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Interdecadal variability of summer rainfall in the late 1990s in the Korea and north China region

Jae-Won Choi *

College of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing, China

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ABSTRACT

This study analyzed the trend of increasing summer (June to August) rainfall in the Korea and North China region (35 - 40°N, 110 - 130°E) in the late 1990s. In order to investigate the causes of the increase in summer rainfall since 1998 in the Korea and North China region, we analyzed the differences in summer averages between 1998 - 2012 and 1981 - 1997. The analysis of the 850 hPa stream flows showed that the anomalous huge anticyclonic circulations were reinforced in the North Pacific and eastern Australia. In both hemispheres, the anomalous easterlies (anomalous trade winds) were reinforced from the equatorial central Pacific to the tropical western Pacific by the anomalous circulations, which was an anomalous circulation pattern that appeared in the La Niña years. As for the 200 hPa stream flows, the anomalous huge cyclonic circulations were also reinforced in both the South Pacific and North Pacific. These two anomalous circulations reinforced the anomalous westerlies in the equatorial central and western Pacific, leading to the increase in summer rainfall in the Korea and North China region beginning in the late 1990s that was associated with the La Niña pattern, which was connected to reinforcement in the Walker circulation. Recently in East Asia, the local Hadley circulation has been reinforced to induce upward flows in the equatorial western Pacific and mid-latitude region of East Asia that have descended in the subtropical western Pacific.

1. INTRODUCTION

The East Asian region, including Korea and China, is under the influence of the East Asian summer monsoon, and summer rainfall in East Asia is characterized by multi-time scale variations (Wang et al. 2005; Ding 2007) (Table 1). Among these variations, decadal variation is the most distinct (Li et al. 2003; Zhao and Nan 2006). Recently, many researchers have studied decadal and interdecadal variations in rainfall in China and East Asia (Simmonds et al. 1996, 1999; Hu 1997; Huang et al. 1999; Zhai et al. 1999; Chang et al. 2000; Gong and Ho 2002; Ding and Sun 2003; Sun and Chen 2003; Zhang et al. 2003; Zhou and Huang 2003; Yang and Lau 2004; Yu et al. 2004; Ha et al. 2005; Yu and Zhou 2007; Zhou et al. 2009; Li et al. 2010; Qian and Zhou 2014; Song et al. 2014; Yang et al. 2017a, b), finding clear interdecadal variations in summer rainfall in China over the past 50 years. Wang et al. (2000) argued that distinct decadal variation in dry and wet cycles existed in eastern China between 1880 and 2002, and there were no long-term trends in annual and seasonal rainfalls. Shi et al. (1995) mentioned that five decadal climate shifts existed between wet and dry episodes in eastern China during the last century. For example, 1902/03 was characterized by a climate shift from abnormal dry to abnormal wet, 1918/19 by a climate shift from abnormal wet to abnormal dry, 1930/31 by a climate shift from abnormal dry to abnormal wet, 1944/45 by a climate shift to abnormal wet, and 1964/65 by a climate shift to abnormal dry. In eastern China, decadal rainfall variations exhibit the characteristics of complex spatial distribution (Qin 2005). It was shown that there were distinct differences in rainfall among such regions as North China, the Yangtze River Valley, and South China on a decadal time scale. For example, the rainfall variation in North China often shows an opposite pattern from the rainfall variation in the middle and lower reaches of the Yangtze River. Sometimes the rainfall variation in South China shows the same pattern as that in North China. It was shown that eastern China experienced a

* *Corresponding author*
E-mail: jaewonchoi@nuist.edu.cn

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distinct decadal shift in its summer climate in the late 1970s. Based on the analysis of summer rainfall data in China in the period from 1951 - 1994, Huang et al. (1999) found a large change in summer rainfall between the 1970s and 1980s. In both the Yangtze River Valley and Huaihe River Valley, flood disaster events caused by excessive rainfall increased sharply in the late 1970s. Meanwhile, the rainfall distinctly decreased in the 1980s compared to the 1970s in both the southern and northern parts of China. Zhang and Wu (2001) examined rainfall data from 1958 - 1999 and showed that abnormally low rainfall, or droughts, existed in the climatic term in the Yangtze River Valley before the late 1970s. Chen (1999) analyzed a decadal climate variation of summer rainfall in North China and pointed out that two abrupt drying processes existed in North China during the period from 1951 - 1997. One period existed in the mid-1960s, while another period existed in the late 1970s, and the dry condition of the latter period had a greater scale and scope than the former period did. Chen et al. (1998) and Shi and Xu (2007) argued that both Northeast China and the lower and middle reaches of the Yangtze River recorded abnormally low rainfall in the 1960s and 1970s, and a decadal climate shift existed in the late 1970s. Both regions recorded more rainfall in the 1980s. On the other hand, both South and North China shifted from wet to dry in the late 1970s.

Many investigators, who studied the physical attributes of the decadal climate shift of summer rainfall in eastern China during the late 1970s from different angles, believed that the shift was associated with a range of decadal variations in other natural elements of the climate system, including such decadal variations as the 'decadal ENSO cycle' (Huang et al. 1999), thermal forcing of the Tibetan Plateau (Zhao and Chen 2001), the Pacific decadal oscillation (PDO) (Li and Xian 2003; Yang et al. 2004), the decadal cooling of the upper troposphere in the summer in eastern China (Yu et al. 2004), the decadal change of the surface temperature difference between the Northwest Pacific and East Asia in the spring, and the summer temperature difference in the middle and upper troposphere between the Asian continent and the northern Pacific (Zhao et al. 2007). Furthermore, other studies pointed out that the increased aerosol concentration caused by human activities in eastern China was a major cause of the decadal climate shift of summer rainfall in eastern China in the late 1970s (Xu 2001; Menon et al. 2002). All the mentioned studies shared the claim that the decadal variation of these physical elements was associated with the movement of the summer rain belt to the south, which caused the reduction of rainfall in the Yangtze and Huaihe River Valleys and in South and North China, which resulted in the weakening of the East Asian summer monsoon. Zhang et al. (2008) argued that a distinct decadal shift in the summer climate occurred in eastern China in the late 1980s. In relation to this decadal climate shift, it was shown that more rainfall occurred in the southern region of eastern China beginning in the late 1980s. Kwon et al. (2007) showed that there was a large-scale change due to the weakening of the upper-tropospheric wind in the East Asian region in 1993 and 1994 (93/94). Regarding the variation of rainfall in South China in 92/93, Wu et al. (2010) explained that the cause of rainfall variation was the changes in the sea surface temperature of the Indian Ocean and the Tibetan Plateau snow cover, which induced lower-tropospheric divergence in the East China Sea and the North China, respectively. Eventually, the subsequent convergence in South China was strengthened.

As a result, the time of the decadal climate shift for summer rainfall in the East Asian region varies by study. In this study, the decadal climate shift for summer rainfall in North China and the Korean Peninsula, and the cause of the shift, were examined using more recent data. North China and the Korean Peninsula are located in the same latitude band and these regions are significantly damaged by heavy rainfall during the summer rainy season. Therefore, investigation into the variation of summer rainfall in these regions is meaningful for the prevention of hydro-meteorological disaster and for providing seasonal forecasts.

Section 2 introduces the data and analysis method. Section 3 analyzes the time series for Korea and North China summer rainfall. Section 4 analyzes the cause of the decadal climate shift. Finally, section 5 provides a summary of the research.

Table 1. Characteristics of years of the regime shift, geographical distribution, and references in East Asia.

