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The Long-Term Variability of Changma in the East Asian Summer Monsoon System: A Review and Revisit

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Abstract: Changma, which is a vital part of East Asian summer monsoon (EASM) system, plays a critical role in modulating water and energy cycles in Korea. Better understanding of its long-term variability and change is therefore a matter of scientific and societal importance. It has been indicated that characteristics of Changma have undergone significant interdecadal changes in association with the mid-1970s global-scale climate shift and the mid-1990s EASM shift. This paper reviews and revisits the characteristics on the long-term changes of Changma focusing on the underlying mechanisms for the changes. The four important features are manifested mainly during the last few decades: 1) mean and extreme rainfalls during Changma period from June to September have been increased with the amplification of diurnal cycle of rainfall, 2) the dry spell between the first and second rainy periods has become shorter, 3) the rainfall amount as well as the number of rainy days during August have significantly increased, probably due to the increase in typhoon landfalls, and 4) the relationship between the Changma rainfall and Western Pacific Subtropical High on interannual time scale has been enhanced. The typhoon contribution to the increase in heavy rainfall is attributable to enhanced interaction between typhoons and midlatitude baroclinic environment. It is noted that the change in the relationship between Changma and the tropical sea surface temperature (SST) over the Indian, Pacific, and Atlantic Oceans is a key factor in the long-term changes of Changma and EASM. Possible sources for the recent mid-1990s change include 1) the tropical dipole-like SST pattern between the central Pacific and Indo-Pacific region (the global warming hiatus pattern), 2) the recent intensification of tropical SST gradients among the Indian Ocean, the western Pacific, and the eastern Pacific, and 3) the tropical Atlantic SST warming.

Key words: Changma, East Asian summer monsoon, interdecadal change, Typhoon landfalls, ENSO

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1. Introduction

Changma is a major rainy season in Korea as one of major sub-monsoon components of the East Asian summer monsoon (EASM) system and thus has great impacts on water and energy cycles in Korea. During summer monsoon season, preferentially from June to September (JJAS), Changma shows well-defined two peaks of rainfall, which mainly appear in early July and early September. The former, which is referred to as the (*first*) Changma or *primary rainy period*, is concurrent with the climatological onset around 19th-25th June and withdrawal date around 20th-25th July (Ho and Kang, 1988; Seo et al., 2011; Park et al., 2015). The latter is called as the *second* or *fall* Changma and it is mainly associated with typhoon activity during the late summer. Traditionally and etymologically, Changma has been only referred as the first rainy period. However, recent studies, including this review, have regarded Changma as a sub-monsoon system of the EASM spanning the entire rainy summer season including the active and break cycle. The complex subseasonal structure of Changma makes it still difficult and challengeable to predict its characteristics such as onset, withdrawal date, amount, and intensity (Lee and Seo, 2013; Park et al., 2015; Jeong et al., 2016).

Changma is conventionally defined by a successive rainy period accompanied with the zonally elongated and quasi-stationary front over Korean Peninsula. It tends to follow *Meiyu* in China and *Baiu* in Japan with a-couple-of-day lags and shares with them the stationary slanted frontal system that is anchored by the westerly jet tilted northward with height and large low-level moisture transport from the south (Sampe and Xie, 2010). Although Changma shares key structures with Meiyu and Baiu, there are also distinct differences among them (Seo et al., 2015; Oh and Ha, 2015). The difference is largely caused by complex influencing factors of five different air masses including tropical North Pacific air mass, cold Okhotsk sea air mass, tropical monsoon air mass related to the intertropical convergence zone (ITCZ), tropical continental air mass over North China, and intermittently polar continental air mass (Seo et al., 2015). Hence, strong meridional gradient of moisture and temperature forms along the Changma front (Seo et al., 2011). On the other hand, Mei-yu is mainly influenced by the contrast between tropical monsoon and tropical continental air masses with strong meridional moisture gradient, whereas Baiu is associated with the contrast between tropical North Pacific and cold Okhotsk sea air masses and resultant strong meridional gradient of temperature and moisture (Tomita et al., 2011; Seo et al., 2011, 2015).

The variability in the characteristics of Changma has been further understood in the framework of EASM variability. The onset date of Changma is mainly determined by the northward migration of the EASM rain band from about 20° to 40°N (Kang et al., 1999; Wang and LinHo, 2002; Lee et al., 2013; Park et al., 2015). The intensity of Changma is strongly modulated by two major large-scale circulation variabilities of (1) western Pacific (WP) subtropical high (WPSH) associated with the western North Pacific summer monsoon (WNPSM) and (2) circumglobal teleconnection (CGT) related to the Indian summer monsoon (ISM) (Ding et al., 2011; Wang et al., 2013a; Lee et al., 2011, 2014b; Lee and Ha, 2015). On one hand, the enhanced WPSH leads to the weakening of the WNPSM but strengthening of the EASM (e.g., out-of-phase relationship between WNPSM and EASM). On the other hand, the enhanced CGT associated with above normal rainfall over the ISM results in the weakening of the EASM (e.g., out-of-phase relationship between ISM and EASM; Ha et al., 2016). It is also worth noting that the variability of EASM and Changma tends to be intensified (weakened) during the decaying phase of El Niño (La Niña) (Wang et al., 2013a; Kosaka et al., 2013; Lee and Ha, 2015; Stuecker et al., 2015; Oh and Ha, 2015; Seo at al., 2015; Kim et al., 2017).

Many previous studies have shown that the characteristics of Changma have experienced sudden changes around the late-1970s (Ho et al., 2003; Kim et al., 2006; Park et al., 2008; Lee et al., 2010) and the mid-1990s (Yoon et al., 2006; Kim and Suh, 2008; Choi et al., 2017). For example, the dry spell between the two peaks becomes shorter during recent several decades (Ho et al., 2003; Ko et al., 2005) and rainfall amount in addition to the number of rainy days during August has been recently increased (Ho et al., 2004; Lee and Kwon, 2004; Kim et al., 2006; Yoon et al., 2006; Kim and Suh, 2008; Park et al., 2008; Ha et al., 2009; Lee et al., 2010). In line with Changma, it has been recognized that the EASM system has experienced a significant interdecadal shift occurred around the mid-1990s (Kwon et al., 2005; Kwon et al., 2007; Lu et al., 2011; Xiang and Wang, 2013). After the mid-1990s, the variability of EASM circulation has been weakened together with a decrease in rainfall (Kwon et al., 2005), which is likely due to stronger impact of the central Pacific (CP) sea surface temperature (SST) than the eastern Pacific (EP) SST (Yim et al., 2014). There is still vigorous debate as to what extent the mid-1990s shift affected Changma characteristics.

Undoubtedly, it is of importance to understand the relationship between tropical SSTs and Changma variability. A special focus has been placed on the effect of El Niño-Southern Oscillation (ENSO) on the Changma and EASM (Lee et al., 2010; Yun et al., 2010; Wang et al., 2013; Seo et al., 2015). After the mid-1970s, the ENSO-EASM relationship has strengthened, which results from stronger atmospheric teleconnections (e.g., Pacific-Japan pattern) spanning the Indo-WNP warm pool (Ding et al., 2010; Xie et al., 2010). The warming of tropical Indian Ocean (IO)-WP warm pool SST is instrumental in bridging ENSO into Changma variability, via the modulation of WPSH (Kosaka et al., 2013). On the other hand, recent researches have demonstrated the significant roles of tropical SST gradients among IO, WP, and EP (Chen and Zhou, 2014; Yun et al., 2014; He and Zhou, 2014, 2015). It has been also suggested that the tropical Atlantic SSTs have a significant impact on the Changma and EASM changes (Hong et al., 2014; Seo et al., 2015; Park et al., 2015; Ham et al., 2016). Despite the considerable efforts in previous studies, many features about the roles of tropical SSTs on the long-term variability of Changma have not been well organized.

This article reviews previous studies and further investigates on how the structure of Changma has been changed during recent several decades and discuss controlling mechanisms of long-term variability of Changma. Section 2 provides information of data used in this study. Characteristics of interdecadal changes in Changma on diurnal, seasonal, interannual and interdecadal time scales are summarized in Section 3. Section 4 focuses on the contribution of tropical cyclone landfalls to the changes particularly during *fall* Changma. Section 5 discusses key factors responsible for the long-term Changma changes occurred around the mid-1970s and the mid-1990s. The last section summarizes the major results of this study.

2. Data

The area-averaged daily precipitation data in Korea are obtained by averaging over 45 weather stations across the Korean Peninsula for 43 years of 1973-2015 provided by the Korea Meteorological Administration (KMA). The area-averaged hourly precipitation data are obtained by averaging over 60 weather stations in South Korea for 37 years of 1977-2013 provided by the KMA.

