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RESEARCH ARTICLE

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Interdecadal variation of Changma (Korean summer monsoon rainy season) retreat date in Korea

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Abstract

This study applied statistical change-point analysis to the time series of the Changma retreat date (CRD) on the Korean Peninsula over a recent 30-year period (1985–2014) and detected that the CRD has been delayed by about 10 days since 2000. The average CRD is July 14 for 1985–1999 and July 24 for 2000–2014. Corresponding to the CRD delay, the July rainfall is concentrated in the northern South Korea during 2000–2014, whereas tends to be intense along the southern coast during 1985–1999. The delayed CRD is associated with, in the lower and mid-troposphere, a strengthened cyclonic circulation around Lake Baikal–eastern Sea of Japan and an enhanced anticyclonic circulation in East China Sea. Thus, northerlies from strengthened cyclones and anomalous southerlies from the enhanced anticyclones converge at the northern-central Korean Peninsula. The anomalous anticyclone is associated with the strengthening of the western North Pacific subtropical high that has strengthened in meridional direction in the later epoch, supplying warm and moist air to Korean Peninsula. The result is verified by the enhanced warm and moist anomalous upward flows in the latitude where Korean Peninsula is placed. The delayed CRD in the latter epoch is related to the decreased spring snowfall over East Asia except for the vicinity of the Lake Baikal, which results in severely hot weather in the East Asia continent from spring to July. The continent heating from spring to July weakened (increases), the thermal gradient between continent and ocean, thereby forming a low-pressure system on East Asia and a high-pressure system in western North Pacific, resulting in the strengthening of Changma rain belt in July and delayed the Changma withdrawal.

KEYWORDS

Changma retreat date, Korean Peninsula, statistical change-point analysis

1 | INTRODUCTION

Most annual rainfalls are concentrated in summer in East Asia because of the influence of the summer monsoon. Heavy rainfalls, which make up the majority of summer rainfalls, cause a great deal of property damage and human casualties due to flooding and also create considerable fluctuations in water resources, thereby affecting overall society, including daily living, agriculture, and industries. Therefore, it is very crucial to examine the summer rainfall variability. The monsoon rainfall in East Asia has a large interannual variation. Thus, the forecast for Changma in summer is one of the important prediction tasks in Korea.

Many previous studies were performed to understand summer monsoon circulation associated with Changma (Park *et al*., 1989; Ha *et al*., 2005). Oh *et al*. (2000)

investigated mid-level features by dividing period into Changma onset, Changma, and Changma retreat, and found an abrupt rise in 500 hPa geopotential height on Korean Peninsula and in southern part of Japan during both the Changma onset and retreat periods and an rise in the geopotential height at mid- to high-latitude a few days before Changma onset. In addition, studies on the role of the Tibetan Plateau and characteristics of rainfall and a monsoon climate have also been conducted in association with onset and end of summer monsoon (Huang *et al*., 1997). Yun *et al*. (2001) reported that summer rainfall intensity around Korea was significantly affected by the western North Pacific subtropical high (WNPSH). In relation to the variation of large-scale atmospheric circulation and monsoon intensity, strong westerlies and strong East Asian summer monsoons were closely correlated (Meehl, 1987; Webster and Song, 1992).

The East Asian summer monsoon rainfall along the subtropical frontal zone has been known as Baiu in Japan, Meiyu in China, and Changma in Korea. However, they have different definitions on start and end dates. In Japan, 5-day average weather chart, sunshine duration, and rainfall are analysed to define Baiu. Ninomiya and Murakami (1987) determined the period of Baiu as a certain period that included the maximum rainfall and the minimum amount of solar radiation from approximately June 1 to July 15. In China, Meiyu is defined as a rainfall period if more than 10 mm of daily rainfall are recorded in two or more locations out of five spots in the downstream area of the Yangtze River. The common characteristics of Baiu and Meiyu are that the monsoon convergence zone is formed and characterized by a stationary front, while the humidity gradient is stronger than the air temperature gradient (Tao and Chen, 1987). Changma is located longitudinally between Baiu and Meiyu and the forcing factors are more complicated than those of the other two regions, which make it more difficult to determine the onset and retreat dates (Lim and Park, 1991). Given the divergent definitions, Wang and Lin (2002) proposed a unified definition of the Asian rainy season using a single rainfall index and a suite of general criteria for defining domain, start, peak, and end of rainy season on most Asian monsoon regions. Their results show that the Meiyu and Biau onset concurrently while the Changma onset is about 10 days later due to its higher latitude. Kripalani *et al*. (2007) had suggested a possible increase in the length of the summer monsoon precipitation period over East Asia from late spring through early autumn. The Korea rainy season consists of Changma and post-Changma separated by an early August break, and the onset, break and final withdrawal of the rainy season show large decadal and centennial variations in the past 227 years (1776–2004) (Wang *et al*., 2006, 2007).

The summer rainfall variability can be derived by a variety of factors that determine the monsoon or large-scale change. The East Asia region had clear changes in rainfall characteristics in some regions along with changes in atmospheric circulation of East Asian summer monsoon starting in 1970s and also in early and mid-1990s (Gong and Ho, 2002; Ho *et al*., 2003; Kwon *et al*., 2005; Kwon and Ha, 2007; Ding *et al*., 2008; Wu *et al*., 2010). Hu (1997) reported the strengthening of the WNPSH compared with previous years, along with changes in atmospheric circulation in Northern Hemisphere in association with increases in sea surface temperatures (SSTs) in western Pacific in late 1970s. Gong and Ho (2002) also reported a rise in rainfalls in Yangtze River watershed in relation to the clear development of WNPSH in western direction in the same period. The development of WNPSH in the western direction was in close associated with the intensity of summer monsoon, as it led to the formation of 850 hPa jet and moisture transport at the edge of the WNPSH (Huang and Sun, 1992; Chang *et al*., 2000; Lu, 2001; Lu and Dong, 2001).

Kwon and Ha (2007) proved that weakening of 200-hPa wind field in East Asia region in 1993 and 1994 (93/94) resulted in changes in large-scale atmospheric circulation. Wu *et al*. (2010) explained that changes in SST over Indian Ocean and the Tibetan Plateau snow cover induced the divergence zone in East China Sea and lower level of northern provinces of China, respectively, thereby strengthening the convergence zone in the southern provinces of China, which was the cause of the rainfall variation.

A large number of studies were performed on the summer rainfalls in Korean Peninsula and found that the summer rainfalls have changed significantly over the past decades, and that the characteristics of the rainfalls have also changed compared with those in the past (Park and Ha, 2002; Lee and Kwon, 2004; Ko *et al*., 2005; Wang *et al*., 2006, 2007; Chang and Kwon, 2007; Park *et al*., 2008). Park *et al*. (2008) analysed the summer rainfall variability at every 10-year interval from 1958 to 2007 and proved the increase in rainfalls in a recent 10-year period (1998–2007) compared with previous rainfalls. Park and Ha (2002) compared the daily rainfall variability before and after the early 1990s and found that maximum summer rainfall, which previously occurred from mid-July to late August, had changed to occur from early July to early August. Moreover, Kim and Jhun (2010) proved that the change in summer rainfall structure on the Korean Peninsula starting from the mid-1990s had a correlation with SST over the Kuroshio region and the SST over Indian Ocean, and Kim *et al*. (2011) reported that inter-seasonal variation displayed after the mid-1990s revealed an earlier northward moving of the Changma front and an increase in moisture transport due to the expansion of the WNPSH after Changma.