Region	Regime shift time	References
China and East Asia	Late 1990s	Simmonds et al. (1996, 1999), Hu (1997), Huang et al. (1999), Zhai et al. (1999), Chang et al. (2000), Gong and Ho (2002), Ding and Sun (2003), Sun and Chen (2003), Zhang et al. (2003), Zhou and Huang (2003), Yang and Lau (2004), Yu et al. (2004), Ha et al. (2005), Kwon et al. (2007), Yu and Zhou (2007), Zhou et al. (2009), Li et al. (2010) , Qian and Zhou (2014), Song et al. (2014), Yang et al. (2017a, b)
Eastern China	Mid 1960s	Shi et al. (1995), Wang et al. (2000), Qin (2005)
	Late 1970s	Huang et al. (1999), Xu (2001), Zhang and Wu (2001), Menon et al. (2002)
North China	Late 1980s	Zhang et al. (2008)
South China	Late 1970s	Chen et al. (1998), Chen (1999), Shi and Xu (2007)
	Early 1990s	Wu et al. (2010)

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2. DATA AND METHODS

2.1 Data

This study used the variables of geopotential height (gpm), zonal and meridional winds (m s^{-1}), air temperature (°C), and total cloud cover (%) data from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis from 1980 - 2014 (Kalnay et al. 1996; Kistler et al. 2001). This NCEP-NCAR reanalysis data consists of spatial resolution information, such as latitude and longitude 2.5° × 2.5° and 17 vertical levels. Also, the velocity potential consists of a grid box, including latitude and longitude 192 × 94 and 5 sigma levels.

In addition, the Climate Prediction Center's (CPC) merged analysis of rainfall (CMAP) data (Xie and Arkin 1997)—which have the same horizontal spatial resolution as the NCEP-NCAR reanalysis dataset—were used. The data are based on the monthly averages and are available from 1979 to the present. The CMAP data, which include global rainfall data, are derived by merging rain gauge observations, five different satellite estimates, and numerical model outputs.

The National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Monthly Sea Surface Temperature (SST) (Reynolds et al. 2002) was also used. The data have a horizontal resolution of 2.0° × 2.0° latitude-longitude and are available from 1854 to the present day.

In addition, the NOAA interpolated Outgoing Long-wave Radiation (OLR) data, retrieved from the NOAA satellite series, are available starting from June 1974 from NOAA's Climate Diagnosis Center (CDC). However, the data are incomplete, as there is a missing period from March to December of 1978. Detailed information about this OLR data can be found on the CDC website (http://www.cdc.noaa.gov) and in the study by Liebmann and Smith (1996).

2.2 Methods

This study used the Student's *t* test to determine significance (Wilks 1995). In the case in which two independent time series follow a *t* distribution and their time averages are denoted as $\overline{x_1}$ and $\overline{x_2}$, respectively, the test statistic is given by

$$t = \frac{\overline{x_1} - \overline{x_2}}{(s_1^2/n_1 + s_2^2/n_2)^{1/2}} \tag{1}$$

where S_1 and S_2 are standard deviations, and n_1 and n_2 are numbers of the two time series, respectively. From the above formula, if the absolute value of *t* is greater than the threshold values with a level of significance, the null hypothesis would be rejected at the α(× 100)% significance level.

Furthermore, statistical change-point analysis was applied to the time series in this study. This analysis method produces the *t* value, and it means that a climate regime shift exists in the year in which the absolute value of *t* is the largest. When statistical change-point analysis was applied to this time series, because this variable does not follow a Poisson distribution, we use a different method to detect climate regime shifts in the temperature or passage frequency series: using a log-linear regression model in which a step function is expressed as an independent variable. If the estimated slope is at least twice as large as its standard error, one may reject the null hypothesis (i.e., which the slope being zero) at the 5% significance level. For more information about this analysis, see Elsner et al. (2000), Chu (2002), and Ho et al. (2004).

As shown in Fig. 1, Korea and North China refers to the region of 35 - 40°N, 110 - 130°E. The reason that this region is selected is that all regions of South Korea and capital regions of China are included, which areas are very important. Northern China is susceptible to catastrophic floods, such as the Northern Chinese Famine of 1876-79 which killed about 13 million, 1938 Yellow River flood which killed up to 800000, 1887 Yellow River flood killed 900000, Chinese famine of 1942-43 killed 3 million and the Great Chinese Famine which killed tens of millions of Mandarin Chinese speaking peoples in Northern China and Sichuan (Li et al. 2015). In Korea, approximately 70 percent of all precipitation occurs from June to September (Kihl and Kim 2006). Therefore, study on summer rainfall variation for this region is important to reduce natural disaster by summer rainfall.

The Walker circulation index in this study is defined as the difference between the 500 hPa omegas that are area-averaged in the equatorial eastern Pacific (160 - 80°W, 5°S - 5°N) and in the equatorial western Pacific and eastern Indian Ocean (80 - 160°E, 5°S - 5°N). Furthermore, the local Hadley circulation index is defined as the difference between the 500 hPa omegas that are area-averaged in the equatorial western Pacific and eastern Indian Ocean (80 - 160°E, 0 - 10°N) and in the middle latitude region of East Asia (80 - 160°E, 20 - 30°N). For these two indices, refer to the study of Vecchi and Soden (2007).

Normalization in this study means dividing standard deviation by average.

3. TIME SERIES ANALYSIS OF SUMMER RAINFALL IN KOREA AND NORTH CHINA

Figure 2a shows the time series of normalized values for the area-averaged summer (June to August) rainfall in the Korea and North China region (35 - 40°N, 110 - 130°E). Overall, it shows distinct interannual and interdecadal variations. Furthermore, an increase trend for 32 years can be seen, which is significant at the 90% confidence level. This increase trend is clear in the mid-to-late 1990s, and it

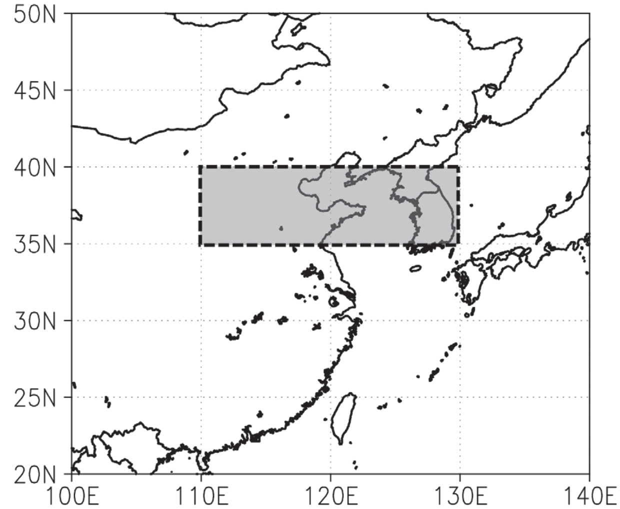

Fig. 1. Korea-north China summer (June to August, JJA) rainfall region (35 - 40°N, 110 - 130°E).