Several other observed datasets used in this study are 1) monthly mean precipitation from Global Precipitation Climatology Project (GPCP, v2.2) datasets from 1979 to 2015 (Huffman et al., 2009), 2) monthly mean circulation data from National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Reanalysis 2 products from 1979 to 2015 (Kanamitsu et al., 2002), and 3) monthly mean SST from NOAA Extended Reconstructed SST (ERSST, v3b) from 1900 to 2015 (Smith and Reynolds, 2003).

3. Characteristics of interdecadal change in Changma rainfall

a. Changes in daily to seasonal mean rainfall

(1) Multidecadal to centennial variation

Korea has the earliest instrumental measurements for rainfall using *Chukwookee* in the world. *Chukwookee* means a rain-measuring device and provides 129-year daily precipitation record in Seoul since 1778 (Kim, 1988; Jhun and Moon, 1997), offering a good opportunity to investigate interannual to multidecadal to centennial variations of summer rainfall. By using the 227-year daily precipitation record of 1778-2004 including the *Chukwookee* record for 1778-1907 and the station gauge data for 1908-2004, Wang et al. (2006, 2007) revealed that the long-term rainy season characteristics in Seoul, that can reflect Changma features, exhibits considerable multidecadal to centennial variability as follows. First, over the past 227 years and in the twentieth century, both total and extreme rainfall amounts during JJAS have increasing trends which are significant at the 95% confidence level and higher

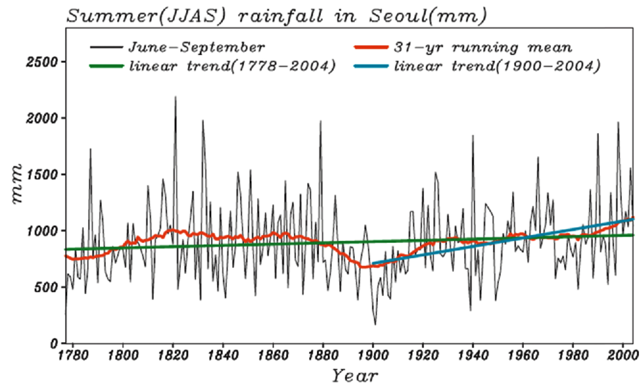

Fig. 1. Time Series of summer (June-September) precipitation in Seoul from 1778 to 2004. The red line denotes 31-year running mean. The green and blue lines represent a linear trend for 1778-2004 and 1900-2004, respectively. This figure is adopted from Wang et al. (2006).

(Fig. 1). In particular, precipitation intensity has been significantly enhanced in the recent 55 years. Analysis of precipi-

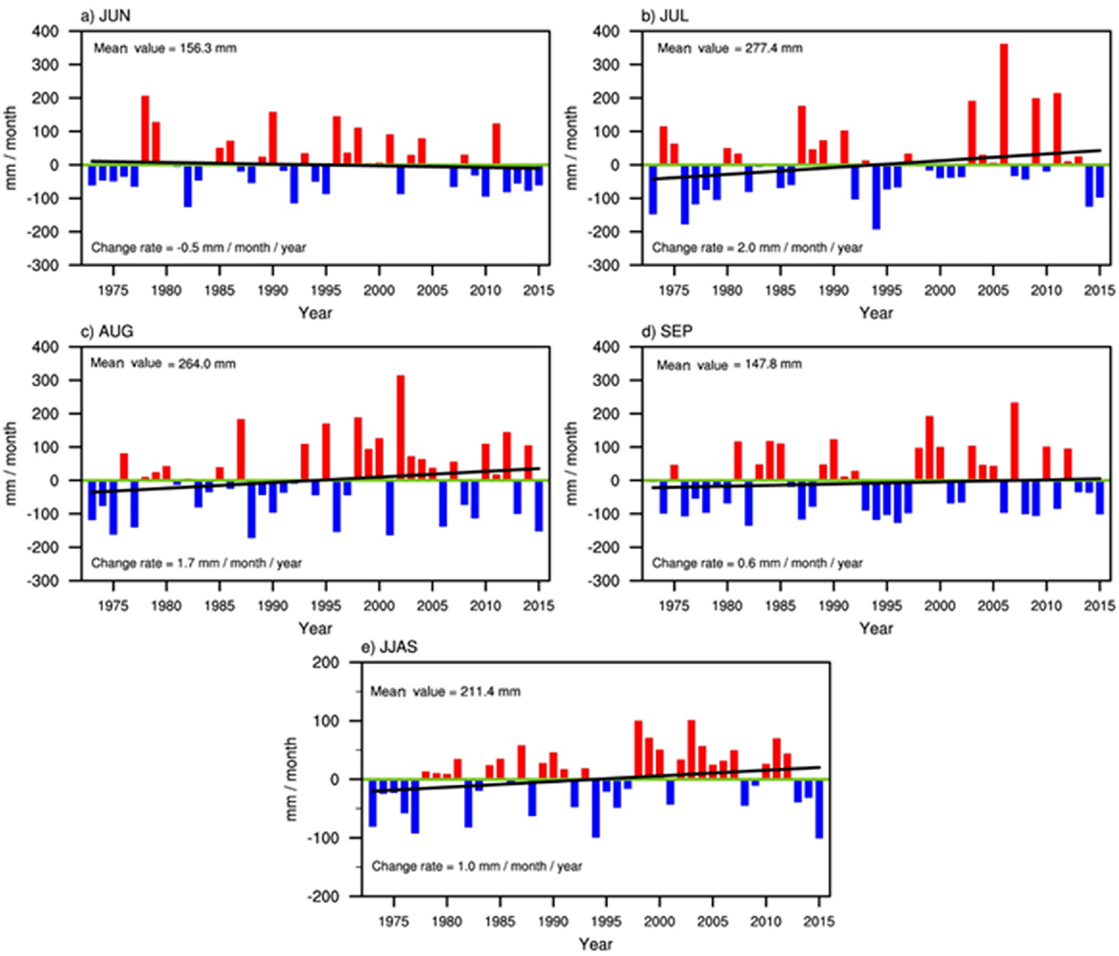

Fig. 2. Time series of monthly precipitation anomaly in (a) June, (b) July, (c) August, and (d) September and summer mean (June to September) precipitation anomaly averaged over 45 weather stations in Korea from 1973 to 2015. The black solid line represents a linear trend for the 43 years. Also shown are the climatological mean value and change rate.

tation averaged over 45 weather stations in Korea further reveals that an increase in JJAS precipitation is significant until 2012, mainly attributable to the intensification of July and August rainfall, whereas for the recent three years of 2013-2015 Korea has experienced less rainfall (Fig. 2). Second, the amplitude of the interannual (2-6 year) variation of summer precipitation shows a prominent fluctuation with a 50-yr rhythm. Third, the severe flood events have a spectral peak at 3 and 19 years, respectively. Lastly, the occurrence of severe drought events exhibits a 4-year spectral peak along with large power on a centennial time scale. The long-term variability in the rainy season features revealed by the *Chukwookee* rainfall record suggests that trends detected by using a 50-year-or-shorter precipitation record likely reflect natural variability as indicated by Wang et al. (2007).

(2) The interdecadal shift around the mid-1970s

It has been noted for several decades that there was a significant change in the tropical Pacific SST and global climate since the mid-1970s (Graham, 1994; Wang, 1995; and many others). Especially, changes in ENSO characteristics including frequency, intensity, structure, and propagation since the mid-1970s (Wang, 1995; An and Wang, 2000) have played a crucial role in the changes of the interannual variability of the ENSO-Asian summer monsoon relationship (Wang et al., 2008; Lee and Ha, 2015). Many previous works have shown that the significant interdecadal transition was concurrent with the major climate shift in the tropical Pacific (Hu, 1997; Wu and Wang, 2002; Chang et al., 2000; Zhang et al., 2004). EASM precipitation anomalies have a contrast of the South-North dipole structure in East Asia between the before and after periods of the mid-1970s.

Associated with the global-scale climate shift around the mid-1970s, considerable changes in the Changma characteristics have been reported and summarized as follows. First, summer mean rainfall amount and the number of heavy rainfall occurrence have increased during the recent epoch in association with a sudden increase in the anomalous anti-cyclonic circulation over central-eastern Asia that may lead to intensification of moisture convergence and convective activity over Korea (Kim et al., 2002; Ho et al., 2003). Second, a shift in Changma onset, dry spell, and withdrawal is observed. After the mid-1970s, the onset of Changma and *second* Changma is advanced about one week and ten days, respectively. Consequently, the dry spell between the two rainfall peaks becomes shorter during the recent epoch (Fig. 3), which is mainly attributable to the significant increase in August rainfall (Ko et al., 2005; Lee and Kwon, 2004). As a matter of fact, the dry spell is not a well-defined terminology because the first and second peaks are commonly vague in the individual year. In this article, the dry spell is recognized by the period between the first and second peaks of precipitation, which are evaluated from decadal means according to Ho et al. (2003).

