

# Possible influence of South Asian high on summer rainfall variability in Korea

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**Abstract** This study was conducted to examine the correlation between the South Asian High (SAH) shift and the summer (June–August) rainfall variability in Korea over the course of 45 years (1958–2002). It is found that the shift in the west–east direction is closely related to the summer rainfall variability in Korea. The atmospheric circulations in the east shift years showed that at 850 hPa, an intensification of the western North Pacific subtropical high allowed a sufficient amount of warm and humid air to be supplied to the lower atmosphere near Korea. On the other hand at 200 hPa, the SAH expanded toward the east, near the southern part of Korea, causing the intensification of the northwesterlies, and this allowed the supply of cold and dry air to the upper atmosphere near Korea. Meanwhile, in the latitudinal zone in which Korea is located, there were anomalous upward flows with warm and humid characteristics in the lower atmosphere and anomalous downward flows with cold and dry characteristics in the upper atmosphere. As such, the cold and warm air masses present in the upper and lower atmosphere near Korea led to thermal instability, and this was analyzed to be a major factor that could potentially increase the amount rainfall in Korea in summer in the east shift years. Moreover, a warm SST anomaly was formed in the mid-latitude zones of East Asia,

and it heated the lower troposphere, thereby intensifying the thermal instability even further. Furthermore, TCs frequently had an impact on Korea in the east shift years, and were another factor that caused the increased rainfall in summer.

**Keywords** South Asian high · Summer rainfall · Western North Pacific subtropical high

## 1 Introduction

The importance of the Tibetan Plateau as a heat source for the establishment and maintenance of the Asian summer monsoon circulation has been investigated by many researchers. The anticyclone dominates a wide region over the middle latitudes of the Northern Hemisphere and its development over the Tibetan Plateau leads to various weather and climate conditions. And the migration, strength, and location of the anticyclone flow are directly related to lower-level monsoon circulation of the East Asia (Lau and Li 1984). This anticyclone is called as the South Asian High (Flohn 1957, 1960) and is also called as the upper-level South Asian High because it develops only on the upper-level (Murakami 1987).

As referenced, studies regarding the cause and origin of the South Asian High are classified into two categories. The first category deals with the causes of the South Asian High. Yeh et al. (1957) found that during summer, an anticyclone occurs at the 3 km above the Tibetan Plateau while there is a huge anticyclone that has its center over the southern Tibetan Plateau from 6 km and above. Ye (1981), Gao et al. (1983), and Murakami (1987) attempted to find the cause of the formation of the South Asian High from seasonal and orographical heating.

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The second category concentrates on the origin of the South Asian High. Krishnamurti (1985), He et al. (1987), and Yanai and Song (1992) suggest that the South Asian High originates from South Asian region. Bao (1987) states that the South Asian High is a result of the equatorial anticyclone. Krishnamurti (1985), using data from mid-April to early-July, showed the origin and development of the South Asian High, but did not present those of the South Asian High after July.

The third category deals with snow cover. Snow cover is interacted with the atmospheric circulation in various scales from synoptic and hemisphere (Davies 1994). Eurasian snow cover has an critical important role in the variability of East Asian monsoon intensity and producing anomalous conditions in the coupled ocean/atmosphere system of the equatorial Pacific by means of the Asian monsoon (Barnett 1985; Yasunari 1990; Yasunari et al. 1991) Hahn and Shukla (1976) and Dickson (1984) found that there is an inverse relationship between the Eurasian winter snow cover and Indian summer monsoon precipitation. In case of positive anomaly of Tibetan snow cover, Barnett et al. (1989) explained that the summer heating of the Asian continent and the difference in air temperature between land and ocean cause a weak monsoon and Verneker et al. (1995) found that the trade winds are weakened in the east-equator Pacific. Shen et al. (1998) showed that the variation of solar radiation by the albedo of the snow in spring season affect the melting action of the snow and then the variation of the sensible heat flux is related to strong and weak monsoons. Moreover, though the negative relation between snow and monsoon rainfall has been documented since the times of Blanford, recent studies document a dipole pattern of correlation with snow over western (eastern) Eurasia having a negative (positive) relation with not only monsoon rainfall over India (Kripalani and Kulkarni 1999) but also with monsoon rainfall over Korea (Kripalani et al. 2002).