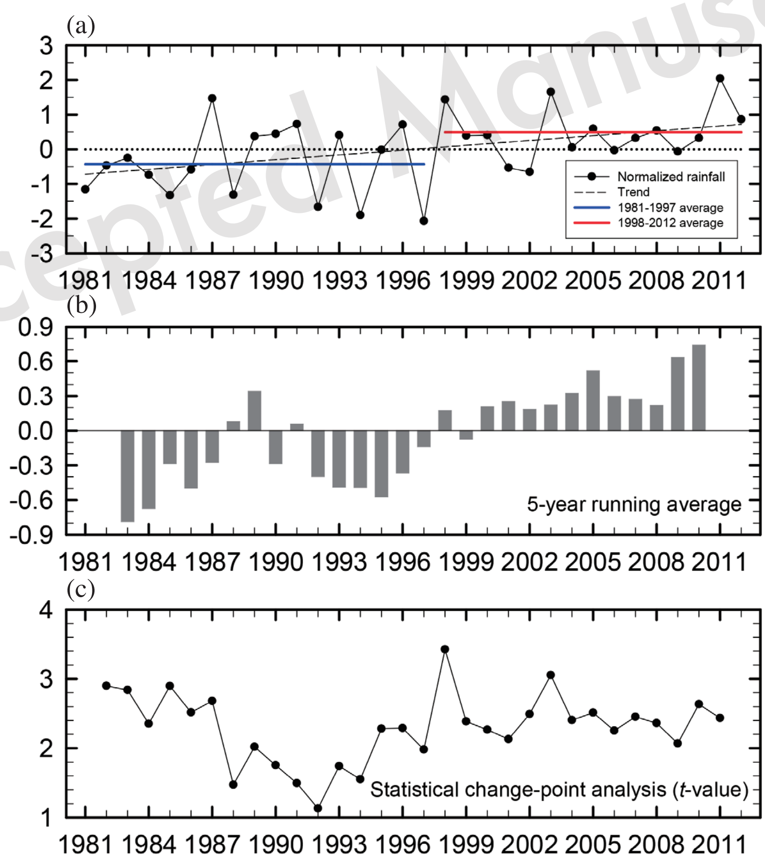

Fig. 2. Time series of (a) normalized Korea-north China summer rainfall, (b) its 5-year running average, and (c) statistical change-point analysis. In (a), blue, red, and dashed lines denote average rainfalls during the period of 1981 - 1997 and during the period of 1998 - 2012 and the trend of rainfall time series, respectively.

is more distinct in the time series of the 5-year running average (see Fig. 2b). From 1983 - 1997, the running averaged values were all negative with the exception of three years (1988, 1989, and 1991), and the running averaged values are all positive since 1998. In addition, statistical change-point analysis was applied to this time series to examine the existence of a climate regime shift in the time series for summer rainfall in the Korea and North China region in the 32-year period. The greatest *t* value existed in 1998 (see Fig. 2c). This indicates that there was a large change in the summer rainfall in the Korea and North China region around 1998. Therefore, the difference between the average for 1998 - 2012 and the average for 1981 - 1997 was analyzed to find the cause of the increasing summer rainfall in the Korea and North China region.

4. DIFFERENCES IN LARGE-SCALE ENVIRONMENTS BETWEEN THE 1998 - 2012 PERIOD AND 1981 - 1997 PERIOD

In this study, the differences in OLR, total cloud cover, and rainfall between the two periods were analyzed (see Fig. 3). First, in the OLR analysis, there are negative anomalies from the southwest to the northeast direction in the central south region of China, and these pass through Korea and the East China Sea to Japan (see Fig. 3a). Furthermore, negative anomalies are also distinct in the Maritime Continent. In contrast, there are positive anomalies from the equatorial eastern Pacific to the equatorial western Pacific. This indicates that summer convection was strengthened recently in the middle and low latitude regions of East Asia and the Maritime Continent, whereas convection was weakened in the equatorial eastern Pacific and the equatorial western Pacific regions. The spatial distribution in this OLR analysis shows an opposite pattern to the spatial distribution for total cloud cover (see Fig. 3b). There are positive anomalies from the central eastern coast of China to the Korean Peninsula, Japan, and the Maritime Continent, but there are negative anomalies from the equatorial tropical and subtropical central Pacific to the equatorial tropical and subtropical western Pacific. This indicates that the possibility of rainfall was higher recently from the central eastern coast of China to the Korean Peninsula, Japan, and the Maritime Continent, while the possibility of rainfall was lower from the equatorial tropical and subtropical central Pacific to the equatorial tropical and subtropical western Pacific regions. The spatial distribution in the rainfall analysis shows a similar pattern to the spatial distribution for the total cloud cover (see Fig. 3c). There are positive anomalies in the middle and low latitudes of East Asia and the Maritime Continent and negative anomalies in the equatorial Pacific.

The rainfall of East Asia is strongly linked to large-scale circulation across the Pacific (Huang et al. 1999; Qin 2005) and thus the difference in 850 hPa stream flows between the two periods was analyzed (see Fig. 4a). In general, the anomalous huge anticyclonic circulations were strengthened in the North Pacific region, and anomalous anticyclonic circulations were also strengthened in the eastern region of Australia in the Southern Hemisphere. Anomalous easterlies (anomalous trade winds) were strengthened from the equatorial central Pacific to the tropical western Pacific. This is an anomalous circulation pattern that appears in La Niña years and negative Pacific Decadal Oscillation. Yoon and Yeh (2010) found that when ENSO and PDO are in (out of) phase, the Eurasian-like pattern acts to enhance (reduce) the extratropics-related rainfall over northeast Asia, resulting in the strengthening (weakening) of the northeast Asian summer monsoon. Feng et al. (2014) showed that when ENSO is in (out of) phase with PDO, an anomalous tripolar (dipole) rainfall pattern exists in East China and WNPSH experienced a one-time (two-time) northward shift. Meanwhile, an anomalous cyclonic circulation formed in the Korea and North China region. As for the 200 hPa stream flows, anomalous cyclonic circulations were strengthened in the tropical central and western Pacific, and anomalous huge cyclonic circulations were also strengthened in the Pacific of the Southern Hemisphere (see Fig. 4b). Anomalous westerlies were strengthened by two such anomalous circulations in the equatorial central and western Pacific. In addition, anomalous cyclonic circulations were formed in the Korea and North China region.

To investigate the characteristics of global-scale atmospheric circulation, the difference in 200 hPa velocity potential between the two periods was analyzed (see Fig. 5). The center of convergence was located in the equatorial central Pacific, and the center of divergence was located in the northwestern sea of Australia. This indicates that the Walker circulation, by which the air current rises in the Maritime Continent and descends down in the equatorial central Pacific, was strengthened recently. In addition, there is a positive anomaly in the subtropical western Pacific and a negative anomaly in China and the Korean Peninsula. This indicates that the local Hadley circulation, by which the air current rises in the Maritime Continent and descends down in the subtropical western Pacific, was strengthened recently. Furthermore, atmospheric circulation was formed in which the air current rises in China and the Korean Peninsula and descends down in the subtropical western Pacific.

As stated above, the center of convergence was located in the equatorial central Pacific, and the center of divergence was located in the northwestern sea of Australia. This indicates that the Walker circulation, by which the air current rises in the Maritime Continent and descends down in the equatorial central Pacific, was strengthened recently. To investigate whether the recent increase of summer rainfall in the Korea and North China region is associated with the recently strengthened La Niña pattern, the time series for the normalized values of the area-averaged 850 and

200 hPa zonal winds in the Niño-4 region (5°S - 5°N, 160°E - 150°W) in summer and the time series for the normalized values of summer rainfall in the Korea and North China region were analyzed (see Fig. 6). First, the relationship between the normalized values of the 850 hPa zonal wind and the normalized values of summer rainfall in the Korea and North China region have a high negative correlation of -0.59 at the 99% confidence level (see Fig. 6a). This indicates that the summer rainfall increases in the Korea and North China region as the anomalous easterlies become stronger in the lower-level of the troposphere in the Niño-4 region, while the summer rainfall decreases as anomalous westerlies become stronger. Meanwhile, the relationship between the normalized values of the 200 hPa zonal wind and the normalized values of the summer rainfall in the Korea and North China region has a high positive correlation of 0.71 at the 99% confidence level (see Fig. 6b). This indicates that the summer rainfall increases in the Korea and North China region as the anomalous westerlies are strengthened in the upper-level of the troposphere in the Niño-4 region, while the summer rainfall decreases as the anomalous easterlies are strengthened.