The recent increase in August rainfall may be contributed by the enhanced interaction of landfalling typhoons and mid-

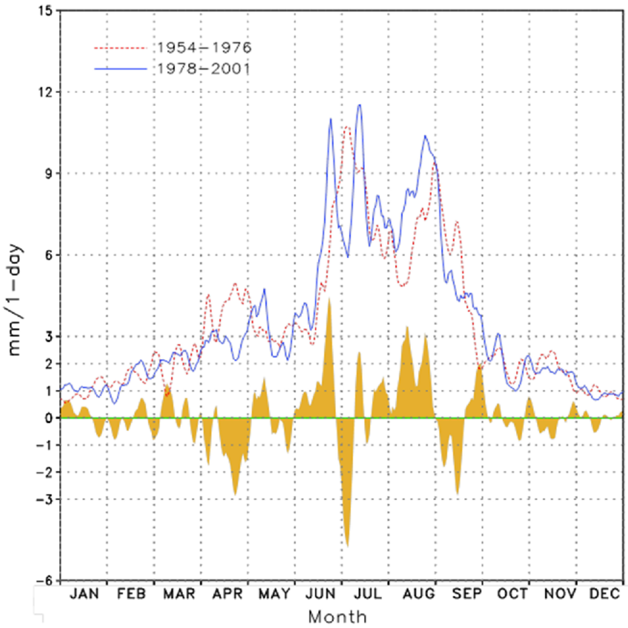

Fig. 3. Time series of two sets of 5-day moving average precipitation climatology for 1954-1977 (dashed line) and 1978-2001 (solid line), respectively. The difference of the two climatologies (1978-2001 minus 1954-77) is shown by the shaded area. This figure is adopted from Ho et al. (2003).

latitude baroclinic environment (Kim et al., 2006; Park et al., 2011). Section 4 separately discusses the role of typhoons in the interdecadal changes in Changma in details, which is particularly critical for the *second* Changma. Third, the linkage of interannual variability of Changma rainfall to the WNPSM and WPSH variability has been enhanced but its association with the CGT has been weakened during the recent epoch (Lee and Ha, 2015). The weakening of CGT impact on Changma is attributable to the weakening of the relationship between CGT and ISM variability (Wang et al., 2012; Lee and Ha, 2015). Lee et al. (2014b) suggested that the linkage between CGT and Changma (EASM) may be further weakened during the latter half of 21st century under anthropogenic global warming.

(3) The interdecadal shift around the mid-1990s and the current status

Evidence has been emerging that the EASM rainfall and circulation experienced considerable changes around the mid-1990s (Kwon et al., 2005, 2007). Section 5b discusses the characteristics of the EASM changes and the mechanism responsible for the change in details.

Associated with the global-scale climate shift around the mid-1990s, considerable changes in Changma characteristics are observed as follows. First, the summer rainy period has been lengthened after the mid-1990s mainly due to the delay of the withdrawal of the *second* Changma (Fig. 4). Second, the dry spell between the two rainfall peaks has become shortened after the mid-1990s, which mainly arises from the increase of August rainfall as suggested by previous studies (Ha et al.,

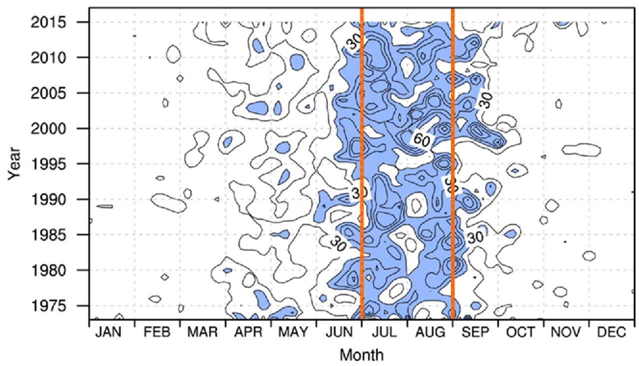

Fig. 4. Year-month cross-section of the pentad precipitation averaged over the 45 weather stations from January to December for 1973-2015. The contour interval is 15 mm pentad^{-1}.

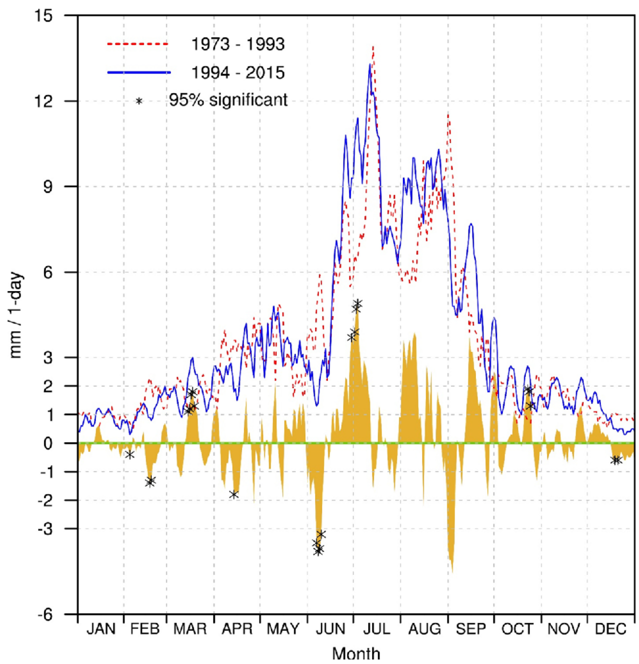

Fig. 5. Same as Fig. 3 but for climatology for 1973-1993 (dashed line) and 1994-2015 (solid line), respectively. Asterisk indicates the difference is significant at 95% confidence level.

2005; Yoon et al., 2006; Park et al., 2008, 2011; Kim et al., 2011, 2012; Choi et al., 2017). Figure 5 further indicates that the recent epoch (1994-2015) has received more rainfall during mid-June to early July, early August, and mid-September but less rainfall during early June and early September than the previous epoch (1973-1993). It is further noted that the shortening of the dry spell between the two peaks is more obvious over the middle part (19 stations) than the southern part (26 station including Jeju island) of Korea (not shown). Over the middle (southern) part, the increasing trend in July (August) precipitation is larger than that in August (July) precipitation for the last 40 years. Finally, the number of dry days as well as the occurrence of heavy rainfall has been increasing since the mid-1990s (Yoon et al., 2006; Min et al., 2015), indicating the increase in extreme climate event during summer.

b. Changes in diurnal variation of rainfall

(1) Basic characteristics of diurnal cycle

The diurnal variation of rainfall is one of the important characteristics of regional climate (e.g. Yang and Slingo, 2001) and has been studied for several decades. Over the EAM region, including Korea, China, and Japan, the two maximum peaks of rainfall are observed in the afternoon and early morning (Ramage, 1952; Lim and Kwon, 1998; Jung and Suh, 2005), depending on the location. The early morning maximum peak of rainfall occurs along the coastal region, while both weak early morning maximum and strong late afternoon maximum peaks occur over the inland area (Jung and Suh, 2005; Choi et al., 2015; Jin, 2016). However, several recent studies pointed out that the complex topographic effect can result in the distinct features of diurnal variations related to different precipitation processes for the Mei-yu, Changma, and Baiu (Yuan et al., 2012; Park et al., 2016).

As the Korean peninsula is located in the eastern edge of the continent, diurnal variations of summer rainfall in Korea are characterized by strong early morning peak at 0600-0800 local standard time (LST) and weak late afternoon peak at 1500-1700 LST (Lim and Kwon, 1998; Jung and Suh, 2005; Lee and Seo, 2008; Jin, 2016). In the coastal region, the diurnal cycle with morning peak is dominant, while the semi-diurnal cycle with both morning and afternoon peak occurs in the inland area (Jung and Suh, 2005). Sohn et al. (2013) showed that the morning peak over the Korean peninsula is induced by the warm liquid-water-rich lower clouds transported along the northwestern periphery of the North Pacific high under near-neutral moist adiabatic condition. Park et al. (2016) pointed out that the rainfall in the morning in the coastal region including the southern part of Korean peninsula is due to the significant increase in the mid-level storms and the favorable modulation of synoptic circulation based on the premise that a diversity in the diurnal variation of surface rainfall is induced by the different contribution of topography, local surface heating, land-sea breeze, large-scale diurnal variations in low-level atmospheric circulations, convective instability due to boundary layer heating, and diurnal propagations of convective systems (Huang et al., 2010; Yuan et al., 2012).

