMO–ISM connection using CESM large-ensemble simulations and found an unstable connection in the 1800-year pre-industrial simulation, which they attributed to internal climatic processes. Their analysis suggests a substantial role played by subtropical WNP SSTs in modulating the link between the ISM and AMO.

A link has been found between the spring Atlantic meridional mode (AMM) and ISM rainfall (Vittal et al., 2020). Vittal et al. (2020) showed that ISM rainfall increases (decreases) during positive (negative) phases of the AMM. During a positive phase of the spring AMM, positive SST anomalies in the tropical North Atlantic Ocean strengthen anomalies of cyclonic circulation and convection over the Sahel region, which in turn modulate the winds over the western Indian Ocean, thereby cooling the SST there and strengthening the monsoon circulation over India.

6. Summary and discussion

This paper reviews the multi-scale climate variations and mechanisms of the Asian monsoon, with an emphasis on the latest research progress in the past several years. Previous studies on the EASM were primarily devoted to its onset over the SCS and its intensity, whereas attention in recent years has also been paid to its seasonal evolution (i.e., monsoon onset, withdrawal, and that between). For example, recent studies have investigated the climatological (Hu et al., 2019b), interdecadal (Hu et al., 2019a), interannual (Hu et al., 2019b, 2020b, c), and intraseasonal (Hu et al., 2019c) variations of SCSSM withdrawal. Since Chen et al. (2022a) already reviewed the progress made in the onset and withdrawal of the SCSSM, we mainly focus here on more recent advances, especially regarding monsoon onset. Results indicate that the local monsoon onset tends to be synchronously advanced or delayed over the Arabian Sea, Bay of Bengal, Indochina Peninsula, and SCS; and this synchronized variation of local monsoon onset can be attributed to both atmospheric internal processes (e.g., 30–80-day oscillation) and external forcings (e.g., ENSO, IPO, and the Tibetan Plateau thermal condition), depending on the time scale of the variations. Results also indicate that substantial achievements have been made in understanding the interdecadal change in the SCSSM onset around the mid-to-late 1990s. Moreover, it has been suggested that the average date of SCSSM onset was delayed again in the early 2010s. In addition, the relationship between SCSSM onset and extreme rainfall over southern China and Southeast Asia has been investigated.

Among the achievements in research on SCSSM onset, a particularly interesting result is the weakened relationship between ENSO and SCSSM onset in recent years. Conventionally, ENSO is regarded as the most important predictor of SCSSM onset (Zhu and Li, 2017; Martin et al., 2019). However, the weakened relationship between ENSO and SCSSM onset has driven us to look for other factors that may be of influence. Recent studies have highlighted the extratropical factors affecting SCSSM onset, including the midlatitude Rossby wave train (Liu and Zhu, 2019; Deng et al., 2020; Xu and Li, 2021), AO (Hu et al., 2021), Victoria mode (Hu et al., 2022b), PDO (Hu et al., 2022c), and quasi-biweekly oscillation originated from the Tibetan Plateau (Liu and Zhu, 2021). These factors need to be taken into account to create a new forecasting model that can hopefully overcome forecast errors like those in 2018 (Liu and Zhu, 2020) and 2019 (Hu et al., 2020a).

Regarding the EASM, the record-breaking mei-yu in 2020 has been extensively investigated, revealing the contributing factors at different time scales (interdecadal, interannual, subseasonal, synoptic, and diurnal). Among them, the warming Indian Ocean and the SST anomalies in both the tropical Pacific and Atlantic have been suggested as having contributed directly to this super mei-yu event. Also, the extremely low Arctic sea ice in late spring and early summer may have played a role. In addition to impacts from natural variability, the 2020 extreme summer rainfall might have been related to the reduction in aerosols during the COVID-19 pandemic. Besides, the link between the summer monsoon rainfall over East Asia and South Asia has been further investigated. Recent advances include understanding the non-stationary and intraseasonal variation of their linkage. It is worth mentioning that earlier studies considered the SASM as a more active influencing factor, with the EASM as a passive recipient of influences. However, recent results have also revealed the impacts and feedbacks of the EASM on the SASM, with several mechanisms proposed.