The present study investigates the changes in the Changma retreat date (CRD) trend in the last 30 years and the cause of this delayed trend. Data and methodology are introduced in Section 2 and CRD time series is examined in Section 3. The cause of the delayed CRD in recent years is analysed in Section 4 and the results are briefed in Section 5.

2 | DATA AND METHODOLOGY

2.1 | Data

The present study employed CRD data produced at the Korea Meteorological Administration (KMA) from 1985 to 2014 (study period of 30 years). In this study, the CRD is defined as the day of Changma end in the central area of the Korean Peninsula.

This study also used daily rainfall data observed at 75 KMA weather stations over 30 years. It is because the number of weather station in Korea significantly increases from 61 to 75 after 1985.

Large-scale atmospheric conditions were analysed using reanalysis data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR; Kalnay *et al*., 1996; Kistler *et al*., 2001) for the period 1985–2014. The present study also uses Climate Prediction Center Merged Analysis of Precipitation (CMAP) data (Xie and Arkin, 1997). In addition, sensible heat net flux (W/m^2), water equivalent of accumulated snow depth (WEASD, kg/m^2), and the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed monthly SST (Reynolds *et al*., 2002) was also used.

Tropical cyclone (TC) data were based on the best track archives of the Regional Specialized Meteorological Center, Tokyo-Typhoon Center.

2.2 | Methodology

The Student's t test was used to determine significance (Wilks, 1995).

In order to determine whether a year of climate regime shift was present in the time series of the CRD, statistical change-point analysis was applied to the time series (Elsner *et al*., 2000; Chu, 2002; Ho *et al*., 2004).

3 | TIME SERIES ANALYSIS OF CHANGMA RETREAT DATE

Figure 1 shows time series of the CRD for recent 30 years of the study period. Overall, the time series shows clear interannual and interdecadal variations (solid line with dot) and somewhat delayed CRD trend (dashed line). However, this

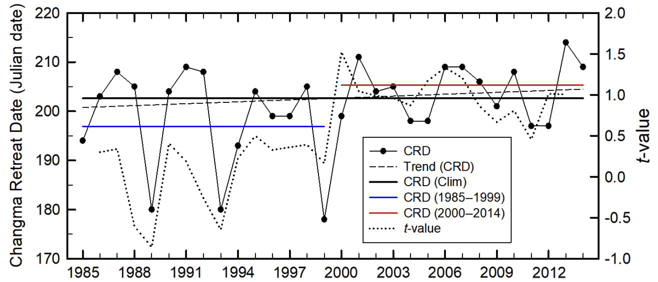

FIGURE 1 Time series of Changma retreat date (CRD, solid line with a closed circle) for 30 years (1985–2014) and statistical change-point analysis (dotted line) [Colour figure can be viewed at wileyonlinelibrary.com]

trend is not statistically significant. To determine whether a year of climate regime shift is present in time series, statistical change-point analysis was applied to this time series (dotted line). Result showed that the largest absolute t value was present in 2000. Thus, the total analysis period (30 years) was divided into two: the early CRD period from 1985 to 1999 (hereafter referred to as the 1985–1999 period) and the late CRD period from 2000 to 2014 (hereafter referred to as the 2000–2014 period). The average CRD for 30 years was July 21 (thick solid line). The average CRD for the 1985–1999 period was July 14, which was 7 days earlier than the 30-year average (blue line), while that of the 2000–2014 period was July 24, which was 3 days later (red line). Thus, the average CRD of the 2000–2014 period was approximately 10 days later than that of the 1985–1999 period. A difference in the average CRD between the two periods is statistically significant at a 95% confidence level. Therefore, the present study aims to analyse a difference in July average between the two periods about the large-scale environments to determine reason for the delayed CRD in recent years (2000–2014 period). The reason for the selection of July was that of all the 30-year average CRDs, CRDs in the 1985–1999 and the 2000–2014 periods occurred in July.

4 | DIFFERENCES BETWEEN 2000–2014 AND 1985–1999

4.1 | Seasonal variations in rainfalls

First, the seasonal variations in rainfalls during the two periods were analysed (Figure 2a). This study employed 7-day running average rainfalls to analyse the seasonal variation. Ha *et al*. (2005) used the 7-day running average rainfall effectively to analyse the presence of climate regime shift before and after late 1960s in interannual variation of August rainfalls on the Korean Peninsula. In general, the spring rainy season on the Korean Peninsula is defined as the

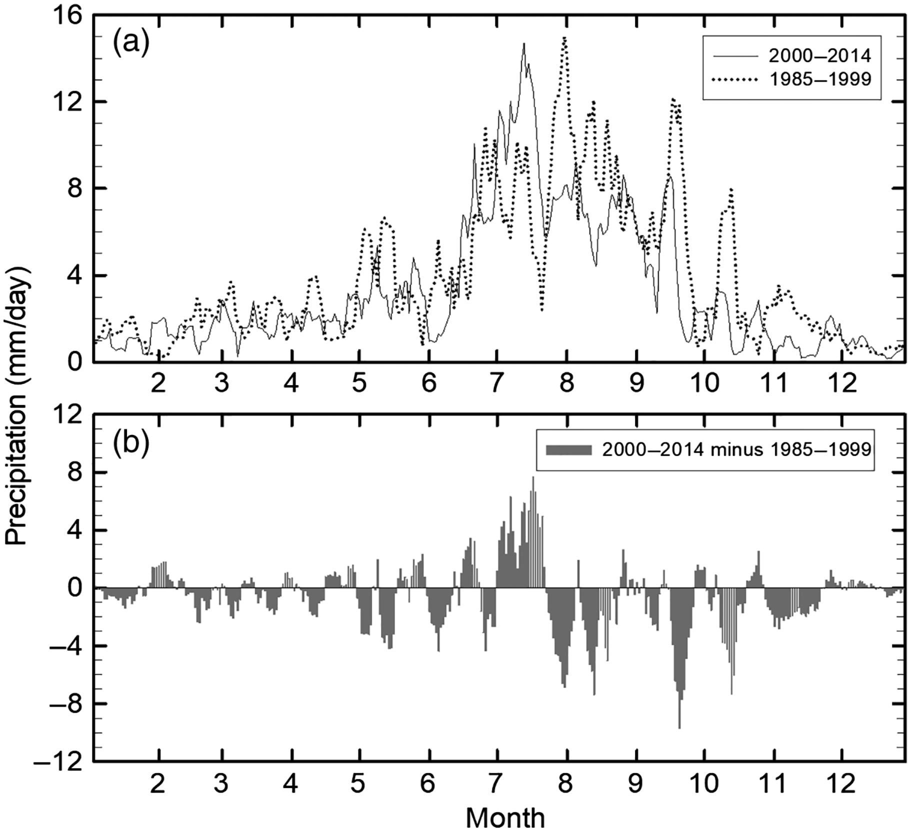

FIGURE 2 Temporal variabilities of the 7-day running averaged rainfall for (a) the mean of the period 2000–2014 (solid line) and (b) the mean of the period 1985–1999 (dotted line), and the difference between the mean of the period 2000–2014 and the mean of the period 1985–1999

period from early April to mid-May (Byun and Lee, 2002). The rainfalls in both the 1985–1999 and the 2000–2014 periods start to increase slowly at the end of April and then decrease from the end of May. Thus, both the periods revealed that onset and retreat of spring rainy season were delayed.