The diurnal variation of precipitation is fundamentally dominated by the frequency of precipitation occurrence rather than precipitation intensity (Lim and Kwon, 1998). The pattern of diurnal variation is mainly caused by that of the frequency, although the characteristics of diurnal variation vary with month, precipitation intensity, and geographic region (Jung and Suh, 2005). The amplitude of diurnal cycle increases as precipitation intensity increases, and the timing for the morning peak is slightly earlier for the intense precipitation (Jung and Suh, 2005) and that of the afternoon peak tends to

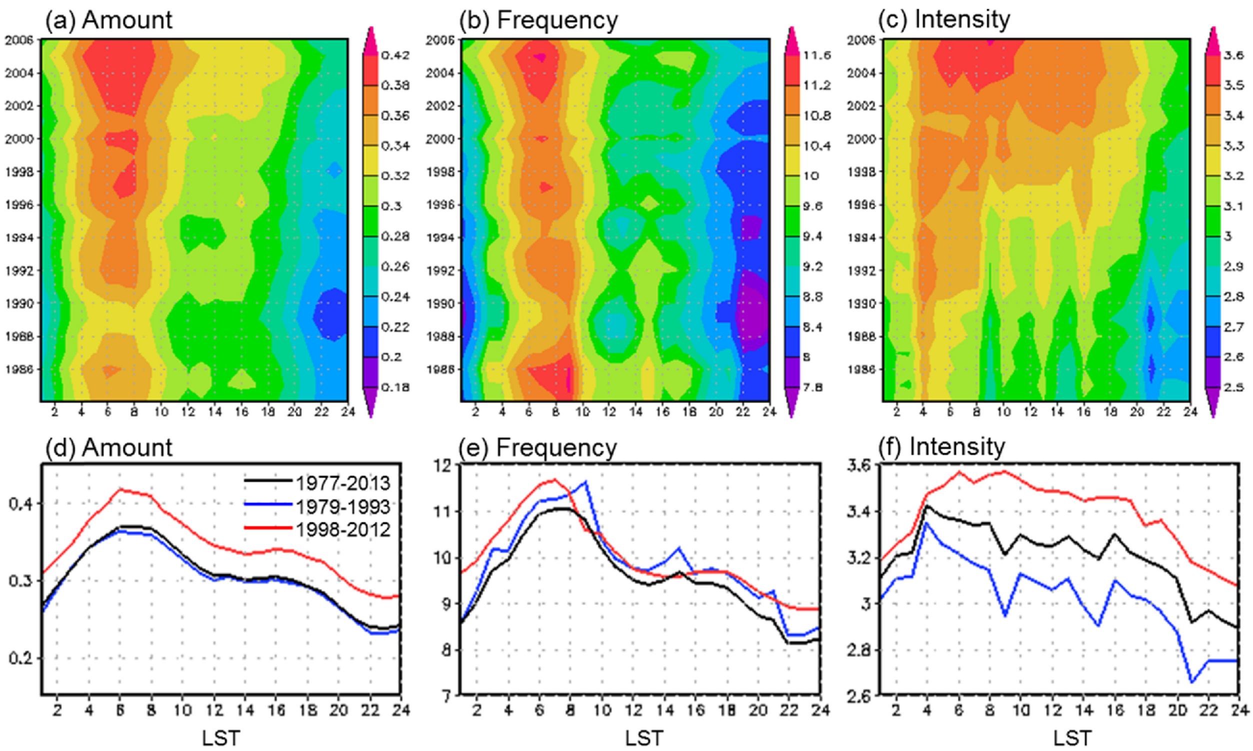

Fig. 6. The diurnal variations of JJAS hourly mean precipitation (mm h^{-1}) averaged over the 60 weather stations in Korea for 1977-2013. Upper panels show the year-LST cross-section of the 15-year moving average of JJAS hourly mean precipitation amount (mm h^{-1}), frequency (%) and intensity (mm h^{-1}). In these panels, y-axis denotes the middle year of the 15 years calculated. Lower panels show the climatological diurnal variations of the JJAS hourly mean precipitation amount, frequency and intensity for 37 years (black, 1977-2013) and 15 years (blue for 1979-1993 and red for 1998-2012), respectively.

be delayed with increasing rain rate (Jin, 2016). The amplitudes of diurnal variation of July and August are greatly larger than those of June and September, which is in good agreement with the monthly mean rainfall amount (Jin, 2016).

(2) Changes in diurnal cycle after the mid-1990s

The diurnal phase variations for individual years show the significant interannual variability with dominant periods of 2-5 years (Lee and Seo, 2008). However, both morning peak and afternoon peak have become stronger since the mid-1990s, which matches well with the increasing trend of daily mean precipitation amount (Jin, 2016). Based on the 15-year moving average of JJAS hourly precipitation over Korea for the period of 1977-2013 obtained from the area-averaged data over 60 weather stations (Figs. 6a-c), the intensified morning and afternoon peak is evident for the recent two decades. The precipitation intensity increases for all day, while the timing of morning peak occurs earlier and that of afternoon peak is delayed in precipitation frequency. The comparison of diurnal variations between the previous epoch (1979-1993) and recent epoch (1998-2012) indicates that the amplified diurnal variation is induced by the enhanced precipitation intensity and the shifted precipitation frequency is related to the changes in phase for the recent epoch (Figs. 6d-f). The increase of contribution of intense precipitation to total precipitation for the recent epoch mainly leads to the changes in phase and amplitude of diurnal variations of rainfall. The mid-1990s shift of the EASM could be responsible for the changes in diurnal variations since the associated local and remote thermodynamic and dynamic fields for the two epochs are also suddenly changed after the mid-1990s (Jin, 2016).

4. Contribution of typhoon to rainfall changes

a. Climatology

Tropical cyclone (TC) is a mesoscale tropical low pressure system that forms over the tropical and subtropical oceans and ends its life over land or the cold extratropical oceans. Annually, around 27 TCs (reaching tropical storm intensity, ≥ 17 m s^{-1}) form over the WNP basin, which is the highest among basins (Ho et al., 2004). TC is locally called typhoon in the countries adjacent to the WNP basin.

Though wind speed primarily defines typhoon, heavy rainfall also represents its meteorological characteristics. Compared to other tropical convective systems, TC generally induces more intense precipitation because it is a very well organized vortex, but its occurrence is much infrequent. Thus, it was difficult to estimate its contribution to total rainfall on a basin scale until the satellite observations of precipitation were accumulated.

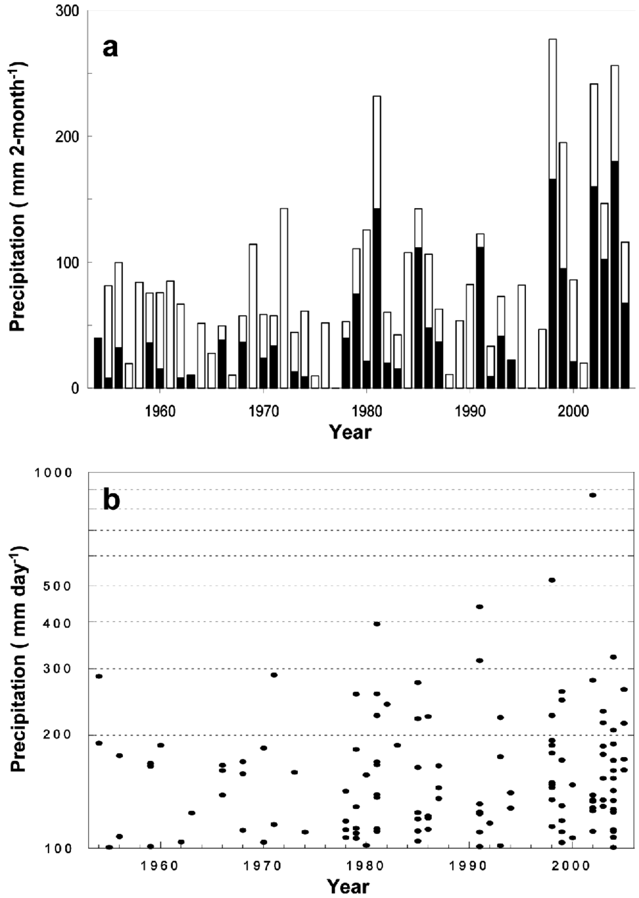

Fig. 7. (a) Time series of the accumulated rainfall averaged over the 12 stations in Korea during heavy rainfall events for August-September. Filled bar denotes the accumulated heavy rainfall influenced only by the landfalling TCs. (b) Precipitation intensity at stations that have a rate equal to or greater than 100 mm day^{-1} and are influenced by the landfalling TCs. Note that a log scale is used for the y-axis. This figure is adopted from Fig. 2 in Kim et al. (2006).