Lee (1991) presented that a large amount of rainfalls over the Korean Peninsula during Changma is related to the location, intensity, and movement of the South Asian High. Byun (1996) hypothesized that the South Asian High by snow cover of the Tibetan Plateau can affect the droughts and floods of the Korean Peninsula. Also, Park and Schubert (Park and Schubert 1998) presented the zonal wind variation by the orographical forcing as the mechanism of the formation of the East Asia circulation anomalies. Choi et al. (1998) investigated the correlation between South Asian High intensity by previous season snow cover over the North Hemisphere including Eurasia and Korean Peninsula summer monsoon rainfall. Kim et al. (2002) suggested that South Asian High and the related northward shift of the subtropical upper-level jet are responsible for the negative correlation between the summer monsoon rainfall over Korea and that over India.

As mentioned above, the South Asian High is one of the major members of the Asian summer monsoon system in the upper levels of the South Asian highland (Krishnamurti and Bhalme 1976; Tao and Chen 1987). Due to the effects of sensible heating in the Tibetan Plateau and latent heating in the monsoon regions (Krishnamurti et al. 1973; Huang 1985; Liu et al. 1999, 2001), SAH is the strongest and persistent anticyclone, stably located in the upper troposphere and lower stratosphere of the Northern Hemisphere in the boreal summer (Mason and Anderson 1963; Tao and Zhu 1964).

In relation to the shift of the SAH, Mason and Anderson (1963) discovered that the SAH underwent a longitudinal shift in summer. Tao and Zhu (1964) noted that the west–east shift of the SAH was opposite to the direction of movement of the western North Pacific subtropical high (WNPSH) at 500 hPa in a quasi-biweekly timescale. With respect to the zonal positions of the SAH, Luo et al. (1982) classified them into three patterns: east pattern, west pattern, and zonal (transitional) pattern. This classification has since been widely used in synoptic analysis. They also discussed the relationship between the three patterns and the rainfall variability in eastern China. Zhang et al. (2002), on the other hand, presented the bimodality (the Tibetan mode and the Iranian mode) of the SAH using climatological data, and explained the differences between the two modes based on an analysis of the west–east shift in the synoptic scale. In addition, they presented that the rainfall patterns in China associated with these two modes were substantially different from each other.

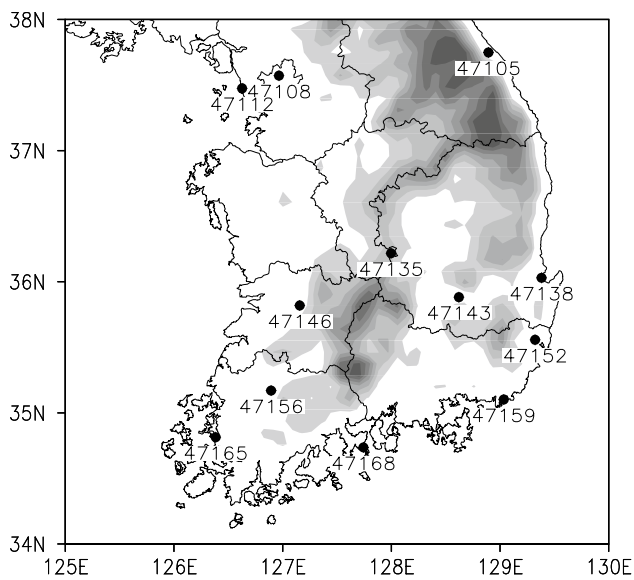
It has been demonstrated that, in the interannual timescale, the SAH varies in both zonal and meridional directions, which have major impact on the summer rainfall over eastern China (Wei et al. 2012, 2014a). However, although the SAH is a factor influencing the summer climate of East Asia, there has been no research on the relationship between the shift of the SAH and the summer monsoon rainfall in Korea. Thus, this study was conducted to delve deeper into this matter.