However, the difference in rainfalls between the two periods is evident in the summer rainy season. The summer rainy season is generally defined as term from June to mid-August (Byun and Lee, 2002). In 2000–2014 period, rainfalls reached maximum peak in mid-July and then decreased and reached the second peak in early August. In the 1985–1999 period, two peaks of rainfalls are present as well, but the times of the peaks are different from those of the 2000–2014 period. That is, the first peak was found between the end of June and mid-July, and the rainfall amount was much smaller than that of the 2000–2014 period. In contrast, the second peak was found between end of July and early August, and rainfall amount was much larger than that of the 2000–2014 period. That is, the rainfall amount in the 2000–2014 period was larger than that of the 1985–1999 period during Changma, whereas it was smaller than that of the 1985–1999 period after Changma. These changes are manifestation of the long-term changes found by Wang *et al*. (2007).

Generally, the second Changma season on the Korean Peninsula is defined as term from mid-August to mid-September (Byun and Lee, 2002). Two peaks of rainfalls are found in the 2000–2014 period, as shown, in the end of August and mid-September. In contrast, only one peak was found in the 1985–1999 period, as shown, in mid-September, but the rainfall amount was larger. In addition, the 1985–1999 period has one more peak in early October.

Thus, the time series of difference in rainfalls between the two periods shows that the rainfall amount in the 2000–2014 period was larger only during Changma (July), whereas it was smaller from the end of July to November compared with that in the 1985–1999 period (Figure 2b). However, no significant difference in rainfall in other months (December–April) was found between the two periods. This was because that period is the cold and dry season in Korea.

4.2 | Spatial distribution of July rainfall

The spatial distributions of July rainfall amounts in two periods were investigated (Figure 3). The rainfalls were concentrated in northern region of the Korean Peninsula in 2000–2014 period (Figure 3a). In particular, the centre of the rainfalls was in the northwest area of the northern region, where the metropolitan region, including Seoul, is located. The rainfalls in the 1985–1999 period tended to be smaller than those in the 2000–2014 period overall (Figure 3b). This was due to the longer duration of Changma in the

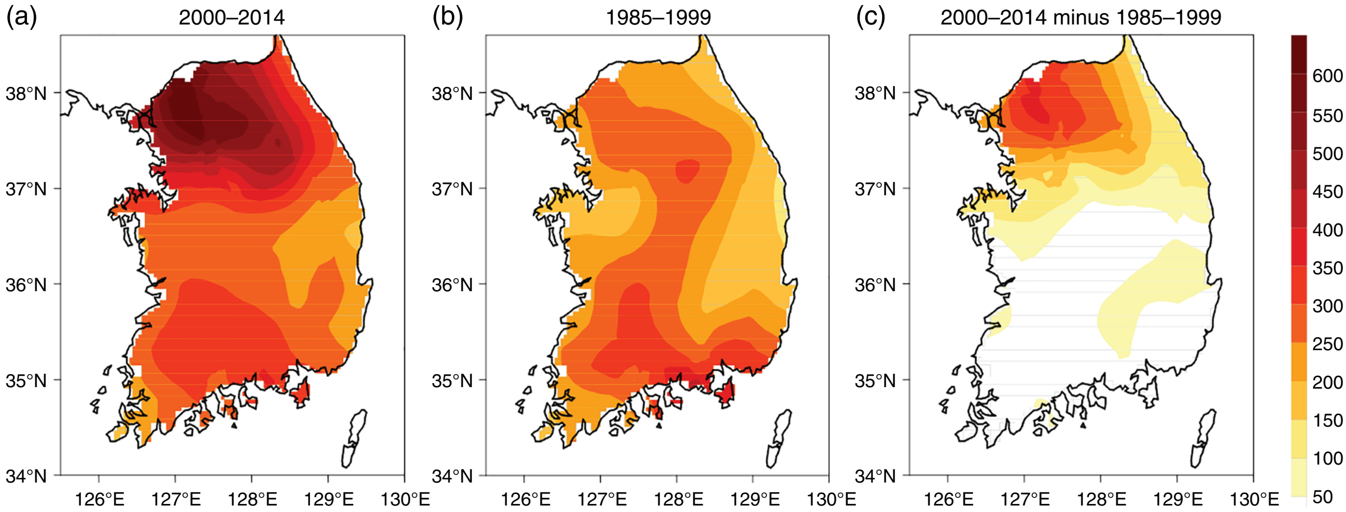

FIGURE 3 July total rainfall in (a) 2000–2014 and (b) 1985–1999, and (c) the difference between 2000–2014 and 1985–1999 periods [Colour figure can be viewed at wileyonlinelibrary.com]

2000–2014 period as analysed above. The rainfalls in the 1985–1999 period were mainly concentrated along the southern coast, and the centre of the rainfalls formed along the southeast coast. The spatial distribution of difference in rainfalls between the two periods showed that more rainfall occurred in northern Korean Peninsula in 2000–2014 period (Figure 3c). In particular, the centre was formed in northwestern Korean Peninsula, where the metropolitan area is located.

4.3 | Large-scale environments

This study analysed the difference in outgoing longwave radiation (OLR) and CMAP rainfall between two periods and climatology (Figure 4). The OLR analysis result exhibited that negative anomalies were developed in eastern Sea of Japan from central northern China via central northern Korean Peninsula in 2000–2014 period (left of Figure 4a). Thus, Changma can be prolonged on the Korean Peninsula in this period. This is the cause of more rainfalls in the central northern Korean Peninsula in 2000–2014 period as analysed above. In contrast, positive anomalies were found over East China Sea from central southern China. OLR spatial distribution in the 1985–1999 period displayed the opposite pattern from that of the 2000–2014 period (left of Figure 4b). Positive anomalies were displayed from the central China to the northeastern Japan through Korean Peninsula. Thus, this environment indicated that Changma could end earlier on the Korean Peninsula in this period. In contrast, other regions in the analysis area showed negative anomalies, and western North Pacific summer monsoon was considerably strengthened.

The CMAP rainfall result showed that positive anomalies were displayed from central China to eastern Sea of Japan via the Korean Peninsula in the 2000–2014 period (right of Figure 4a). In particular, the centre of the positive anomalies was placed in central northern Korean Peninsula. This reflected the previous result that rainfalls occurred more in July in the 2000–2014 period, and the centre of the rainfalls was formed in the west of the central northern region of the Korean Peninsula where the metropolitan area, including Seoul, was located. The spatial distribution of the CMAP rainfall in the 1985–1999 period showed the opposite pattern from that of the 2000–2014 period (Figure 4b). Negative anomalies were displayed from central China to eastern Sea of Japan via the Korean Peninsula. In contrast, positive anomalies were developed in subtropical western North Pacific.