Satellite observations identified that rainfall accompanied by TC contributes 11-12% of the total annual amount of basin-wide rainfall over the WNP (Rodgers et al., 2000; Jiang and Zipser, 2010). At the sub-basin scales, the greatest contribution of TC-induced rainfall occurs around Taiwan, Hainan and the northeast of the Philippines, where the contribution increases to about 40% annually (Ren et al., 2006; Wu et al., 2007) and up to 60% for peak typhoon season (July-September; Chen et al., 2010; Kubota and Wang, 2009). This indicates that TC is a major phenomenon contributing to subtropical rainfall during the summer monsoon season.

The Korean Peninsula is also influenced by ~2-3 TCs every year. On average, the contribution of TC rainfall to total rainfall is ~10% during the typhoon season (June-November; Jiang and Zipser, 2010). Nevertheless, the TC-induced rainfall often causes flash flooding, resulting in a loss of lives and properties. Confined to the heavy rainfall (≥ 100 mm day^{-1}) events of the *second* Changma period (August-September), the TC contribution to the rainfall amount even increases to more than 40% based on the 50-yr climatology (Kim et al., 2006). This indicates that the TC landfall event has been one of the critical factors for heavy rainfall in Korea.

b. Interdecadal changes

(1) The mid-1970s shift

The global-scale climate regime shift occurred around the mid-1970s has also influenced on the local and regional influences of TCs as well as the TC activities (genesis, track, and intensity). Based on the historical best-track archive, the long-term changes in TC activities have been identified in many studies (e.g., Matsuura, et al., 2003; Ho et al., 2004; Park et al., 2008, 2011). However, the aspects of interdecadal variation are different among genesis, track, and intensity. The direct impact of the climate shift in the mid-1970s on the TC activities is manifested by the shift in the seasonal tracks (Ho et al., 2004). In response to the westward expansion of the North Pacific subtropical high in the mid-1970s, the more TCs have passed over the East Asian coastal seas (particularly around the Luzon Strait and Taiwan) during the recent epoch. However, no long-term signal toward enhancement has been found in terms of the frequency of landfalls over Korea. Rather, the half-century long-term change in landfalling TCs can be characterized by the approaching direction shifted from the west-southwest to the south-southwest (Choi et al., 2010).

Concurrent with the mid-1970s climate shift, both the number of heavy rainfall events (≥ 100 mm day^{-1}) and the accumulated heavy rainfall show interdecadal upswing shifts for the *second* Changma period (August-September) in Korea (Kim et al., 2006). This abrupt change is almost explained by the contribution of landfalling TCs. Namely, the interdecadal shift in the heavy rainfall amount in the *second* Changma period could not be found without the TC contribution (Fig. 7). In the previous epoch before the mid-1970s, the TC contribution was about 25%, but during the recent epoch the contribution has increased by a factor of two (i.e., more than 50%). This means that the TC landfall has become more critical for the rainfall amount of the *second* Changma since the mid-1970s. The plausible mechanism to explain this interdecadal change is an enhanced interaction of the TC and upper-tropospheric trough as a result of the southward shift of the subtropical westerly jet (Kim et al., 2006). With the background state after the mid-1970s, the TCs approaching Korea would have earlier chances to interact with the midlatitude baroclinc environment. The observed composite features of the upper- and low-tropospheric circulations at landfall over Korea reveal the stronger upper-tropospheric outflow jet and the divergence over the downstream side of the midlatitude westerly trough as well as the stronger convergence of the lower-tropospheric moisture flux in Korea (see Fig. 4 of Kim et al., 2006).

(2) The mid-1990s shift

Recently, Choi et al. (2017) further indicated that the distinct

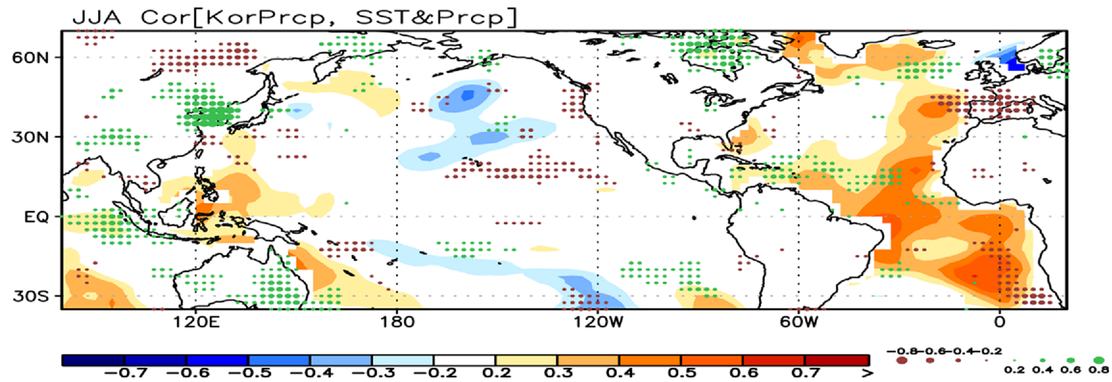

Fig. 8. Correlation maps of June-July-August (JJA)-mean precipitation (dotted) and SST anomalies (shaded) with respect to the Korean precipitation index (JJA-mean precipitation anomalies averaged over 120-130°E, 35-40°N) for the 1979-2010 period. Correlation coefficient of 0.34 corresponds to statistical significance at the 95% level with 30 degrees of freedom based on the two-sided Student's t-test. This figure is adopted from Fig. 1 of Ham et al. (2016).

change in TC influence on the August rainfall occurred around the mid- or late-1990s attributable to the changes in the shape of the WPSH associated with the recent global warming hiatus. Differently from the mid-1970s shift with an insignificant TC frequency change, the frequency of TC influence on the August rainfall became higher during 1998-2012 period than that during 1975-1997. During the recent epoch, the averaged frequency is 2.7, but that is 1.3 during the previous epoch. Accordingly, the number of rainy days and total rainfall amount in August have significantly increased during the recent epoch.

The changes in the TC influence on the August rainfall occurred during the mid-1970s and the mid-1990s can be better understood in context of the large-scale climate shifts that will be discussed in the next section.

5. Possible Mechanisms for the decadal changes

a. The mid-1970s shift

(1) Warming of tropical IO-WP warm pool SST

It has been suggested that one of key factors in the changes of Changma and EASM occurred around the mid-1970s is robust warming of the mean SST over the tropical IO and WP. Especially, many previous studies have empathized that the warming of tropical IO SST should strengthen the ENSO-EASM relationship (e.g., Ding et al., 2010; Xie et al., 2010; Yun et al., 2010; Kosaka et al., 2013). The warming of tropical IO SST tends to induce a baroclinic Kelvin wave into the Pacific and Ekman divergence in the WP, which consequently produces suppressed convection over the WNP and anomalous WPSH. The warming of tropical IO SST tends to persist until the late summer, thereby resulting in strengthened impacts of IO SST anomaly on the EASM (Xie et al., 2010). Ding et al. (2010) further indicated that the northern IO (Indian Ocean Dipole) has strengthened (weakened) its influence on the EASM after the mid-1970s.

(2) The role of tropical Atlantic Ocean

The analysis of the millennial-scale glacial data suggests that the East Asia monsoon system is likely to link with the climate variation over the Atlantic (Porter and An, 1995; Vandenberghe et al., 2006; Sun et al., 2012; Liu et al., 2013; Li et al., 2015). The slowdown of the Atlantic Meridional Overturning Circulation (AMOC) can supply dust to the Loess Plateau and a reduction in summer monsoon precipitation over East Asia (Sun et al., 2012). The analysis of the observational data after the 20th century also exhibits the consistent role of the Atlantic SST over the East Asian monsoonal variation (Linderholm et al., 2011; Wang et al., 2013). Wang et al. (2013b) mentioned that the SST warming over the northern Atlantic related to the Atlantic Multidecadal Oscillation (AMO) corresponds to the suppressed rainfall in the tropical central Pacific and easterly anomalies over the WP and westerly anomalies over the rest of the northern tropics (from 120°W to 100°E) (Ham et al., 2013a, 2013b; Hong et al., 2013), which enhances the Northern Hemisphere summer monsoon through the intensification of WPSH.

While most of previous literatures about the East Asian monsoon are focused on the monsoon over China, Ham et al. (2016) recently found a robust positive relationship between the tropical Atlantic SST and precipitation variability over the Korean peninsula during the boreal summer season. Figure 8 shows the correlation maps of June-July-August (JJA)-mean precipitation and SST anomalies with respect to the Korean precipitation for the 1979-2010 period. It clearly shows that the Korean summer precipitation is highly correlated to the tropical Atlantic over 30°S-30°N. Ham et al. (2016) argued that the warm tropical Atlantic SST leads to the intensification of the Philippine anticyclone associated with the easterlies over the tropical WP, which is a key to the tropical Atlantic-Korea teleconnection.