In this paper, Sect. 2 provides a description of the data and methodology used, and Sect. 3 provides the definition of the South Asian High index. The differences between the east shift years and west shift years of the SAH will be explained in Sect. 4, and a summary of the research results will be provided in Sect. 5.

## 2 Data and methodology

### 2.1 Data

The data used in this study were provided by the European Centre for Medium-Range Weather Forecast (ECMWF)



**Fig. 1** 12 Weather observation stations in Korea. Shaded area indicates height

(ERA-40, Uppala et al. 2005) for a 45 years period between 1958 and 2002 for the following variables: geopotential height (in gpm), zonal and meridional winds (in  $\text{m s}^{-1}$ ), air temperature (in  $^{\circ}\text{C}$ ), relative humidity (in %).

Also, the average amount of rainfall between the months of June and August measured by twelve weather observation stations on the Korean peninsula during the aforementioned time period was used. The locations of the weather observation stations are shown in Fig. 1, and their information is provided in Table 1.

**Table 1** Information of 12 weather observation stations in Korea

Station Name	ID	Geographic features			Observation starting date (year-month-day)
		Lat ( $^{\circ}\text{N}$ )	Lon ( $^{\circ}\text{E}$ )	Elevation (m)	
Gangneung	47105	37.73	128.88	25.91	1911-10-03
Seoul	47108	37.56	126.96	85.50	1907-10-01
Incheon	47112	37.46	126.62	68.85	1904-08-29
Chupung-nyeong	47135	36.13	127.99	242.00	1935-09-01
Pohang	47138	36.02	129.36	1.88	1944-07-17
Daegu	47143	35.87	128.62	57.64	1907-01-31
Jeonju	47146	35.82	127.15	53.48	1918-06-23
Ulsan	47152	35.55	129.31	34.69	1932-01-06
Gwangju	47156	35.17	126.88	70.53	1939-05-01
Busan	47159	35.10	129.03	69.23	1904-04-09
Mokpo	47165	34.80	126.38	37.88	1904-04-08
Yeosu	47168	34.73	127.73	66.05	1942-03-01

Also, the National Oceanic and Atmospheric Administration (NOAA) interpolated Outgoing Longwave 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, with 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).

The NOAA Extended Reconstructed monthly Sea Surface Temperature (SST) (Reynolds et al. 2002), available from the same organization, was also used. The data have a horizontal resolution of  $2.0^{\circ} \times 2.0^{\circ}$  latitude–longitude and are available for the period of 1854 to the present day.

In addition, the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997), the horizontal spatial resolution of which is the same as the NCEP-NCAR reanalysis dataset. This data is based on the monthly average and is available from 1979 to the present day. The CMAP data, which is global precipitation data that covers the ocean, are derived by merging rain gauge observations, five different satellite estimates, and numerical model outputs.

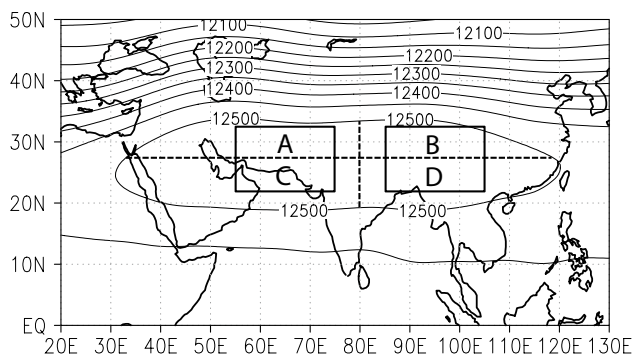
The tropical cyclone (TC) data in this study was obtained from the Best-track of TC provided by Regional Specialized Meteorological Center (RSMC)-Tokyo Typhoon Center. This data consist of TC name, latitude and longitude location of TC, TC central pressure, and TC Maximum Sustained Wind Speed (MSWS), which were observed in every 6 h for 35 years from 1978 to 2012. TC is generally classified into four classes by the criteria of MSWS as follows: Tropical Depression (TD,  $\text{MSWS} < 17 \text{ m s}^{-1}$ ), Tropical Storm (TS,  $17 \text{ m s}^{-1} \leq \text{MSWS} \leq 24 \text{ m s}^{-1}$ ), Severe Tropical Storm (STS,  $25 \text{ m s}^{-1} \leq \text{MSWS} \leq 32 \text{ m s}^{-1}$ ), Typhoon (TY,  $\text{MSWS} \geq 33 \text{ m s}^{-1}$ ). Along with the four classes of TC above, this study included extratropical cyclone, which was transformed from TC for analysis. This was because such extratropical cyclone also incurred great damage on property and human in the mid-latitude regions in East Asia.