To know the influence of the large-scale environments on delayed CRD in 2000–2014 period, a difference in the 850 hPa stream flows between the two periods was analysed (Figure 5a). Anomalous cyclonic circulations were formed in northwest to southeast direction from the eastern Lake Baikal to the northeastern Sea of Japan, and anomalous anticyclonic circulations were strengthened in southern Sea of Japan (or East China Sea). That is, a south-high-north-low type of anomalous pressure system pattern was formed around Korean Peninsula. Thus, anomalous southwesterlies and anomalous northwesterlies converged on the Korean Peninsula via these two anomalous pressure systems, and centre of the convergence was the central northern region of Korean Peninsula. The formation of the convergence in this region implied that the Changma rainband was strengthened.

The south-high-north-low type of anomalous pressure system pattern was clearly seen around the Korean Peninsula in the 500 hPa as well. The anomalous southwesterlies and anomalous northwesterlies converged on the Korean

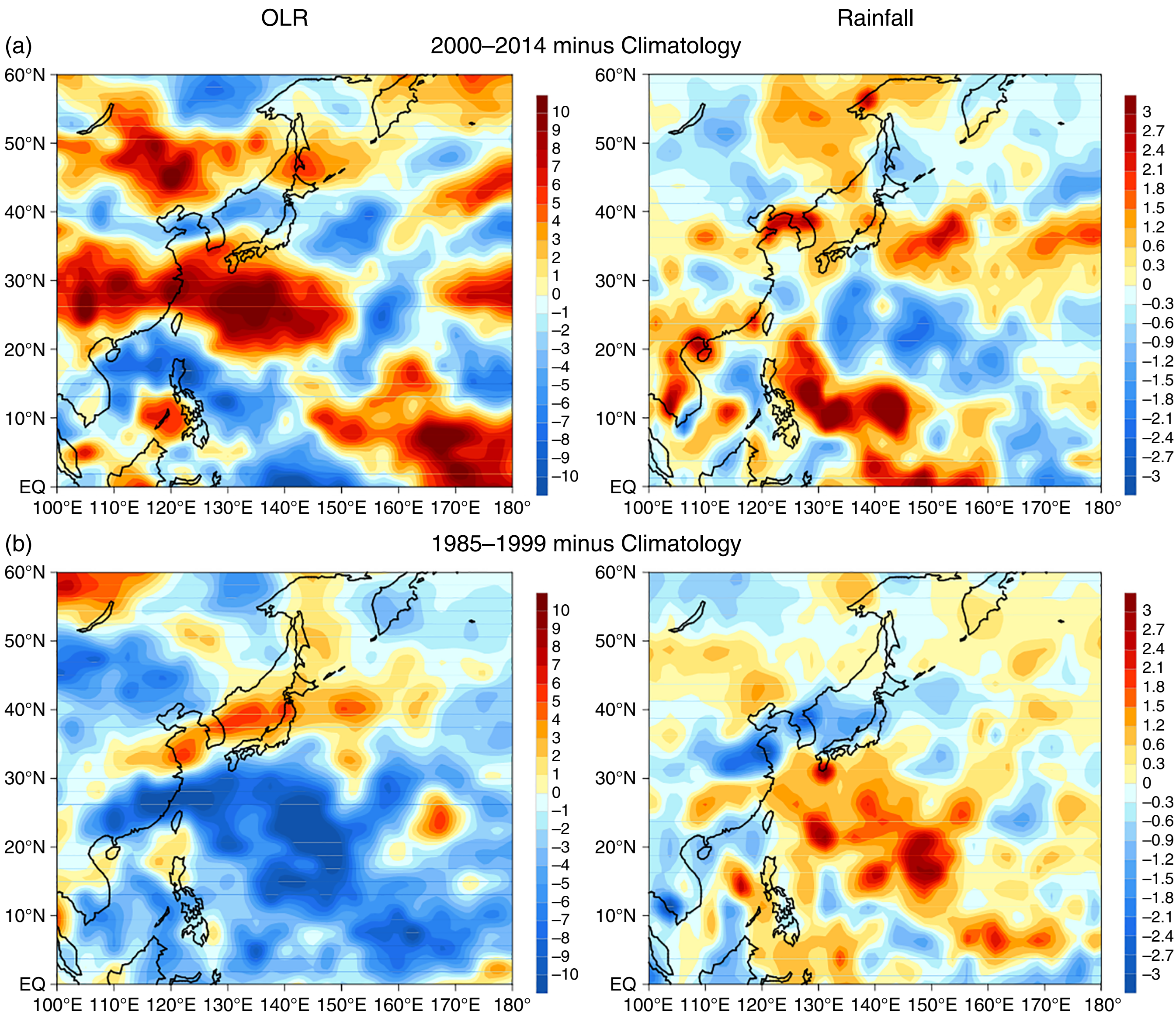

FIGURE 4 Differences in OLR (left panel) and rainfall (right panel) (a) between 2000–2014 and climatology and (b) between 1985–1999 and climatology [Colour figure can be viewed at wileyonlinelibrary.com]

Peninsula, and centre of the convergence was also located in the central northern region of Korean Peninsula (Figure 5b).

Anomalous pressure system patterns such as anomalous anticyclones formed in the south of Japan and anomalous cyclones formed in northeastern Japan in 850 hPa displayed a similar spatial distribution as that of negative Pacific-Japan (PJ) pattern (Nitta, 1987, 1989). Thus, correlation between CRDs and the July average PJ index in the 30 years of the study period was analysed (Figure 6). Until recently, the PJ index tended to increase, though the increases were not significant statistically. However, a clear negative relationship between two time series was shown so that a negative correlation of −.56 was found between two variables. This negative correlation is statistically significant at a 99% confidence level. This implied that as PJ pattern became stronger (weaker), the CRD became earlier (later). That is, when anomalous cyclones (anticyclones) in southern Japan, and when anomalous anticyclones (cyclones) in the northeast of Japan are strengthened, the CRD is earlier (delayed). This result is in agreement with the study result of Ha *et al.* (2005), in which propagation of anomalous pressure system wave to the northeast due to the variation in SST around the Philippines significantly affected the Changma variable of the Korean Peninsula.

The anomalous anticyclones that were developed in southern Japan in 2000–2014 period implied that the WNPSH was developed considerably. So, the strengthening scale of WNPSH between the two periods was analysed in this study (Figure 7). Here, WNPSH was defined as a region more than 5,875 gpm. The WNPSH in 2000–2014 period was strengthened not only in west up to the southern inland area of China but also in the north up to southern sea of the Korean Peninsula (solid line). In contrast, the WNPSH in 1985–1999 period was not only contracted to east of 135°E but also weakened in southern and northern directions (dashed line). Preethi *et al*. (2017) also documented the westward shift of this subtropical high by about 7° of longitude. Therefore, the CRD was delayed in the 2000–2014 period as the WNPSH in the 2000–2014 period was placed in southern sea of Korean Peninsula in that period, which maintained the Changma rainband continuously.