This tropical Atlantic-Korea teleconnection exhibits a strong decadal modulation. Figure 9 shows the 15-yr moving correlation between the Korean precipitation and the tropical

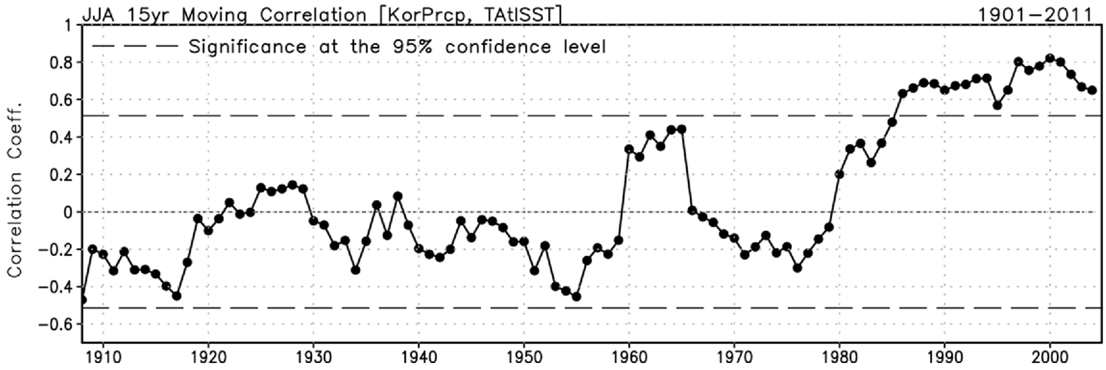

Fig. 9. The 15-yr moving correlation between the JJA Korean precipitation and the tropical Atlantic SST anomalies defined as the area-averaged SST anomalies over the 80°W-20°E, 30°S-30°N during 1900-2011. The dashed line denotes the 95% confidence level with two-sided student t-test, and the linear-trend within the 15-yr window is removed before calculating correlation.

Atlantic SST index defined as area-averaged SST anomalies over the 80°W-20°E, 30°S-30°N during 1900-2011. As shown in Fig. 9, the strong positive relationship is shown after the mid-1980s; on the other hand, the negative correlation is also shown during the mid-1910s, mid-1950s, and mid-1970s, which indicates that an abrupt decadal modulation occurred in the tropical Atlantic-Korea teleconnection. Especially, the correlation between the tropical Atlantic and the Korean precipitation increases systematically from mid-1970s, which eventually exhibits a significant positive value after mid-1980s. The maximum positive correlation around 2000 reaches up to 0.8, which explains about 65% of total precipitation variability over the Korea. The recent background change might play critical roles in the recent changes in the tropical Atlantic-Korea teleconnection during boreal summer season (McGregor et al., 2014; Chikamoto et al., 2015).

b. The mid-1990s shift

(1) Characteristics in the EASM mean change

Recently, the mid-1990s shift of the EASM including Changma as its regional component has been recognized (Kwon et al., 2005; Kwon et al., 2007; Lu et al., 2011; Xiang and Wang, 2013; Yim et al., 2014). The EASM undergoes decadal change in the three distinctive time scales, which are decadal, inter-annual, and intraseasonal scales. Spatial patterns of the decadal change in the strength of the East Asian subtropical jet for summertime are displayed in Fig.10a. The similar changes in zonal wind at other levels are also significant. Figure 10a also shows an abrupt increase in summer-mean precipitation in the southeastern part of China after the mid-1990s. Accordingly, decadal variations in the dynamic variable of zonal wind and the thermodynamic variable of precipitation amount seem to be dynamically linked for the summertime in East Asia. As a matter of fact, such a circulation change could be understood as a barotropic response to steady forcing (Fig. 10b). These results imply that an anomalous heating due to the increased precipitation in the

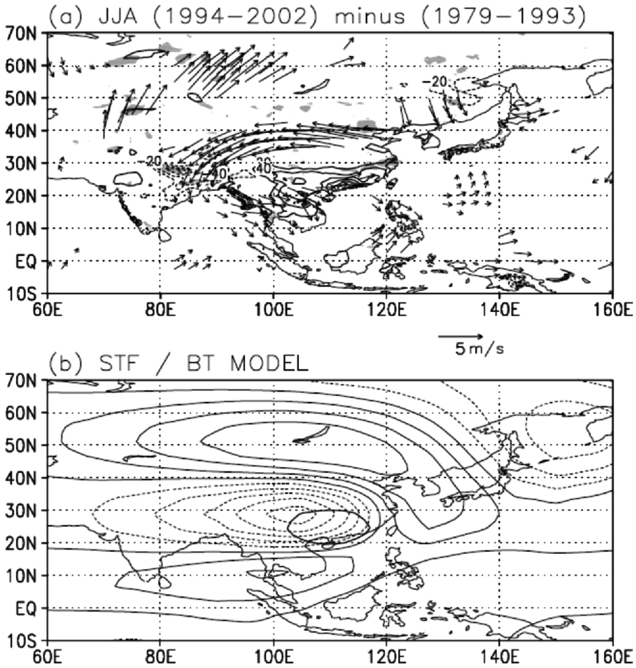

Fig. 10. (a) Difference of June-July-August (JJA)-mean precipitation (CRU) and difference of JJA-mean 200 hPa horizontal winds (ECMWF) between the periods 1979-1993 and 1994-2002. Shaded areas for precipitation represent a confidence level of 95% by the Lepage test. Plotted arrows are significant at 95% confidence level. Contour unit is mm $month^{-1}$ and arrow unit is $m\,s^{-1}$. (b) Stream function anomalies as a barotropic response due to a steady divergence forcing over the region (100E-120E, 20N-30N) under 500 hPa climatological mean winds based on observations (ECMWF) during 1958-2002. Thick solid closed lines indicate divergence forcing. Contour interval is $1.0 \times 10^5\ m^2 s^{-1}$. The maximum value of the half-period sinusoidal divergence forcing is $1.0 \times 10^{-6}\ s^{-1}$. This figure is adopted from Fig. 2 of Kwon et al. (2007).

southeastern part of China could give rise to a significant decrease of the Asian subtropical jet strength. The typhoon activity in the WP is a candidate for the causes of the summer precipitation increase over the southeastern part of China after