## 2.2 Methods

In order to calculate TC passage frequencies, each TC was calculated after being relocated within a  $5^{\circ} \times 5^{\circ}$  grid. Even if a TC passed over the same grid multiple times, it was regarded as a single passage.

To test the reliability of the results produced from this study, the statistical method of Student's *t* test was applied (e.g., Wilks 1995).

In this study, ENSO years in June–August are selected from the website of CPC NOAA ([http://www.cpc.noaa.gov/products/analysis\\_monitoring/ensostuff/ensoyear.shtml](http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyear.shtml)).



**Fig. 2** 200 hPa geopotential height composite on climatology (1958–2002). Contour interval is 50 gpm

### 3 Definition of shift of South Asian high (SAH) index

Figure 2 shows the mean 200 hPa geopotential height in the 45 years period (1958 and 2002). Here, SAH is defined as a zone with values  $>12,500$  gpm. The SAH extends from the Arabian Peninsula to southern China and is located between the  $20^{\circ}\text{N}$  and  $35^{\circ}\text{N}$  latitudes. In this study, the central region of the SAH was classified into four areas: A-area ( $27.5\text{--}32.5^{\circ}\text{N}$ ,  $55\text{--}75^{\circ}\text{E}$ ), B-area ( $27.5\text{--}32.5^{\circ}\text{N}$ ,  $85\text{--}105^{\circ}\text{E}$ ), C-area ( $22.5\text{--}27.5^{\circ}\text{N}$ ,  $55\text{--}75^{\circ}\text{E}$ ), D-area ( $22.5\text{--}27.5^{\circ}\text{N}$ ,  $85\text{--}105^{\circ}\text{E}$ ). The mean values for the four areas were used to obtain the differences between the eastern region (BD area) and western region (AC area), southern region (CD area) and northern region (AB area), southwestern region (C area) and northeastern region (B area), and northwestern region (A area) and southeastern region (D area). Our division of the SAH is similar to that proposed by Wei et al. (2014b), in which the horizontal shifts of the SAH in different direction are investigated to examine their relations to the summer rainfall over India and eastern China.

The four values of the SAH determined in this manner were used to examine the correlation between the north–south, west–east, southwest–northeast and southeast–northwest shifts and the summer rainfall in Korea (Table 2). First, a high positive correlation was observed between the west–east shift and the summer rainfall in Korea at a 99 % confidence level, while there was a low negative correlation with the north–south shift and this was not statistically

significant. More specifically, the summer rainfall in Korea was positively and negatively correlated with the southeast (northwest)—northwest (southeast) shift and the northeast (southwest)—southwest (northeast) shift, respectively, at a 95 % confidence level. Accordingly, this study aimed to investigate into the relationship between the summer rainfall in Korea and the west–east shift of the SAH, which had the highest correlation. The index representing the west–east shift of the SAH is calculated as follows (Wei et al. 2014a):

$$\text{SAH index} = Z200(\text{BD})_{(22.5\text{--}32.5\text{N}, 85\text{--}105\text{E})} - Z200(\text{AC})_{(22.5\text{--}32.5\text{N}, 55\text{--}75\text{E})}$$

This index is defined as the normalized value of the difference between the mean 200 hPa geopotential height in the BD area and the mean 200 hPa geopotential height in the AC area as shown in Fig. 2. Thus, a positive index value means that the center of the SAH shifted eastward, while a negative index represents a westbound shift.