In order to investigate features of vertical atmospheric conditions around the Korean Peninsula, an analysis was conducted of the difference in vertical meridional atmospheric circulations between two periods averaged over 125°–130°E, which is longitudinal band where Korean Peninsula is placed (Figure 8a). The anomalous upward flows were strengthened in all levels of troposphere in latitudinal band of 30°–40°N where Korean Peninsula is placed. In contrast, the anomalous downward flows were strengthened in latitudinal band of 20°–30°N in subtropical western Pacific. This implied that the WNPSH was strengthened

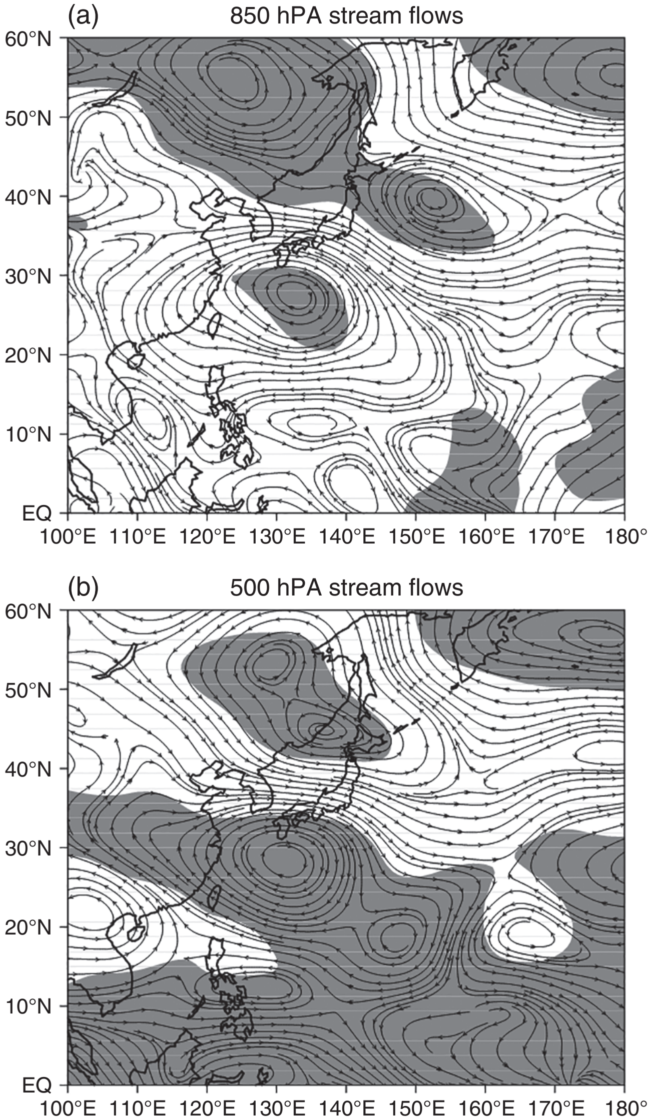

FIGURE 5 Differences in (a) 850 hPa and (b) 500 hPa stream flows between 2000–2014 and 1985–1999. Shaded areas are significant at the 95% confidence level

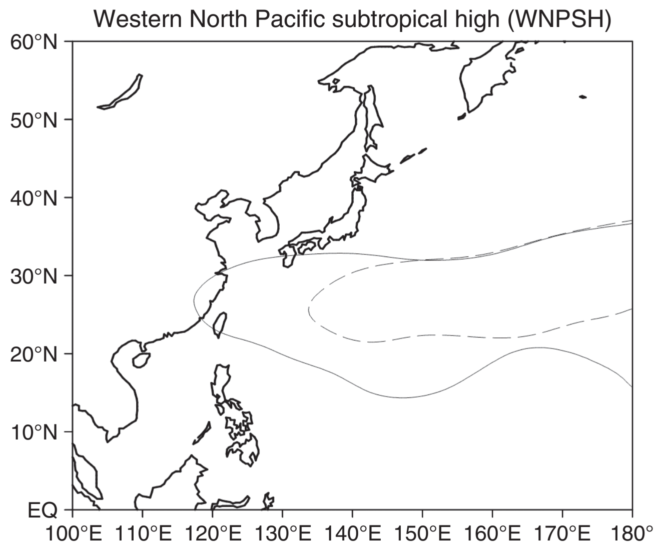

FIGURE 7 Distribution of WNPSHs in 2000–2014 (solid line) and 1985–1999 (dashed line). Here, WNPSH is defined as areas that is greater than 5,875 gpm

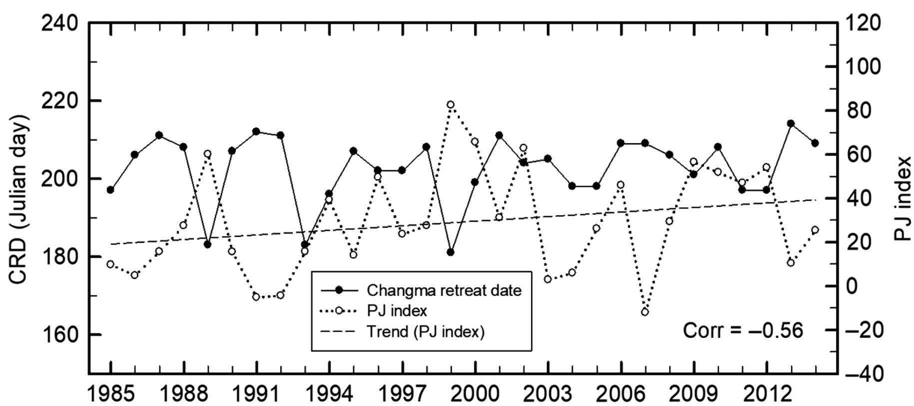

FIGURE 6 Time series of CRD (solid line with a closed circle) and Pacific-Japan (PJ) teleconnection pattern index (dotted line with an open circle)