In pace with the EASM reaching its northernmost position, the rainy season begins in the northern part of China, Korea, and Japan. A southward or northward shift of the summer monsoon northern boundary is often accompanied by summertime dry/wet climate anomalies in Northeast Asia. Since this summer monsoon northern boundary is generally located in the transitional climate belt between southern humid and northern arid regions, the MTZ has suffered from frequent meteorological disasters in recent decades due to the extremely fragile ecosystem with high sensitivity to climate change. Recent studies have investigated the summer precipitation variations and revealed the roles of SST anomalies over the tropical Pacific and North Atlantic on both interannual and interdecadal timescales. Moreover, future changes in MTZ precipitation have been projected, with its uncertainty analyzed by separating the external forcing and internal atmospheric variability. Preliminary observational studies have also found clear interdecadal changes in the EASM northern boundary over the past 70 years. However, climate model simulations suggest a northward extension of the EASM during the mid-Holocene and global warming scenarios (Piao et al., 2020; Wang et al., 2023). Hence, the issue of why the EASM northern boundary has not shown a persistent northward shift in the context of global warming should be addressed. Possible underlying mechanisms for the interdecadal variation in the EASM northern boundary also need to be investigated. It is commonly acknowledged that global warming will continue in the future even under a carbon-neutral scenario, posing a severe threat to ecological balance and sustainable development, especially over regions with fragile ecosystems and high sensitivity to climate change. Thus, further research on the interdecadal changes in the EASM northern boundary will not only advance our understanding of regional climate responses to global warming, but also provide important scientific support for national strategic decision-making in the short to medium term to address climate change.

Regarding the EAWM, significant advances have been made, especially in studies on its interdecadal, long-term, and subseasonal variations. Results suggest that the recovery of EAWM intensity after the early-2000s in the presence of continuing GHG emissions was dominated by internal climate variability (mostly the AO). Moreover, the interannual variability of the EAWM has also been found to have experienced multidecadal changes. However, the mechanisms underlying these changes in the EAWM system, including the Siberian high, need further study in the future. On the subseasonal timescale, the wind variations over East Asia are associated with two Rossby wave trains propagating along the polar front jet and the subtropical jet, which have significant impacts on cold anomalies over this region. The influence of the MJO on the EAWM has been found to be modulated by both the AO and the QBO. The intraseasonal variations of the EAWM have also been shown to interact closely with tropical rainfall/convection over the western Pacific. The ENSO–EAWM relationship has been found to be stronger during early winter than late winter, and the mechanism is possibly related to subseasonal changes in the teleconnections of ENSO over East Asia.

As an important component of the Asian monsoon, research on the ISM has a long history, and many achievements have been made in ISM research in recent years. Specifically, the ISM revival around the end of the last century attracts a wide range of interest. Results suggest that the accelerated warming over South Asia, which exceeds the tropical Indian Ocean warming, was the main driver of the ISM rainfall recovery. Possible factors behind long-term ISM rainfall changes have been explored through observational analysis and numerical model experiments. Additionally, numerous studies have further investigated the influences on the ISM from Pacific Ocean, Indian Ocean, and Atlantic Ocean SST anomalies. In particular, the changes in the ENSO–ISM relationship and the plausible reasons have continued to be a key focus. Results indicate significant spatiotemporal variation in the ISM response to ENSO. Noticeable changes in the ENSO–ISM relationship have been identified from earlier to more recent decades during the onset, peak, and withdrawal phases. Similarly, the interdecadal changes of the relationship of the ISM with the IOD, AZM, and AMO have been explored. In addition, recent results show that the impacts of ENSO and the IOD on the ISM appear to depend upon the distribution of the equatorial Pacific and IOD SST anomaly pattern.

During the past several years, significant advances have been achieved in understanding the variations of the Asian monsoon at different temporal and spatial scales. It is noteworthy that there are complex interactions across both of these scales. A detailed understanding of the changes in the Asian monsoon requires an integrated investigation of these interactions. Moreover, we still face great challenges in predicting and projecting the Asian monsoon successfully, which mainly involves the use of climate models. Obviously, more studies are needed to evaluate the simulation abilities of current models in terms of the interdecadal and intraseasonal variations in the Asian monsoon. Finally, relatively little attention has been paid to the evolution of the EAWM compared with that of the EASM. The changes in EAWM evolution should be emphasized in future studies, which would enrich our understanding of the whole seasonal march of the Asian monsoon.

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