Figure 3 shows the time series of the SAH index calculated using the above equation and the normalized summer rainfall in Korea. Both time series represent the interannual and interdecadal variations and clearly show the in-phase relationship. The east–west shift of the SAH is related to the intensity of the Indian summer monsoon (Wei et al. 2014a), and the El Niño–Southern Oscillation (ENSO) influences both Indian summer monsoon and East Asian summer monsoon (Zhang et al. 1996; Wang et al. 2000). In order to check if the correlation between the SAH index and summer rainfall in Korea is a reflection of the ENSO effect, the correlation between the two variables was analyzed after excluding the El Niño years (1958, 1963, 1965, 1969, 1972, 1982, 1987, 1991, 1997, 2002) and the La Niña years (1964, 1970–1971, 1973–1975, 1985, 1988, 1998–2000) in summer (June to August) (Fig. 4a). A high positive correlation was also observed in the 24 years period under analysis at a 95 % confidence level. Also, the results of the correlation analysis of the two variables with respect to the ENSO years of the summer showed a high positive correlation of 0.46 at a 95 % confidence level (Fig. 4b). This showed that the high correlation between the SAH index and summer rainfall in Korea is not determined by ENSO and it would be reasonable to perform the analysis with the inclusion of the ENSO effects.

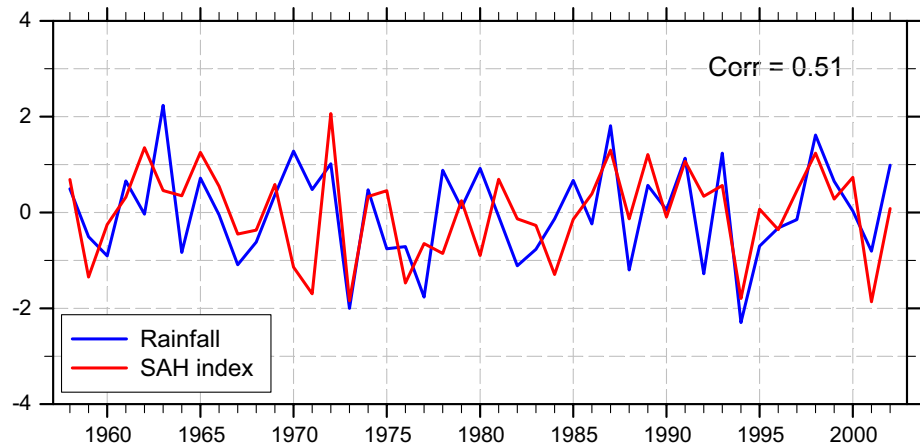
**Table 2** Correlation coefficient between Korea summer rainfall (June–August) and indices according to the shift direction of South Asian high

	Shift direction of South Asian high			
	East–West	North–South	Southeast–Northwest	Northeast–Southwest
Korea summer rainfall	0.51**	−0.12	0.33*	−0.33*