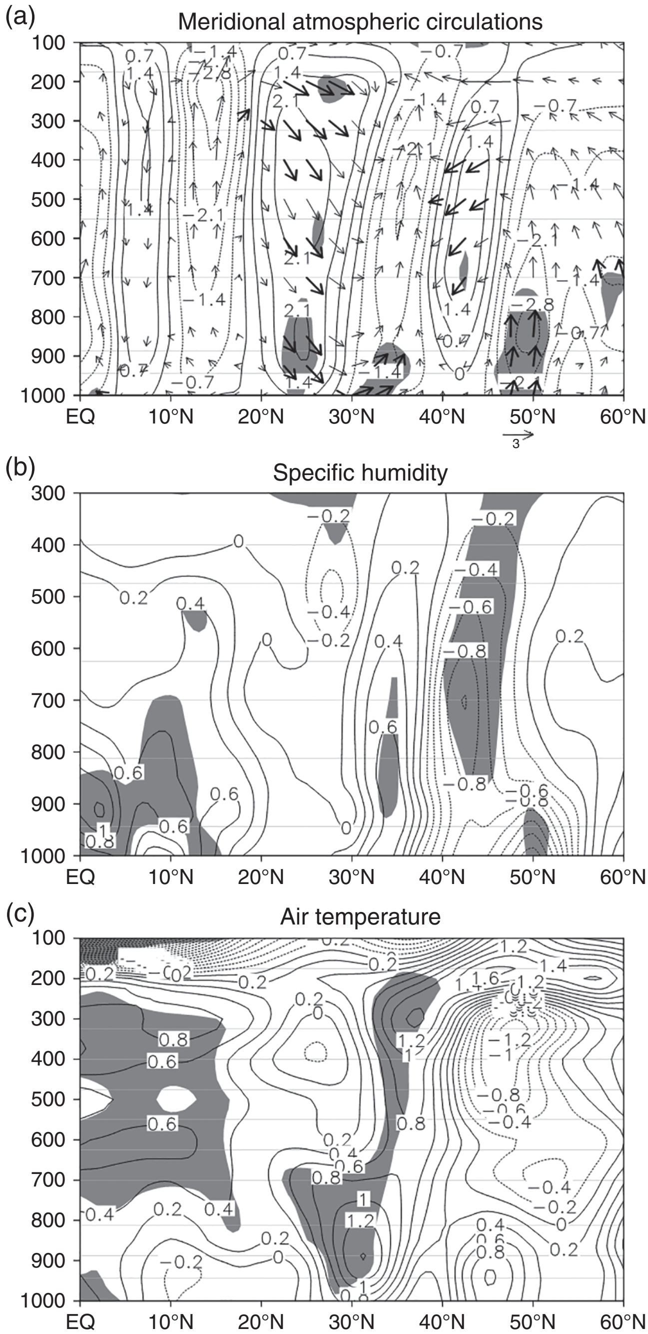

FIGURE 8 Composite differences of latitude–pressure cross section of (a) vertical velocity (contours) and zonal circulations (vectors), (b) specific humidity, and (c) air temperature averaged along 125°–130°E between 2000–2014 and 1985–1999 for July. The values of vertical velocity are multiplied by −100. Bold arrows and shaded areas are significant at the 90% confidence level. Contour intervals are 0.7^{-2} hPa/s for vertical velocity, 0.2 g/kg for specific humidity, and 0.2°C for air temperature, respectively

even to southern sea of Korean Peninsula as analysed above. This result indicated that the Changma rainband was developed more in the 2000–2014 period due to the development of the WNPSH on the Korean Peninsula.

Moreover, the specific humidity and air temperature displayed positive anomalies through all layers in the troposphere in the latitude band where Korean Peninsula is placed (Figure 8b,c). This implied that atmospheric conditions favourable to producing more water vapours in all layers around the Korean Peninsula were formed in the 2000–2014 period.

Generally, upper-level jet develops convergence in lower level troposphere, thereby forming the Changma rainband, resulting in inducement of upward flows and precipitation. So, the present study analysed development intensity of upper-level tropospheric (200 hPa) jet for the two periods (Figure 9a). Here, jet was defined as a region where the

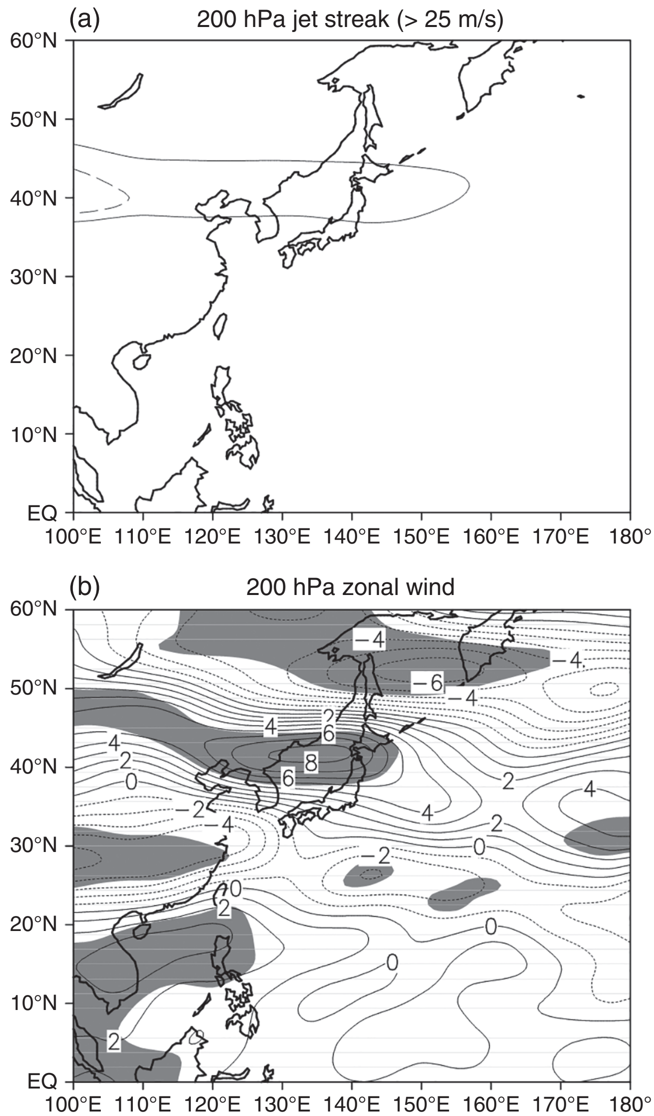

FIGURE 9 (a) 200 hPa jet streaks of 2000–2014 (solid line) and 1985–1999 (dashed line) and (b) difference in 200 hPa zonal wind between 2000–2014 and 1985–1999. Here, jet streak is an area that zonal wind at 200 hPa is greater than 25 m/s. In (b), contour interval is 1 m/s and shaded areas are significant at the 95% confidence level

zonal wind speed was larger than 25 m/s. The jet streak in the 2000–2014 period developed in the east up to 160°E and spread around 37°–47°N, including the central northern region of the Korean Peninsula, in the south–north direction. In contrast, the jet streak contracted to the west in the region around 110°E as well as in the south–north direction (dashed line) for the 1985–1999 period. Thus, the upward flows were occurred due to strengthening convergence in lower level in the 2000–2014 period, resulting in maintaining the rainfall band longer. The strengthening of upper-level tropospheric jet in 2000–2014 period can be seen more apparently through difference analysis in upper-level zonal winds (Figure 9b). Positive anomalies were strengthened on Korean Peninsula, including the northern region, whereas negative anomalies were developed in the southern region. This implied that westerlies were more developed in upper-level troposphere in northern Korean Peninsula during the 2000–2014 period.

Oceanic condition can also affect the lower-level tropospheric stability. So, the current study analysed SST difference between the two periods (Figure 10). In general, warm SST provides warm and moist air to lower level, thereby making entire level unstable, which can increase the precipitation formation. In this study, anomalous warm SST anomalies were also shown in many regions in western North Pacific. This made the atmosphere around the Korean Peninsula unstable, thereby helping to maintain the Changma rainband in the 2000–2014 period.