To investigate whether the anomalous atmospheric circulation of the La Niña pattern was strengthened recently, the difference in the 500 hPa omega between the two periods was analyzed (see Fig. 7a). Negative anomalies are formed in the Maritime Continent, while positive anomalies are formed in the equatorial central and eastern Pacific. This indicates that the Walker circulation, by which the air current rises in the Maritime Continent and descends down in the equatorial central and eastern Pacific, was recently strengthened. Thus, the time series for the Walker circulation index and the time series for the normalized values of summer rainfall in the Korea and North China region were analyzed (see Fig. 7b). The Walker circulation index has shown a steadily increasing trend until recently, and this increasing trend is significant at the 90% confidence level. Furthermore, there is an in-phase relationship between the two variables, with a highly positive correlation of 0.65. This correlation is significant at the 99% confidence level. This indicates that the stronger the Walker circulation is, the higher the summer rainfall becomes in the Korea and North China region, while the weaker the Walker circulation, the lower the summer rainfall.

Figure 7a shows that it is not only the Walker circulation that is strengthened but also the local Hadley circulation. Negative anomalies are strengthened in the Maritime Continent, while positive anomalies are strengthened in the subtropical western Pacific. In the middle latitude region of East Asia, on the contrary, negative anomalies and the local Hadley circulation, by which the air current rises in the middle latitude region of East Asia and descends down in the subtropical western Pacific, are strengthened. To investigate whether the local Hadley circulation is actually associated with the variation of summer rainfall in the Korea and North China region, the time series of the local Hadley circulation index and the time series for the normalized values of summer rainfall in the Korea and North China region were analyzed (see Fig. 7c). The local Hadley circulation index showed an increasing trend until recently, and this increasing trend is significant at the 90% confidence level. Furthermore, there is a distinct in-phase relationship between the two variables with a high positive correlation of 0.59. This correlation is significant at the 99% confidence level. This indicates that when the local Hadley circulation is strengthened, the summer rainfall increases in the Korea and North China region.

To investigate whether the Walker circulation was actually strengthened recently, the difference between the two periods in terms of the zonal atmospheric circulation that was averaged for 5S° - 5°N was analyzed (see Fig. 8a). The results show that the anomalous Walker circulation, where the air rises in the equatorial Pacific and descends down in the equatorial central and eastern Pacific, was strengthened recently. For the difference in air temperature between the two periods, an anomalous warm air temperature was formed in the equatorial western Pacific, whereas an anomalous cold air temperature was formed in the equatorial central and eastern Pacific (see Fig. 8b). This is a typical vertical zonal distribution of air temperature that appears in the La Niña pattern. Furthermore, to investigate whether the local Hadley circulation was strengthened recently, the difference between the two periods was analyzed with regard to the meridional vertical atmospheric circulation, which is averaged for the longitude band of 110 - 130°E (Korea and North China region) (see Fig. 9a). As explained above, the local Hadley circulation, where the air rises from 10°S - 0° and descends down in 0 - 20°N, was strengthened recently. Furthermore, the air current rising from 20 - 30°N also descends down in 0 - 20°N. Thus, the characteristics of the zonal and meridional vertical atmospheric circulations imply that the recent increase in summer rainfall in the Korea and North China region is associated with the intensification of the Walker circulation and local Hadley circulation. Meanwhile, with regard to the difference in air temperature between the two periods, an anomalous warm air temperature was formed at 10°S - 10°N and 20 - 40°N, whereas an anomalous cold air temperature formed at 10 - 20°N (see Fig. 9b).

The summer rainfall in the middle latitude region of East Asia is greatly influenced by the western North Pacific subtropical high (WNPSH) (Wu and Zhou 2008; He and Zhou 2015; Huang et al. 2015; Liu et al. 2018). Thus, the conditions of the WNPSH for these two periods were analyzed (see Fig. 10). WNPSH here is defined as an area that has a value greater than 5875 gpm at 500 hPa. The WNPSH during the period from 1998 - 2012 is more developed to the northwest than the WNPSH during the period from 1981 - 1997. Thus, there is a possibility that warm and moist air

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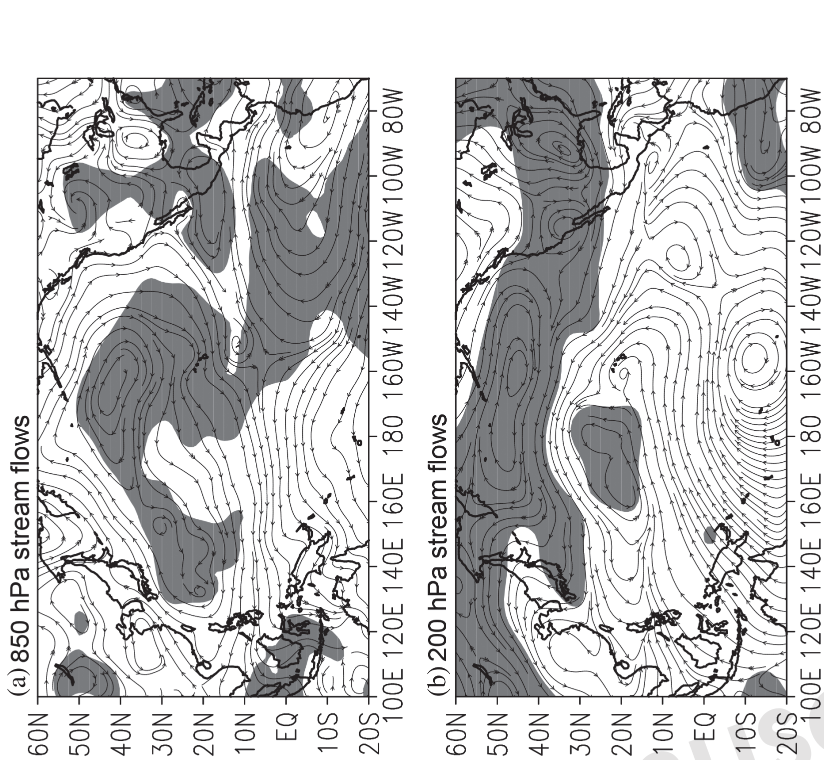

Fig. 4. Same as in Fig. 3, but for (a) 850 hPa and (b) 200 hPa stream flows. Shaded areas are significant at the 95% confidence level on geopotential height.