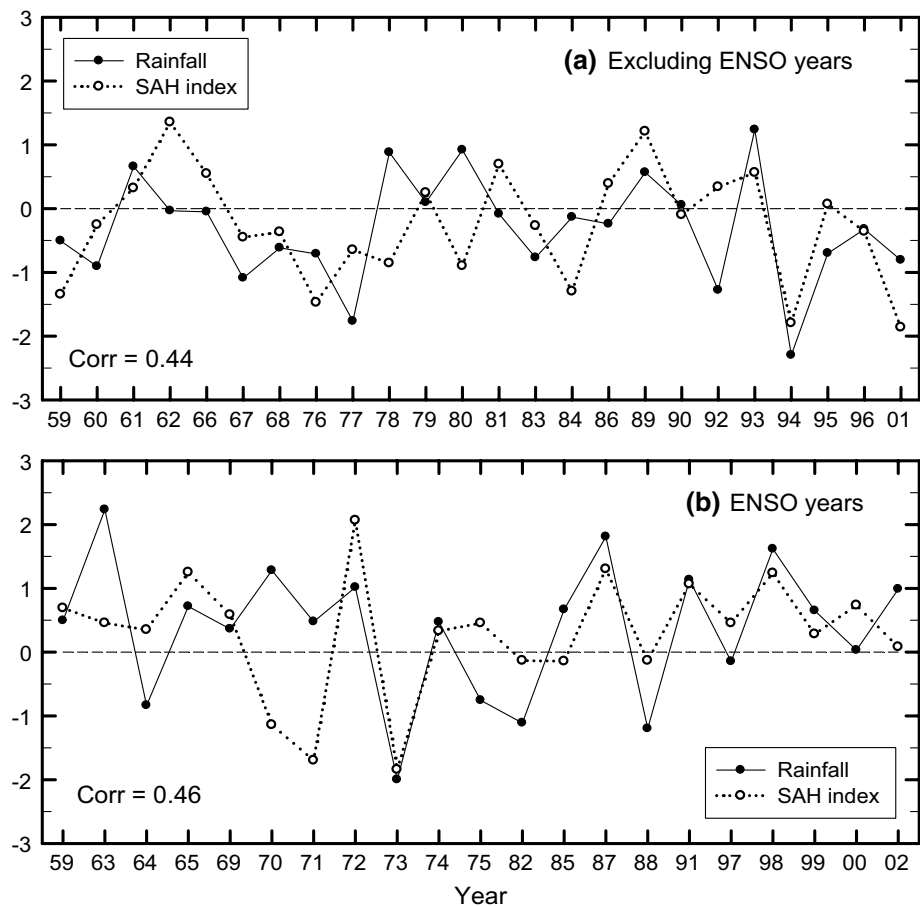
\* Denotes that correlation coefficient is significant at the 95 % confidence level

\*\* Denotes that correlation coefficient is significant at the 99 % confidence level

**Fig. 3** Time series of normalized Korea summer rainfall (blue line) and normalized index of East–West shift of South Asian high (red line)



**Fig. 4** Same as in Fig. 3, but for **a** excluding ENSO years and **b** ENSO years



#### 4 Differences between east shift years and west shift years

In order to examine the effects of the west–east shift of the SAH center on the summer rainfall in Korea, the ten with the highest indices (referred to as the east shift years) and the 10 years with the lowest indices (referred to as the west shift years; Table 3) were chosen from the time series of the

SAH index shown in Fig. 3. There was one east shift year (1962) and there were five west shift years (1959, 1973, 1976, 1994 and 2001), in which the rainfall was <600 mm. The average rainfall difference between these two groups was about 170 mm, which was significant at a 99 % confidence level.

The composite of the 200 hPa geopotential height for each of the two groups was analyzed (Fig. 4a, b). Once

**Table 3** Statistics on 10 East shift years and 10 West shift years of South Asian high

East shift years		West shift years	
Year	Rainfall (mm)	Year	Rainfall (mm)
1958	639.2	1959	485.4
1962	571.0	1970	808.2
1965	700.4	1971	685.5
1972	774.2	1973	302.6
1981	634.6	1976	517.1
1987	955.4	1978	775.3
1989	767.2	1980	789.1
1991	863.9	1984	638.1
1998	966.7	1994	334.6
2000	724.2	2001	595.8
Average	759.7	Average	593.2
SD	127.6	SD	172.3