4.4 | Diagnosis of preceding environments

In order to determine the cause of greater strengthening of the Changma rainband in the 2000–2014 period, the difference in sensible heat net flux between the two periods was analysed (Figure 11). Positive anomalies were displayed in all regions except for areas around Lake Baikal in the East Asia continent during the March–May period (Figure 11a). This meant that the East Asia continent was more heated in the 2000–2014 period than in the previous period. The heating of the East Asia continent continued up to July (Figure 11b). The level of heating was more clearly seen in central northern China, southern Siberia, and Manchuria. In contrast, negative anomalies from central China to Korean Peninsula were due to strengthening of Changma rainband in the region. The warming continent from spring to July weakened thermal gradient between continent and ocean, thereby forming a low-pressure system in the East Asia

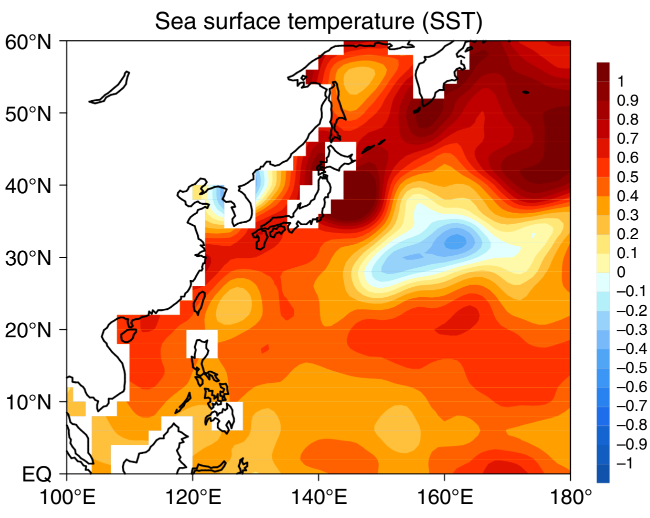

FIGURE 10 Difference in sea surface temperature between 2000–2014 and 1985–1999 periods [Colour figure can be viewed at wileyonlinelibrary.com]

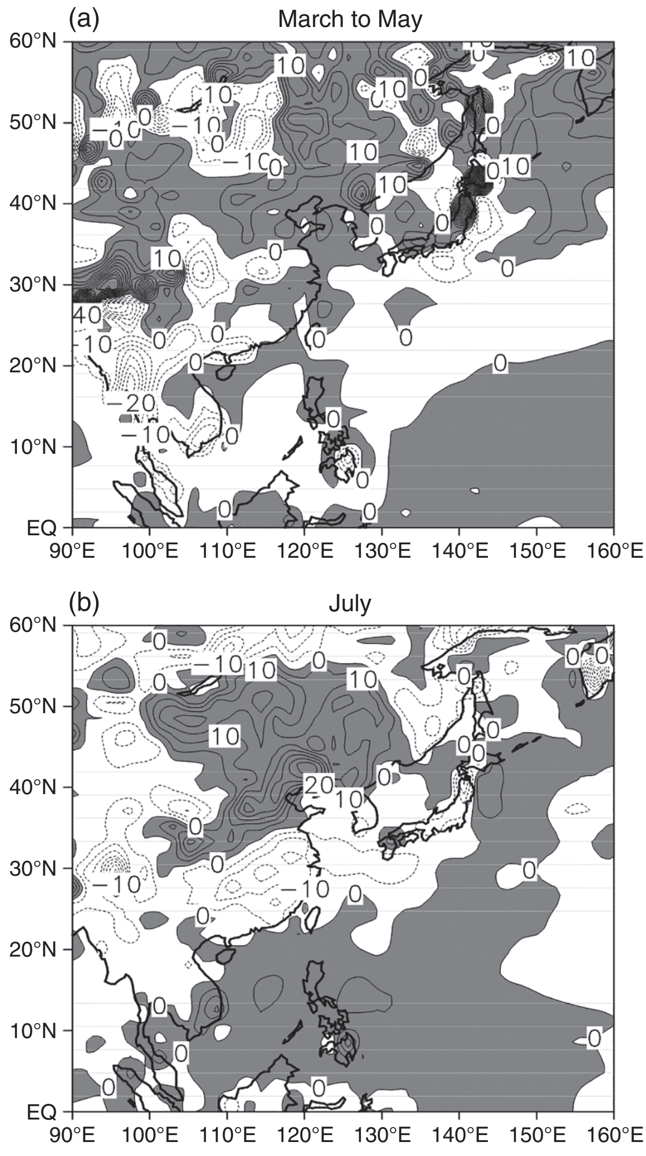

FIGURE 11 Difference in sensible heat net flux in (a) March to May and (b) July. Contour interval is 5 W/m^2. Shaded areas are positive values

continent and a high-pressure system in western North Pacific, resulting in strengthening of East Asian summer monsoon.

Warming level on continent during spring season was affected by snow. Thus, a snow-depth difference between the two periods from March to May was analysed (Figure 12). Negative anomalies were displayed in many regions of East Asia except for areas around Lake Baikal. Snow plays a role in lowering land temperatures by reflecting solar light as well as cooling the surrounding air. Thus, the East Asia continent in the 2000–2014 period would be more heated due to a reduced snow area.

TC could also influence the July precipitation on the Korean Peninsula. Therefore, a TC track difference between the two periods was investigated (Figure 13). TCs in the 2000–2014 period clearly tended to move from the far east of the Philippines to west and land in southern China. In contrast, TCs in the 1985–1999 period tended to move from the far southeastern Sea of Japan to northwest, affect Korean Peninsula, and move to the northeast region of Japan. The TCs' passage tendency during the two periods can be deduced from the results of the analysis of the WNPSH in the above (Figure 7). The WNPSH was not only strengthened in meridional direction in 2000–2014 period but also extended up to the southern inland of China, in which TCs in this period were prone to influence the southern inland of China. In contrast, the WNPSH in 1985–1999 period was not only narrowed in south–north direction but also failed to be extended to the west, in which TCs in this period could influence the mid-latitudes of East Asia. In other words, the Korean Peninsula was not easily influenced by the precipitation due to TCs in the 2000–2014 period when the Changma rainband was further developed on the Korean Peninsula.

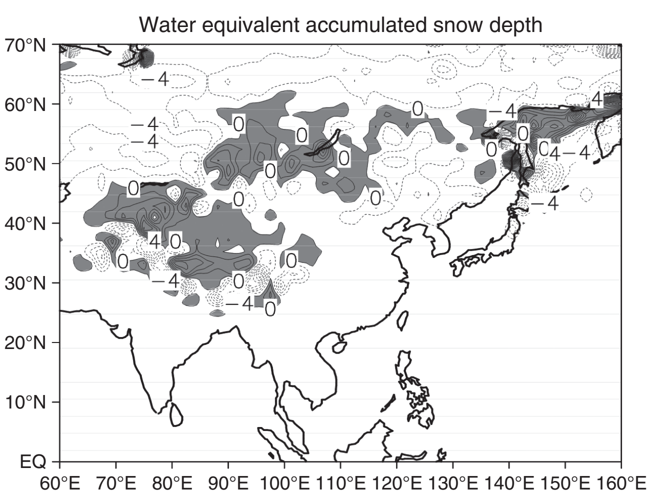

FIGURE 12 Difference in water equivalent accumulated snow depth in March to May. Contour interval is 2 kg/m^2. Shaded areas are positive value

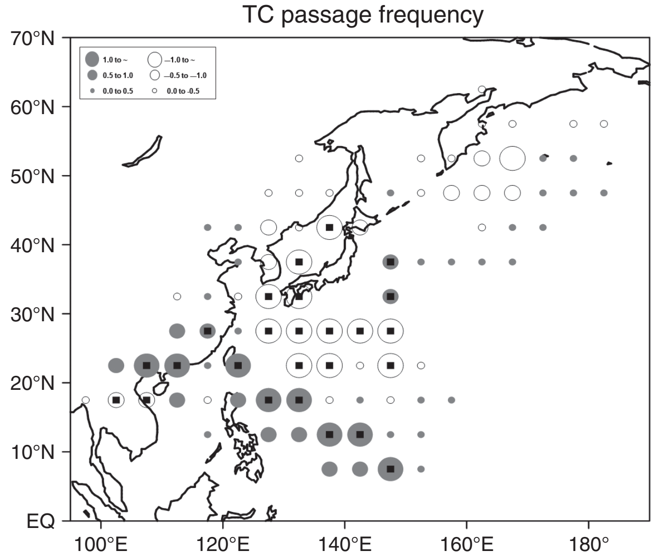

FIGURE 13 Differences in TC passage frequency between 2000–2014 and 1985–1999 periods for July in each 5° × 5° latitude–longitude grid box. Squares inside circles indicate that the differences are significant at the 95% confidence level

This result is in agreement with the result of Sobel and Camargo (2005), who found that it was difficult for TCs to move in a northern direction when the Changma rainband was developed in mid-latitudes of East Asia.