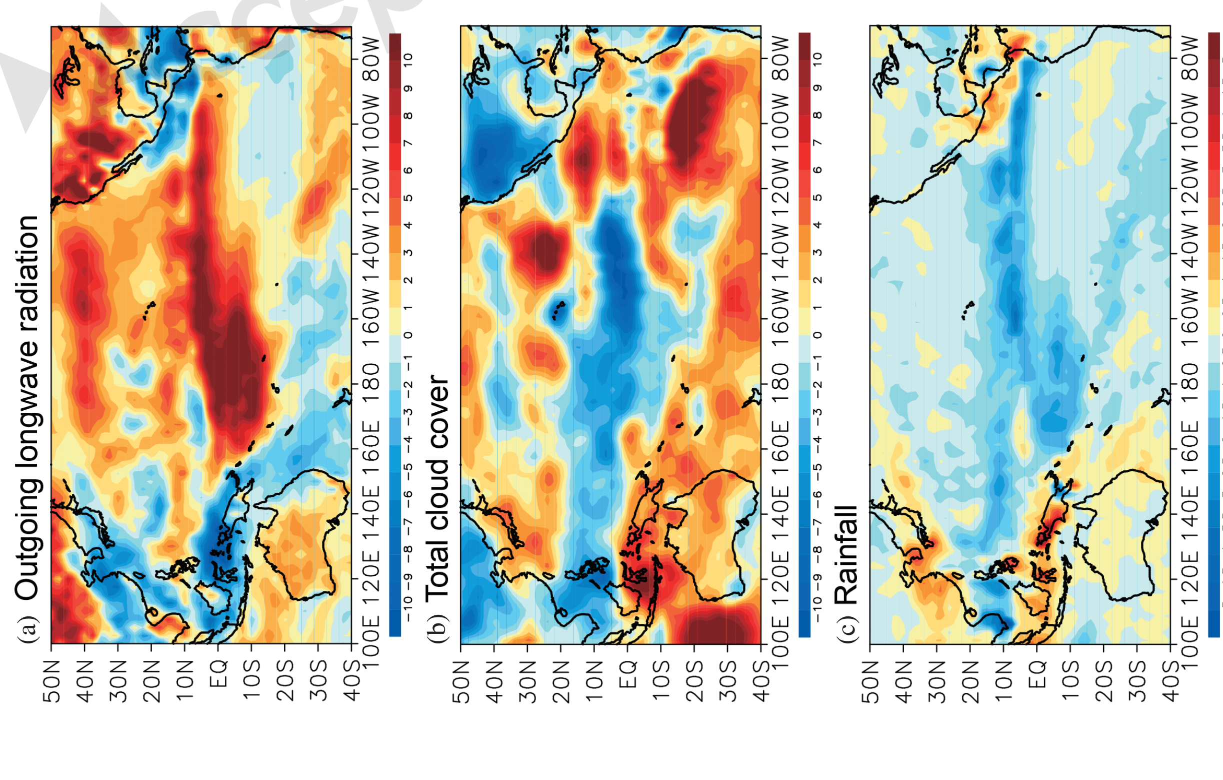

Fig. 3. Differences in (a) outgoing longwave radiation (OLR), (b) total cloud cover, and (c) rainfall between 1998 - 2012 and 1981 - 1997.

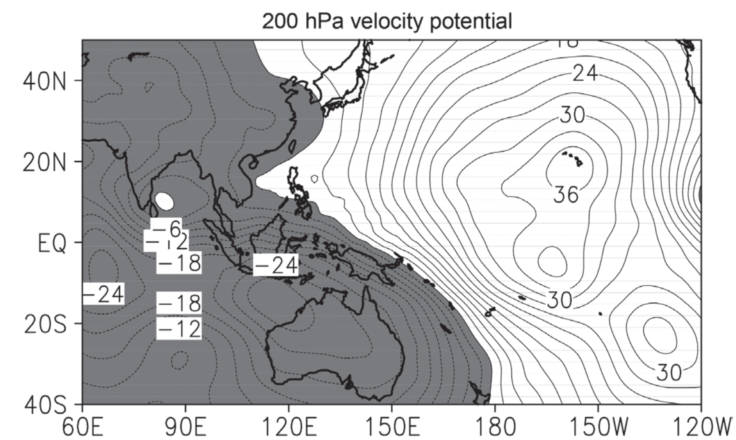

Fig. 5. Same as in Fig. 3, but for 200 hPa velocity potential. Shaded areas denote negative anomalies. Contour interval is 3 $m^2 s^{-1} 10^{-6}$.

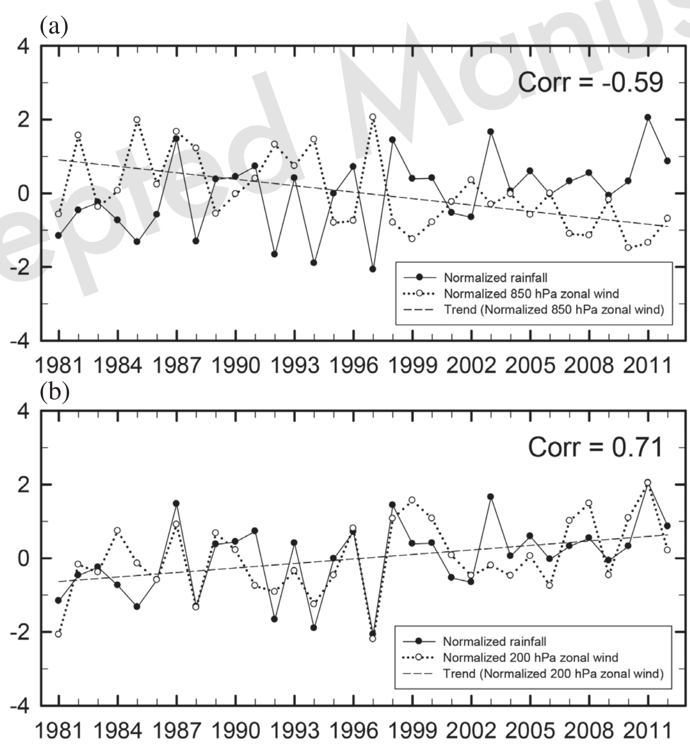

Fig. 6. Time series of (a) normalized Korea-north China summer rainfall (solid line with a closed circle) and normalized 850 hPa zonal wind averaged over Niño-4 region (5°S - 5°N, 160°E - 150°W) (dotted line with an open circle) and (b) normalized 200 hPa zonal wind averaged over Niño-4 region (dotted line with an open circle).

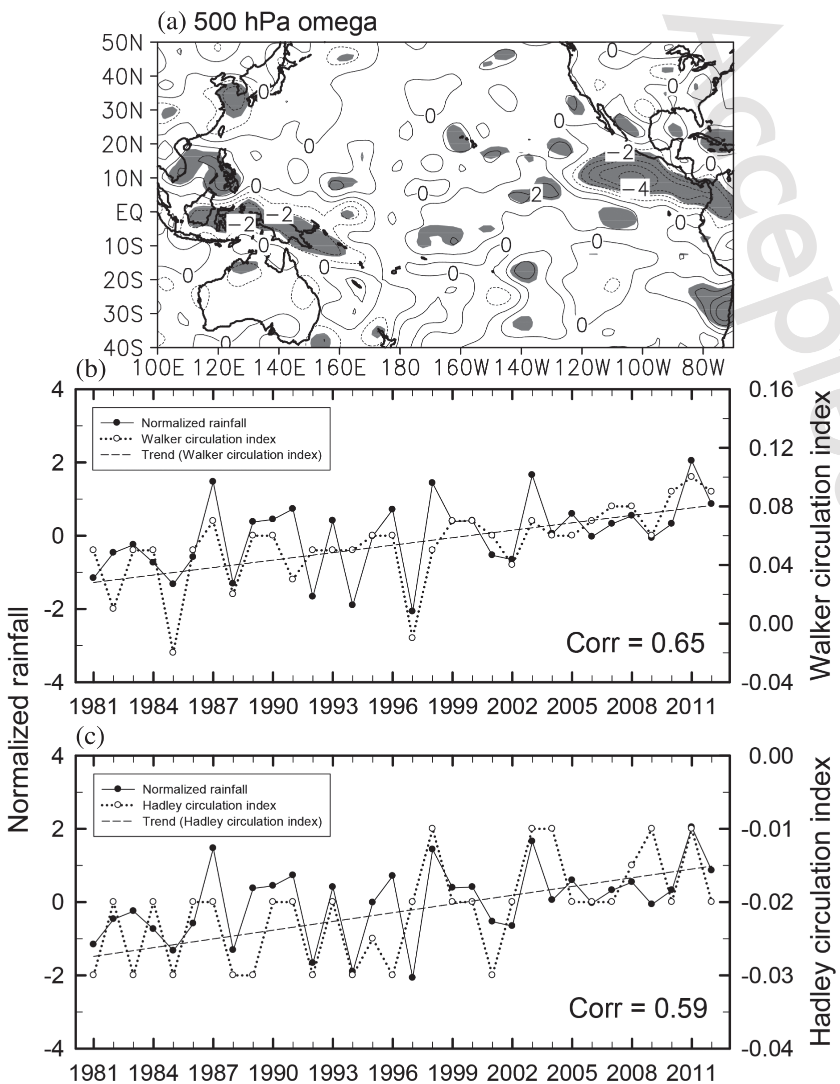

Fig. 7. Differences in (a) 500 hPa omega between 1998 - 2012 and 1981 - 1997. Time series of (b) walker circulation index and (c) hadley circulation index and their trends.