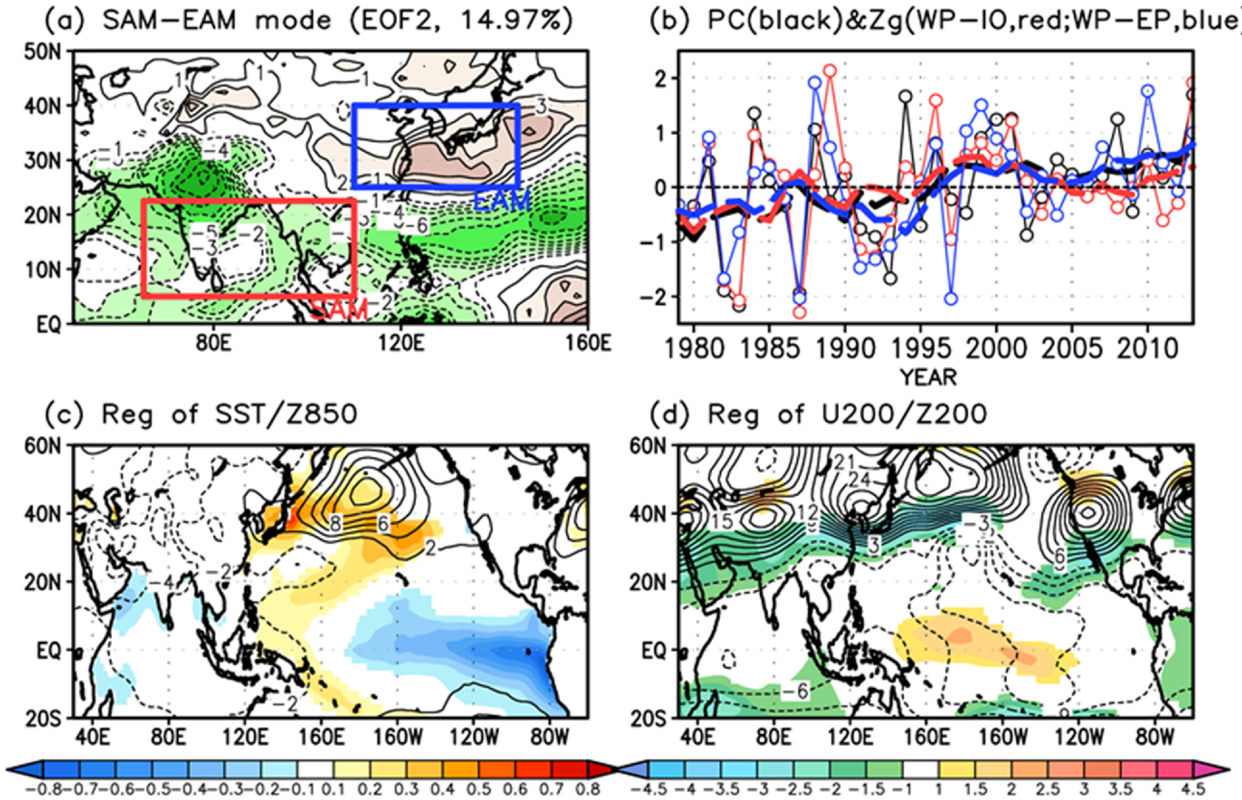

Fig. 11. (a) Spatial patterns of the second EOF mode for the June-July OLR anomaly. (b) Time series of its associated PC, WP-EP_zg index, and WP-IO_zg index during the period from 1979 to 2013. Here, WP-EP_zg (WP-IO_zg) index is defined as the SST difference between WP [20°S-20°N, 120°E-160°E] and EP [10°S-10°N, 160°W-120°W] (IO [20°S-20°N, 50°E-100°E]). Dashed lines in (b) denote the 7-yr running averaged PC time series and tropical SST gradient indices, respectively. (c) Regression of simultaneous SST (shading) and geopotential height at 850 hPa (contours) against the PC time series. (d) Same as (c), but for zonal wind and geopotential height at 200 hPa. Shading in (c) and (d) is only shown for SST and zonal wind anomalies significant above the 90% confidence level. This figure is adopted from Yun et al. (2014).

the mid-1990s (Kwon et al., 2007). This distinct increase in typhoon activity for the two epochs is one of evidences for a significant climate shift in the mid-1990s that should be also related to the increase of TC influence on the August rainfall in Korea.

(2) The role of tropical SST pattern in the EASM mean change

It has been suggested that the mid-1990s EASM shift is related to the recent global warming hiatus characterized by a La Nina-like cooling pattern and the negative phase of the Pacific Decadal Oscillation (Weller et al., 2016). Ueda et al. (2015) showed that the tropical SST dipole pattern (Indo-Pacific warm pool warming and eastern Pacific cooling) is responsible for pronounced regional anomalies in the decreased East Asian rainfall with increased WIO and WP rainfalls. Based on model experiments, they suggested that the tropical pacific SST anomaly is a primary factor in enhancing convection over the WP region and consequently leads to the decreased EASM rainfall.

Recent studies have further emphasized the importance of the tropical zonal SST gradient between IO and Pacific Ocean on the WNP-EASM climate during recent few decades (e.g., Chen and Zhou, 2014; Yun et al., 2014; Zheng et al., 2014; He and Zhou, 2015). The SST gradient pattern is somewhat different from the global warming hiatus pattern previously discussed. Yun et al. (2014) showed that the strengthening of the zonal SST gradient tends to increase convection activity in the South Asian monsoon (SAM) but decrease in the East Asian monsoon (EAM) during June-July. Figure 11a displays the contrast between SAM and EAM represented by the second EOF mode of June-July convection anomalies, which is also significantly related to the SAM-EAM contrast in both mean and extreme precipitations during June-July-August (Figs. 12a-b). The sub-monsoon contrast shows a significant relationship with the zonal gradient of the tropical SST (a La Nina pattern) and the northward shift of jet stream (Figs. 11c-d). Both sub-monsoon contrast and zonal SST gradient between WP, IO, and EP exhibit a clear rising trend (Fig. 11b). The strengthening of zonal SST gradient leads to enhanced convection over the Maritime continent and then provides a favorable condition for the northwestward emanation of Rossby

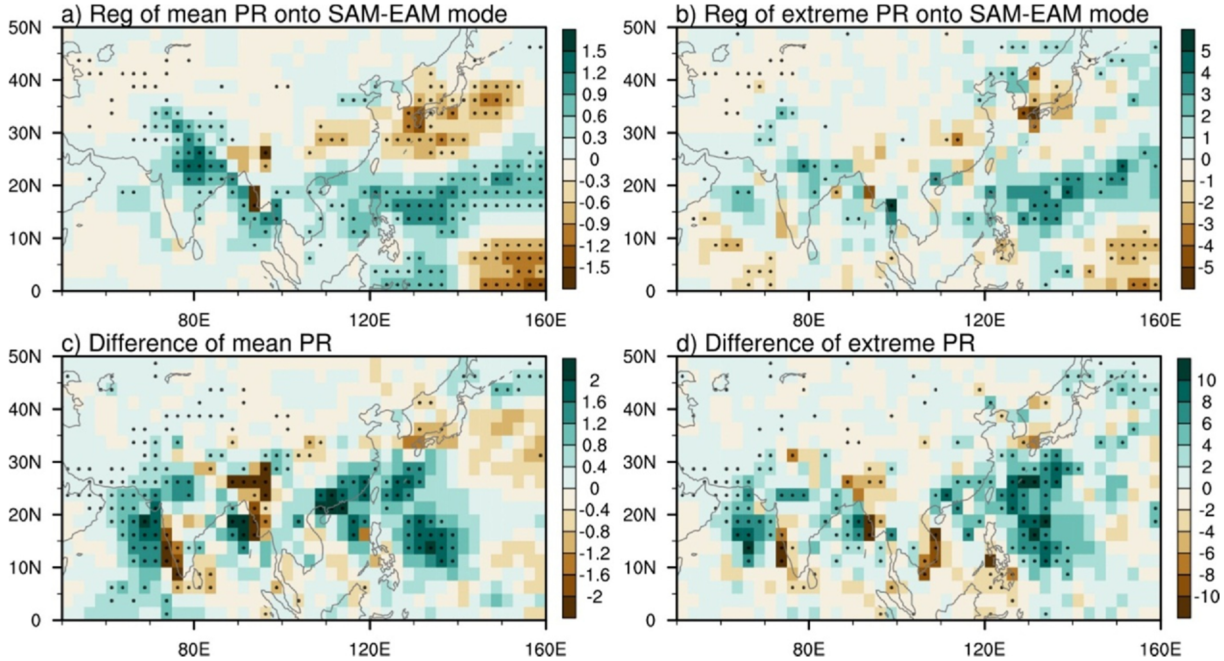

Fig. 12. (a-b) Regression of June-July (a) mean and (b) extreme precipitations against the SAM-EAM mode. (c-d) Difference in June-July (c) mean and (d) extreme precipitations between 1994-2013 and 1979-1993. The precipitation is analyzed using GPCP data. Extreme precipitation is calculated by the maximum of pentad precipitations during June-July. The dots indicate the significant value at the 90% confidence level.

waves. The resultant anomalous cyclone over the SAM region can effectively modulate the local Hadley circulation, resulting in the recent strengthening of the contrast between SAM and EAM. Preethi et al. (2017) reconfirmed the result of Yun et al. (2014) and further demonstrated that the western IO SST is related to the decreasing rainfall trend over Northern part of India and China, whereas the WP SST is associated with the increasing trend of rainfall anomalies over the southern part of India. Based on the CMIP5 model projection, He and Zhou (2015) also found that the simulated WPSH variability is tightly related to the zonal SST gradient between the IO and Pacific Ocean.

Figures 12c and d show the decadal difference of climatological June-July mean and extreme precipitations between 1994-2013 and 1979-1993 over the Asian-Australian monsoon region. Significant increase in both mean and extreme precipitations after the mid-1990s appears over the SAM and WNPSM, while a decrease is observed over the southern region of Korea and Japan. Note that the decadal change is quite similar to the regressed patterns against the SAM-EAM contrast (see Figs. 12a, b), reflecting the critical role of zonal SST gradient changes between IO, WP, and EP on the mid-1990s shift (Yun et al., 2014; Ueda et al., 2015).

(3) Changes in interannual EASM-ENSO relationship

It is of importance to note that interdecadal modulation in interannual variability of the EASM appears after the mid-1990s besides of the mean state changes (Kwon et al., 2005; Yim et al., 2008). Basically, the intensity of the EASM tends to be controlled by convective activity in association with the western North summer monsoon, namely Pacific-Japan pattern (e.g., Nitta, 1987; Kosaka and Nakamura, 2006; Wang et al., 2013a). There exist distinctive differences in the teleconnection pattern due to the western North Pacific convection in summertime before and after the mid-1990s (Kwon et al., 2005). While the convective precipitation pattern is related to eastern Pacific ENSO before the mid-1990s, it is more linked to the central Pacific ENSO during the recent epoch (Yim et al., 2008; Fan et al., 2013; Lee et al., 2014a).