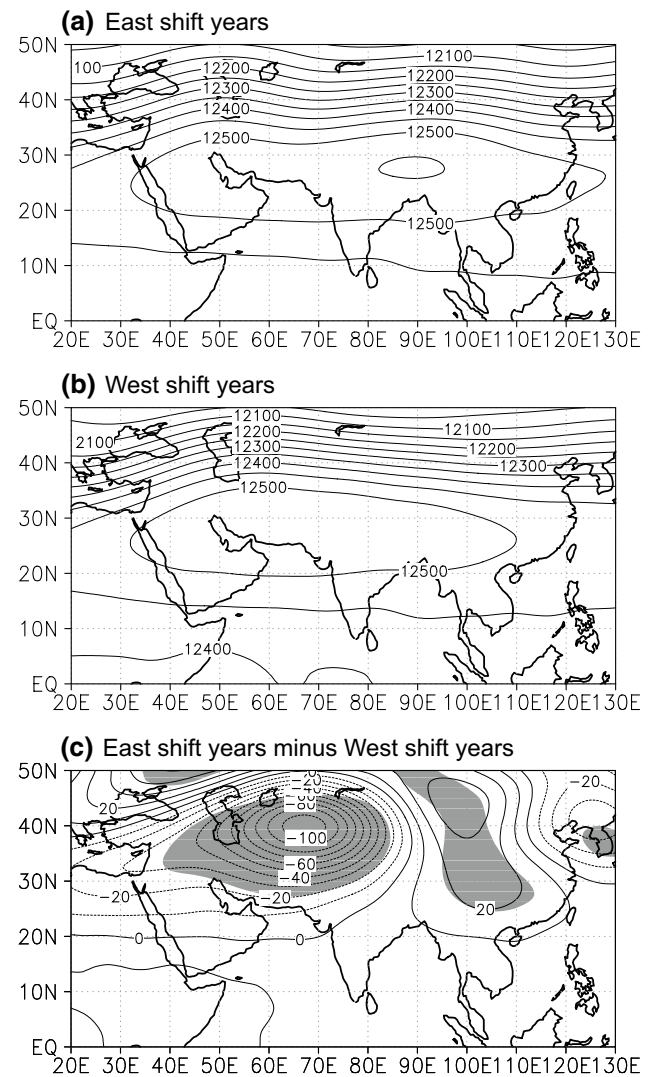
The SD means a standard deviation

again, SAH is defined as the zone with values greater than 12,500 gpm. First, the SAH center in the east shift years was located in the Tibetan Plateau and extended eastward to about 130°E (Fig. 5a). On the other hand, the SAH center in the west shift years was not visible, but the eastern boundary was contracted westward to about 110°E (Fig. 5b). Thus, with respect to the 200 hPa geopotential height difference, there was a negative anomaly in the west and a positive anomaly in the east, with the 80–90°E longitude serving as the boundary (Fig. 5c).

#### 4.1 Spatiotemporal variation of rainfall in Korea

The spatial distribution of the rainfall in Korea was examined (Fig. 6). Due to the positive correlation between the SAH index and the summer rainfall in Korea, all of the twelve weather observation stations presented a positive anomaly. Generally, the magnitude of the positive anomaly was greater in the southern region than in the northern region of Korea. In fact, the average positive anomaly measured by the twelve weather observation stations was about 300 mm. The values reported by all of the weather observation stations in the southern region except one (47146, Jeonju) were higher than the average value, while the values reported by all of the weather observation stations in the northern region except one (47108, Seoul) were below the average. This was similar to the findings reported by Choi et al. (2010), who proved that the gradual decline in the rainfall received by the northern region of Korea.

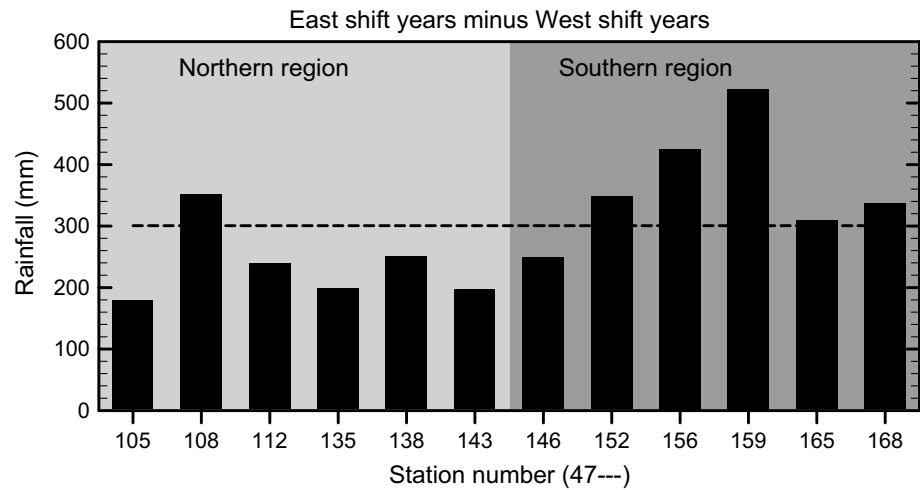
The annual variations of rainfall were examined (Fig. 7a). The 7 day running averaged rainfall was used for the analysis of the annual rainfall variations in this study. With respect to the 7 day running averaged rainfall, Ha