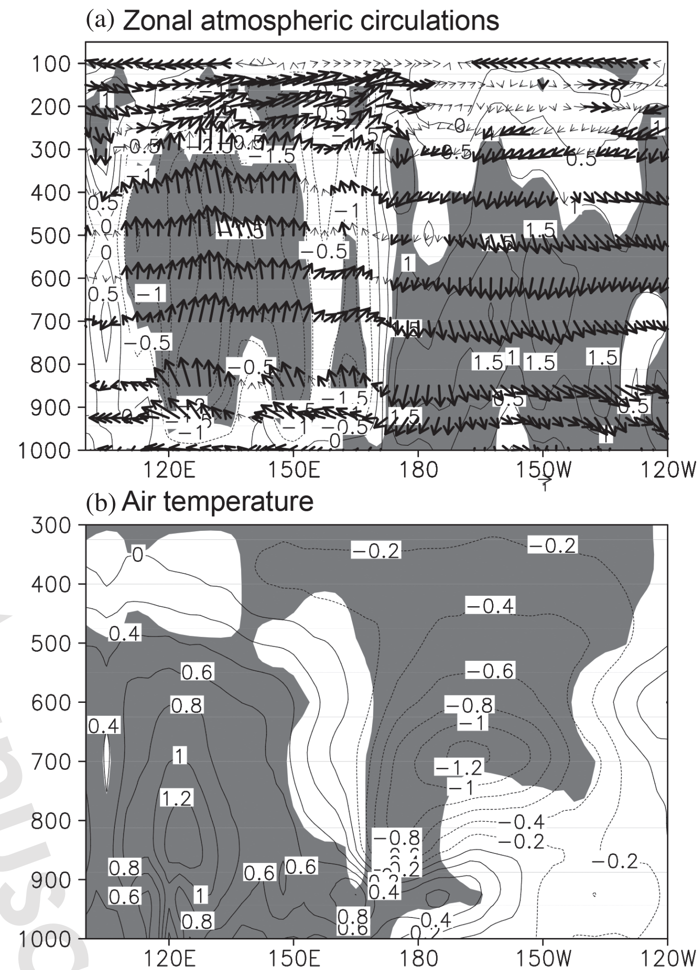

Fig. 8. Composite differences of longitude-pressure cross section of (a) vertical velocity (contours) and zonal circulations (vectors) and (b) air temperature averaged along 5S° - 5°N between 1998 - 2012 and 1981 - 1997 for JJA. The values of vertical velocity are multiplied by -100. Bold arrows and shaded areas are significant at the 95% confidence level. Contour intervals are 0.5^{-2} hPa s^{-1} for vertical velocity and 0.2°C for air temperature, respectively.

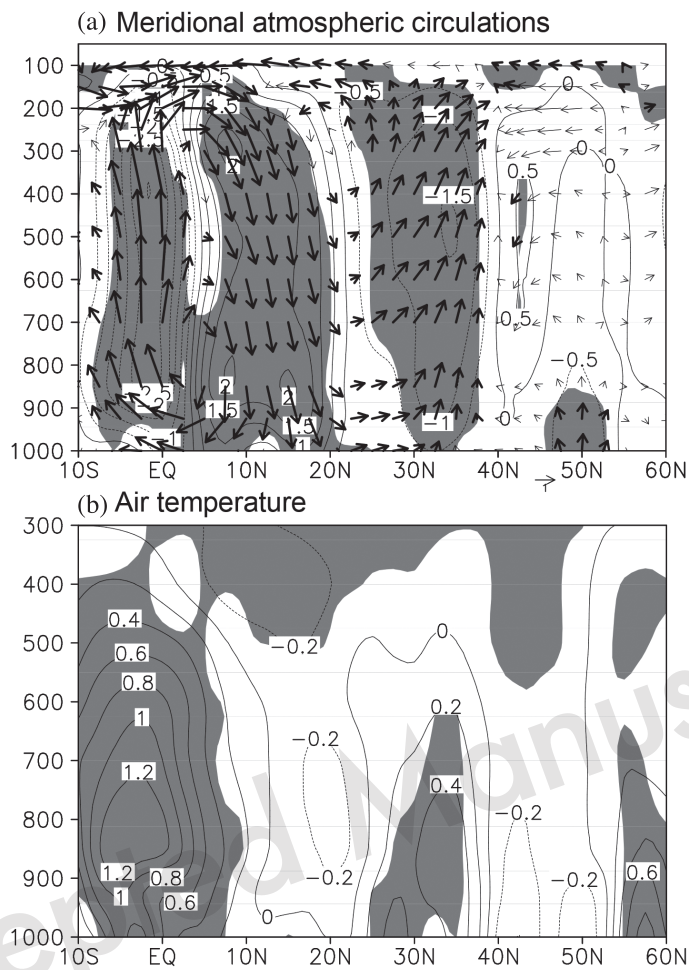

Fig. 9. Composite differences of latitude-pressure cross section of (a) vertical velocity (contours) and meridional circulations (vectors) and (b) air temperature averaged along 110 - 130°E between 1998 - 2012 and 1981 - 1997 for JJA. The values of vertical velocity are multiplied by -100. Bold arrows and shaded areas are significant at the 95% confidence level. Contour intervals are 0.5^{-2} hPa s^{-1} for vertical velocity and 0.2°C for air temperature, respectively.

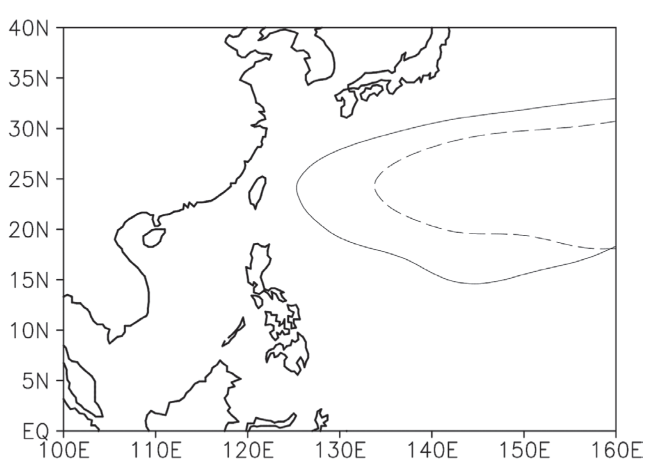

Fig. 10. Development extent of western North Pacific subtropical high (WNPSH) in 1998 - 2012 (solid line) and in 1981 - 1997 (dashed line) for JJA. Here, the WNPSH is defined as areas that are greater than 5875 gpm.

flows, which help the formation of rainfall, could have been supplied more to the Korea and North China region recently.

The upper troposphere jet stream is the main factor that strengthens upward flows. The upper-level jet can strengthen convergence to form upward flows, which can thereby induce precipitation (Liang and Wang 1998; Lau and Nath 2000). The location and intensity of the upper-level jet also influences the formation of rainfall. Thus, the conditions of the upper-level jet for the two periods were analyzed in this study (see Fig. 11a). Here, the jet axis is defined as an area in which the zonal wind speed is greater than 25 m s^{-1} at 200 hPa. The jet covered the Korea and North China region during the period from 1998 - 2012, whereas it was to the west of 110°E during the period from 1981 - 1997. In the lower-level of the jet streak, the formation of rainfall was easier because the upward flows were strengthened. Therefore, more rainfall could have formed in this region during the period from 1998 - 2012 when the upper-level jet was covering the Korea and North China region. The fact that the upper-level jet was stronger in the period from 1998 - 2012 can be verified by analyzing the difference in the 200 hPa zonal winds between the two periods (see Fig. 11b). Anomalous westerlies were strengthened from the central north region of China and passed through the Korean Peninsula to the northeast sea of Japan. This indicates that the upper-level jet was strengthened in this region during the period from 1998 - 2012.