In order to determine the characteristics of global atmospheric circulation, a difference in upper-level velocity potential (divergent wind) between two periods was analysed (Figure 14). Strong divergence was placed in subtropical region of the Central Pacific in both hemispheres and convergence was placed in the north Indian Ocean. The Korean Peninsula was included in divergence region. This meant that anomalous convergence was formed in the lower level troposphere, which implied a strengthening of the Changma rainband.

5 | SUMMARY AND CONCLUSIONS

Statistical change-point analysis was applied on time series of CRDs on the Korean Peninsula for a recent 30-year period (1985–2014) and discovered that the CRD has been delayed since 2000. The average CRD during the 1985–1999 period was July 14, whereas that during the 2000–2014 period was July 24, which was 10 days later.

The seasonal evolution of rainfalls in the two periods were analysed. The rainfalls in both the 1985–1999 period and the 2000–2014 period begun to increase slowly at late April and then decreased from end of May. Thus, the start and end of spring rainy season were delayed in both of the periods.

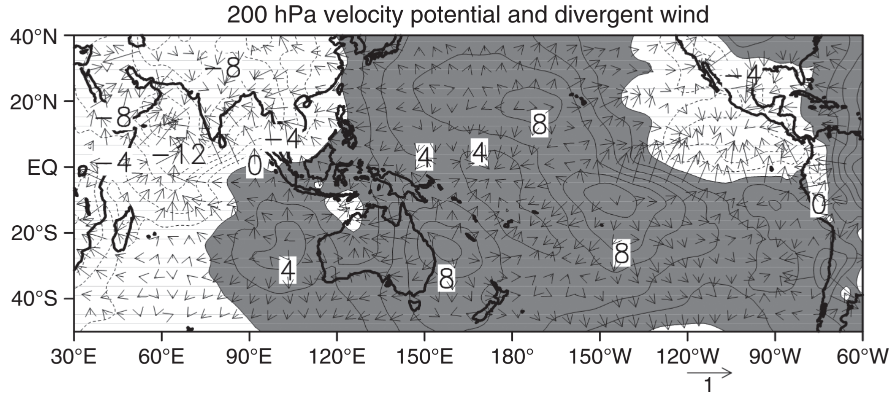

FIGURE 14 Differences in 200 hPa velocity potential (divergent wind) between 2000–2014 and 1985–1999 periods. Shaded areas denote positive anomalies. Contour interval is 3 m^2 s–1$10^{-6}$

In the 2000–2014 period, rainfalls reached the maximum peak in mid-July and then reduced and reached a second peak in the beginning of August during summer rainy season on Korean Peninsula. In the 1985–1999 period, two peaks of rainfalls were present as well, but the times of the peaks were different from those of the 2000–2014 period. That is, the first peak was found between the end of June and mid-July, and the rainfall amount was much smaller than that of the 2000–2014 period. In contrast, the second peak was found between the end of July and early August, and the rainfall amount was much larger than that of the 2000–2014 period. That is, the rainfall amount in the 2000–2014 period was larger than that of the 1985–1999 period during Changma, whereas it was smaller than that of the 1985–1999 period after Changma.

Two peaks of rainfalls were found in the 2000–2014 period, as shown, in the end of August and mid-September during the second Changma season on the Korean Peninsula. In contrast, only one peak was found in the 1985–1999 period, as shown, in mid-September, but the rainfall amount was larger. In addition, the 1985–1999 period had one more peak in early October.

Accordingly, the time series of differences in rainfalls between the two periods shows that rainfall amounts in the 2000–2014 period were larger only during Changma (July), whereas they were smaller from the end of July to November compared with rainfalls in the 1985–1999 period.

The spatial distribution of the July rainfall amount in the 2000–2014 period displayed a large amount of rainfall in the west of the central and northern region on the Korean Peninsula, whereas the rainfall amount in the 1985–1999 period tended to be concentrated in the southern coast on the Korean Peninsula.

As described above, the CRDs in the 2000–2014 period were delayed compared with those in the 1985–1999 period. In order to examine the feature of delayed CRDs, the large-scale environment differences between the two periods were investigated. The 850 and 500 hPa stream flows revealed that anomalous cyclones were developed from regions around Lake Baikal to eastern Sea of Japan in a northwest to southeast direction, whereas anomalous anticyclones were occurred around the East China Sea. Thus, anomalous northerlies from anomalous cyclones placed in northern Korean Peninsula and anomalous southerlies from the anomalous anticyclones placed in southern Korean Peninsula met at central northern Korean Peninsula.

Anomalous pressure system pattern of south-high-north-low type around Korean Peninsula showed similar spatial distribution to the PJ pattern, and the CRD and July PJ index had a high negative correlation. This result indicated that the CRD was affected by the PJ pattern, as reported in a previous study.

The anomalous anticyclones placed in southern Korean Peninsula were also related to the development of the WNPSH. The WNPSH in 2000–2014 period was strengthened further in west, up to the southern inland of China, than in the 1985–1999 period. At the same time, it was strengthened further in the south–north direction as well, supplying more warm and humid air to the Korean Peninsula. This was ultimately related to the delayed CRD in the former period. The result could be verified by the vertical atmospheric conditions averaged over the latitude zone of the Korean Peninsula. That is, warmer and more humid upward flows were developed in latitude band where the Korean Peninsula was placed.

However, WNPSH in latter period was expanded to the west. Thus, most TCs in this period were directed to the southern inland of China, resulting in small effects of TCs on July precipitation on the Korean Peninsula.

In addition, the 200 hPa jet streak was also strengthened in the central northern region of the Korean Peninsula in latter period because of strengthening of WNPSH in north in this period, which formed the convergence in the lower level troposphere, thereby maintaining the Changma rainband strongly around the Korean Peninsula.

Anomalous warm SST anomalies were also showed in many regions in western North Pacific. This made the atmosphere around the Korean Peninsula unstable, thereby helping to maintain the Changma rainfall band in the 2000–2014 period.

The delayed CRD in the latter period was related to the snow in the spring season. Many regions of East Asia showed less snow in latter period, except regions around Lake Baikal. As a result, the East Asia continent had more severe heat from spring to July. The warming continent from spring to July undeveloped thermal gradient between continent and ocean, thereby forming a low-pressure system in East Asia continent and a high-pressure system in western North Pacific, resulting in the development of East Asian summer monsoon.

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