It was noted that the WNP-EASM variability after the mid-1990s is more strongly regulated by the tropical dipole SST pattern between CP and WP (or Maritime continent) with 2-3-year periodicity, which is coincident with the developing ENSO phase (Chen and Zhou, 2014; He and Zhou, 2014; Lee et al., 2014a). The cooling of tropical CP SST is responsible for the enhanced WPSH variability and EASM rainfall via modulation of the Walker circulation and local Hadley circulation (Wang et al., 2013a), which creates a synergetic effect with the warming of tropical WP SST (Chen and Zhou, 2014; He and Zhou et al. 2015; Yun et al., 2015). On the other hand, before the mid-1990s, the WNP-EASM variability is more related to the tripole SST pattern between western IO, WP, and EP in relation to the decaying ENSO, which shows 4-5-year periodicity (Chen and Zhou, 2014; Lee et al., 2014a). It should be also noted that the warming of tropical IO SST among the tripole SSTs is the most important factor on EASM variability before the epoch, while after the mid-1990s, the combined effect between CP cooling and WP warming acts as a primary factor in modulating the EASM in intensity and periodicity. However, the effect of the dipole SST pattern on the EASM rainfall appears to be somewhat in conflict (Chen and Zhou, 2014; Yun et al., 2014; Ueda et al., 2015; Preethi et al., 2017): enhanced rainfall on the interannual timescale (e.g., Chen and Zhou, 2014) but suppressed rainfall on the decadal timescale (e.g., Ueda et al., 2015). The controversy in its effect on the EASM rainfall may be in part attributable to different air-sea interaction in the IO-WP warm pool (Yun et al., 2015), which will be further investigated in the future work.

(4) Changes in EASM intraseasonal variability

The decadal change in background mean state (Kwon et al., 2007) also leads to a shift of the large-scale interaction (Wu and Wang, 2002; Kwon et al., 2005), the boreal summer intraseasonal oscillation (BSISO) characteristics, and the phase-locking of EASM to the calendar months. Climatologically, convectively active monsoon rain bands associated with the EASM initiates in May around 20^{o}N, then makes northward propagation from June to July. The continuous rain spell is known as Mei-yu, Baiu, and Changma in China, Japan, and Korea, respectively. Tomita et al. (2011) found that Baiu front is suddenly shifted northward around the mid-1990s associated with decadal changes in atmospheric circulation changes of the WNPSM (Tomita et al., 2013). The phase speed of the northward movement is about 10-15^o mon^{-1} in the subtropics; however, it considerably slows down to ~5^o mon^{-1} in the mid-latitudes (northward of 30^{o}N). In accordance with the mid-1990s decadal change of the East Asian mean circulation, BSISO activity strengthened in the early 2000s, but the northward-propagating phase speed reduced (Yamaura and Kajikawa, 2016). On the other hand, the northern end of mid-latitude realization of the EASM, Changma, experienced earlier onset about 15 days (from early-mid-July to late-June) in late-1990s-early-2000s in comparison to 1980s-mid-1990s (Kim et al., 2011). The monsoon break period in early August that separated monsoon rain band-related precipitation from subsequent late-summer rainfall over the Korean peninsula also disappeared during the later period. It has been speculated that the altered intraseasonal variability (Kajikawa et al., 2009) and enhanced convective activity over the South China Sea/ Philippines Sea (Kajikawa and Wang, 2012) brought more moisture as well as increased tropical cyclone passage into the northeast Asian region during the late-1990s-early-2000s (Kim et al., 2011). In the recent decade, however, the BSISO activity again has weakened and the phase speed has accelerated (Yamaura and Kajikawa, 2016). The local Hadley circulation enhanced under warmer SST condition in the Maritime continents, which suppressed the southern tropical Indian Ocean BSISO.

6. Summary

It has been recognized that the characteristics of Changma including onset and withdrawal dates, diurnal cycle, intensity, and duration have exhibited considerable variability on long-term and interdecadal timescales in addition to interannual variability. This study reviews and further investigates distinct features on the long-term changes of Changma characteristics focusing on the underlying mechanisms for the changes mainly occurred around the mid-1970s and mid-1990s.

Associated with the global-scale mid-1970s shift, there are three distinct changes in Changma characteristics from the previous epoch (1958-1976) to recent epoch (1977-2012).

- Summer mean rainfall amount and the number of heavy rainfall occurrence from June to September have increased in association with intensification of moisture convergence and convective activity over Korea attributable to the sudden increase in anomalous anticyclonic circulation over the central-eastern Asia.
- The dry spell between the Changma and *second* Changma has become shortened mainly attributable to the significant increase in August rainfall. The recent increase in August rainfall may be contributed by the enhanced interaction of landfalling typhoons and midlatitude baroclinic environment.
- Linkage of interannual variability of Changma rainfall to the WNPSM and WPSH variability has enhanced.

Two possible mechanisms on the mid-1970s shift have been suggested. First, the robust warming of mean SST over the tropical IO and WP warm pool after the mid-1970s possibly plays a crucial role in the Changma and EASM changes by strengthening the ENSO-WNP-EASM relationship. Especially, the warming of tropical IO SST tends to induce a baroclinic Kelvin wave into the Pacific and Ekman divergence in the WP which consequently produces suppressed convection over the WNP and the anomalous WPSH. Second, the tropical Atlantic SST has become an important factor in Changma interannual variability since the mid-1970s. The simultaneous correlation between the tropical Atlantic SST and Korean summer rainfall has increased systematically since the mid-1970s and exhibited a significant positive value mainly after the mid-1980s. The maximum positive correlation around 2000 reaches up to 0.7, which explains about 50% of total rainfall variability over Korea.

Associated with the mid-1990s EASM change, considerable changes in Changma characteristics from the previous epoch (1979-1993) to the recent epoch (1994-2013) are also observed as follows.

- The summer rainy period has lengthened after the mid-1990s mainly due to the delay of the withdrawal of the *second* Changma.
- The number of dry days as well as the occurrence of heavy rainfall has increased, indicating an increase in the extreme climate event during summer.
- The dry spell between the two rainfall peaks has become further shortened mainly in association with the increase of August rainfall. The shortening of the dry spell between the two peaks is more obvious over the middle part (19 stations) than the southern part (26 station

including Jeju island) of Korea.

- The frequency of TC influencing August rainfall has increased from 1.3 in the previous epoch to 2.7 in the recent epoch, which is attributed to the westward shift of WPSH and the enhanced interaction of landfalling typhoons and midlatitude baroclinic environment.
- Both morning and afternoon peaks in Changma rainfall diurnal cycle have become stronger with a link to the increasing trend of daily mean rainfall amount. The rainfall intensity tends to increase for all day, whereas the timing of morning peak occurs earlier and that of afternoon peak is delayed during the recent epoch than during the previous epoch.

Two tropical SST patterns have been proposed as the key factor of the mean changes in Changma and EASM after the mid-1990s. The first is the tropical SST dipole pattern characterized by the Indo-Pacific warm pool warming and the eastern Pacific cooling related to the recent global warming hiatus (a La Nina-like cooling pattern) and the negative phase of the Pacific Decadal Oscillation. The tropical SST dipole pattern can lead to a decrease in East Asian rainfall but an increase in WP rainfall. The second is the intensification of tropical zonal SST gradient characterized by the IO cooling, WP warming, and EP cooling. It is rather contradictory to the former. The strengthening of the zonal SST gradient is suggested to increase convective activity in the South Asian monsoon but to decrease convective activity in the EASM mainly during June-July.

Interannual variability of the Changma and EASM has also experienced an interdecadal shift after the mid-1990s. The WNP and EASM variability after the mid-1990s is more strongly modulated by the tropical dipole SST pattern between the CP and WP (or Maritime continent) with 2-3-year periodicity coincident with the developing ENSO phase. In particular, the cooling of tropical CP SST is responsible for the enhanced WPSH variability and EASM rainfall via modulation of the Walker circulation and local Hadley circulation. On the other hand, before the mid-1990s, the WNP-EASM variability is more related to the tripolar SST pattern between the western IO, WP, and EP in relation to the decaying ENSO, which shows 4-5-year periodicity.

Global warming and changes in aerosol forcing may contribute to the recent changes in EASM system. However, their relative contributions to Changma changes are still elusive and need further investigation. It is also interesting to note that JJAS precipitation anomaly in Korea during the last 4 years since 2013 has been decreased (Fig. 2). In 2016, JJAS precipitation anomaly was also below normal although intensification of Changma was expected in association with the decaying phase of El Nino and developing La Nina. A question is arising to whether another interdecadal shift in Changma characteristics is occurred around mid-2010 accompanied with the phase shift of PDO and AMO. However, it is hard to answer now due to the shortage of sample size we currently have.

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