To investigate whether the La Niña pattern actually intensified recently, the difference in SST between the two periods was analyzed (see Fig. 12a). Cold anomalies formed from the western coast of the USA to the equatorial central Pacific and on the western coast of Peru. In contrast, warm anomalies formed in the western North Pacific and the western South Pacific, indicating a typically strong La Niña pattern. Meanwhile, the correlation between SST and the summer rainfall in the Korea and North China region was analyzed (see Fig. 12b). The spatial distribution of the correlation coefficient is similar to the spatial distribution of the difference in SST between the two periods in Fig. 12a. In particular, there is a very high negative correlation near the western coast of Mexico and a high positive correlation in the south of the Bering Sea. As mentioned above, the reason for this is the intensification of the anomalous huge anticyclonic circulation in the North Pacific. Because the La Niña pattern was strengthened recently, the time series were analyzed between the area-averaged SST (15 - 25°N, 135 - 115°W) on the western coast of Mexico and the summer rainfall in the Korea and North China region (see Fig. 12c). The area-averaged SST for the western coast of Mexico had decreased until recently, and this decreasing trend is significant at the 90% confidence level. Furthermore, these two-time series are clearly out of phase, and there is a high negative correlation of -0.58 between the two variables. This negative correlation is significant at the 99% confidence level. This indicates that when the SST on the western coast of Mexico increases, the summer rainfall in the Korea and North China region decreases, and when there is a decrease in the SST, there is an increase in the summer rainfall.

As described in the above analysis, the existence of interdecadal variations in the late 1990s was examined with indices related to the variation of summer rainfall in the Korea and North China region (see Fig. 13). Statistical change-point analysis was applied to these time series. As a result, the greatest *t* value in the time series existed in 1998 (not shown). Since 1998, the area-averaged 850 and 200 hPa zonal winds in the Niño-4 region became enhanced and stronger, respectively (see Figs. 13a and b). Furthermore, the Walker circulation and local Hadley circulation both became stronger in 1998 (see Figs. 13c and d). Also, the SST on the western coast of Mexico showed a stronger cold anomaly beginning in 1998 (see Fig. 13e).

5. SUMMARY AND CONCLUSION

This study analyzed the distinct increase in the area-averaged summer (June to August) rainfall in the Korea and North China region (35 - 40°N, 110 - 130°E) in the late 1990s. To examine the causes of the increasing summer rainfall since 1998 in the Korea and North China region, the difference in the average summer rainfall between the period from 1998 - 2012 and the period from 1981 - 1997 was analyzed.

In the OLR analysis, there were negative anomalies in a southwest to northeast direction from the central south region of China to Korea and through the East China Sea to Japan. Furthermore, negative anomalies clearly appeared in the Maritime Continent, as well. In contrast, positive anomalies appeared from the equatorial eastern Pacific to the equatorial western Pacific.

To investigate the reason for the increasing summer rainfall in the middle and low latitude region of East Asia, which includes the Korea and North China region and the Maritime Continent, the difference in the 850 hPa stream flows between the two periods was analyzed. Anomalous huge anticyclonic circulations were strengthened in the North Pacific region, and anomalous anticyclonic circulations were also strengthened in the eastern region of Australia in the Southern Hemisphere. These anomalous circulations in both hemispheres strengthened anomalous easterlies (anomalous trade winds) from the equatorial central Pacific to the tropical western Pacific. This was an anomalous circulation pattern that appears in La Niña years. In the 200 hPa stream flows, the anomalous circulations were opposite to the 850 hPa anomalous circulation pattern circulations, and thus anomalous westerlies in the equatorial central and western Pacific.

To investigate whether the recent increase in summer rainfalls in the Korea and North China region is associated

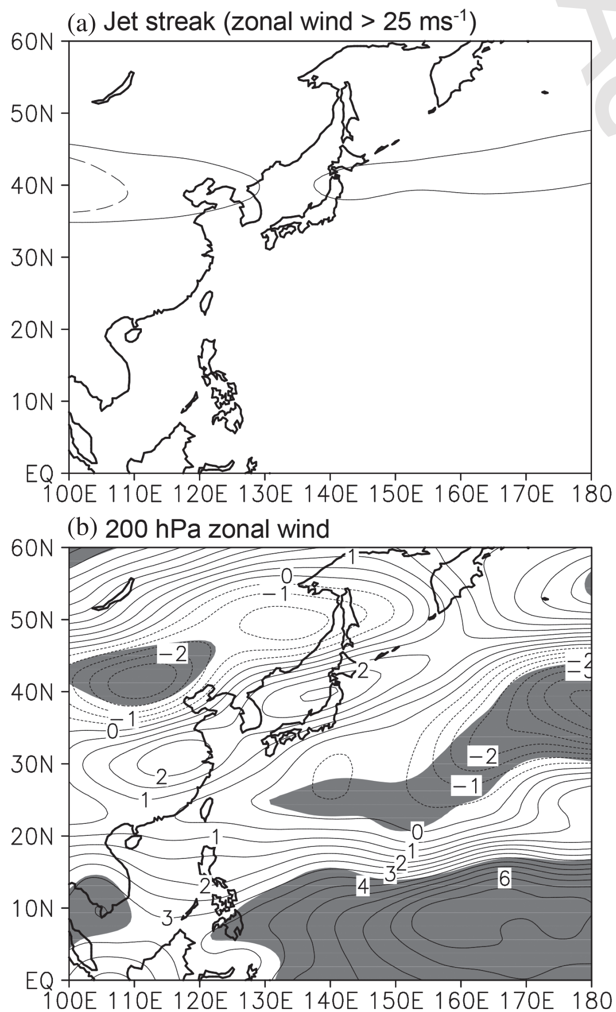

Fig. 11. (a) Jet streaks in 1998 - 2012 (solid line) and in 1981 - 1997 (dashed line) for JJA. Differences in (b) 200 hPa zonal wind between 1998 - 2012 and 1981 - 1997. In (b), contour interval is 0.5 m s[-1] and shaded areas are significant at the 95% confidence level.

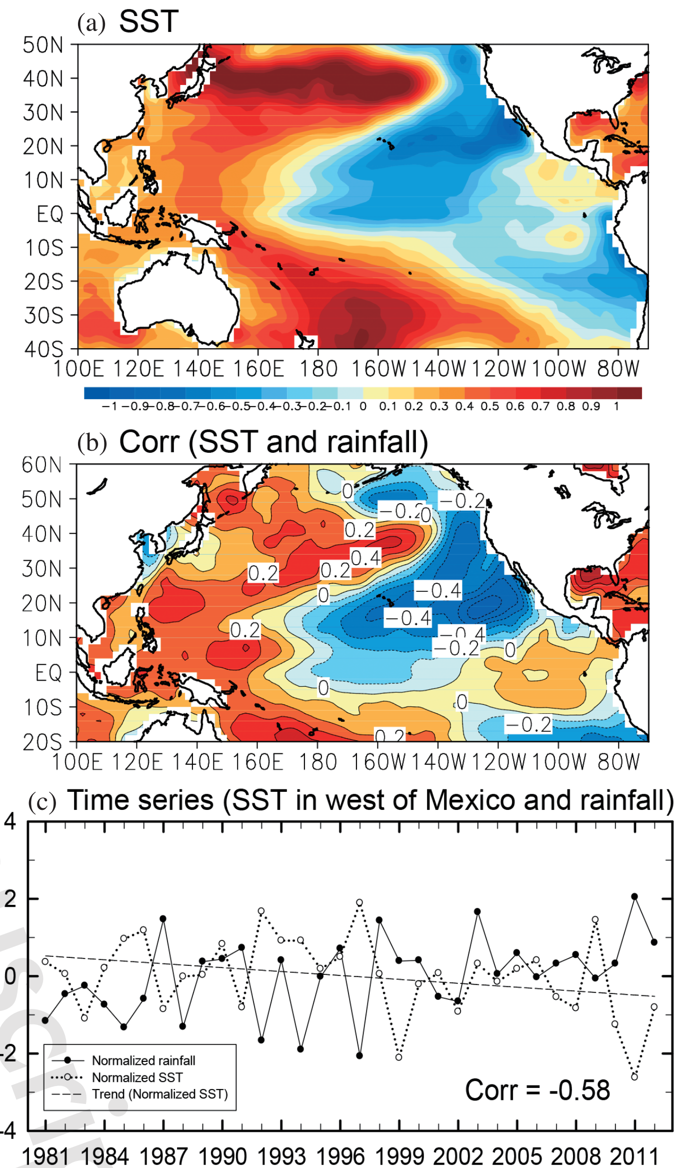

Fig. 12. (a) Difference in SST between 1998 - 2012 and 1981 - 1997, (b) correlation map between normalized Korea-north China summer rainfall and SST, and (c) time series of normalized Korea-north China summer rainfall and SST averaged over the west of Mexico (15 - 25°N and 135 - 115°W).

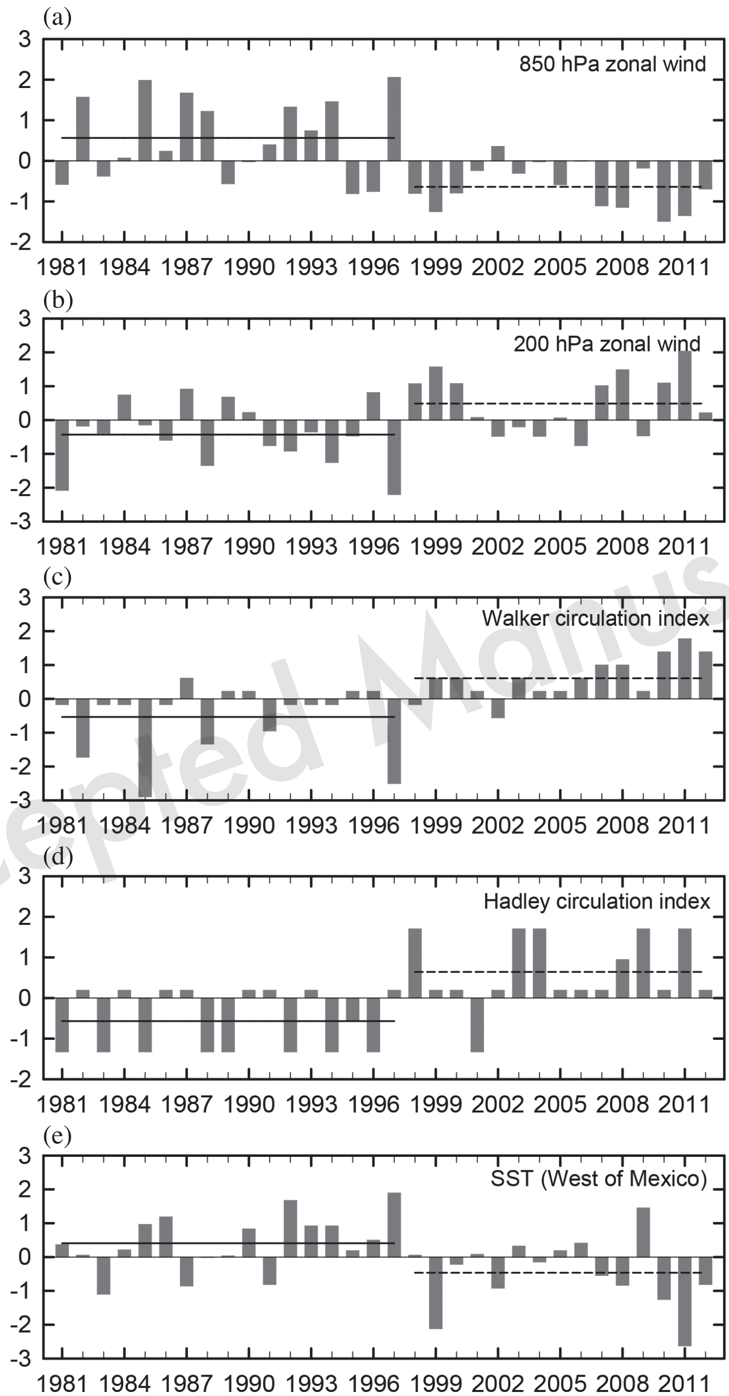

Fig. 13. Interdecadal variations of (a) 850 hPa zonal wind and (b) 200 hPa zonal wind averaged over Niño-4 region, (c) walker circulation index, (d) hadley circulation index, and (e) SST in west of Mexico.

with the recently strengthened La Niña pattern, the time series for the normalized values of the area-averaged 850 and 200 hPa zonal winds in the Niño-4 region in summer and the time series for the normalized values of summer rainfalls in the Korea and North China region were analyzed. First, a high negative correlation of -0.59 was found between the normalized values of the 850 hPa zonal wind and the summer rainfalls in the Korea and North China region. In contrast, a high positive correlation was found between the normalized values of the 200 hPa zonal wind and the summer rainfall in the Korea and North China region.

To investigate if the anomalous atmospheric circulation of the La Niña pattern had been strengthened recently, the time series of the Walker circulation index and the time series for the normalized values of summer rainfall in the Korea and North China region were analyzed. These two variables showed a high positive correlation of 0.65, and this means that as the Walker circulation became stronger, the summer rainfall in the Korea-North China region increased, and as the Walker circulation became weaker, the summer rainfall decreased. Furthermore, the local Hadley circulation index and the normalized values for summer rainfall in the Korea and North China region showed a very high positive correlation of 0.59, and this means that when the local Hadley circulation became stronger, the summer rainfall in the Korea and North China region increased (see Fig. 14).

In addition, the condition of upper-level jet during the two periods was analyzed. During the period from 1998 - 2012, the jet covered the Korea and North China region, whereas during the period from 1981 - 1997, the jet was located to the west of 110°E. Thus, more rainfall was possible in this region during the period from 1998 - 2012 when the upper-level jet was covering the Korea and North China region.

As described in the above analysis, the existence of interdecadal variation in the indices related to the variation of summer rainfall in the Korea and North China region during the late 1990s was examined. Since 1998, the area-averaged 850 and 200 hPa zonal winds in the Niño-4 region became weaker and stronger, respectively. Furthermore, the Walker circulation and local Hadley circulation both became stronger after 1998.

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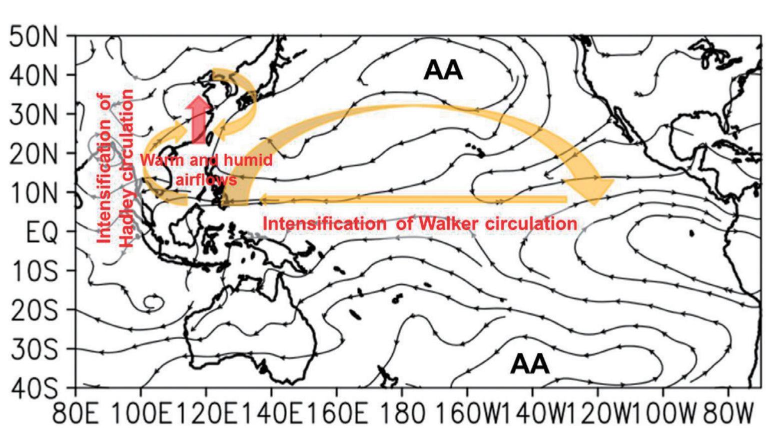

Fig. 14. Schematic illustration of anomalous atmospheric circulation changes on the recent increase of summer rainfall in Korea-north China. Abbreviation of 'AA' indicates 'anomalous anticyclone'.

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