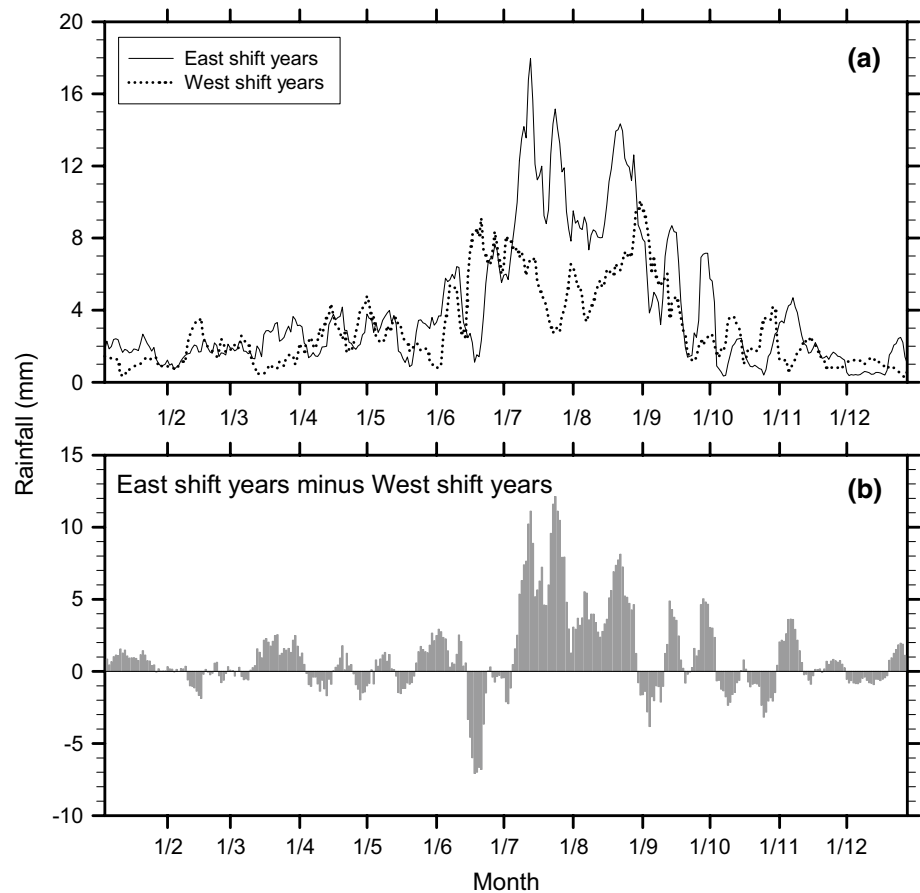
**Fig. 5** a East shift years, b West shift years, and c difference between the two groups. Contour intervals are 50 gpm in (a) and (b) and 10 gpm in (c). In c, shaded areas are significant at the 95 % confidence level

et al. (2009) used such data to successfully show that there was a significant change in the rainfall variability in the month of August in the late 1960s in Korea. Climatologically, the rainy season of Korea can be divided into three seasons (Byun and Lee 2002): the spring rainy season between early April and mid-May; the summer rainy season (Changma in Korea) between late June and late July; and the autumn rainy season (second Changma in Korea) between mid-August and early September. The spring rainy season nearly does not exist in the east shift years (solid line), but in the west shift years, rainfall starts to increase in early April before dropping in mid-May (dotted line). Thus, the spring rainy season in the west shift years coincides with the climatological spring rainy season. In the case of the summer rainy season, the amount of rainfall starts

**Fig. 6** Difference in Korea summer rainfall between East shift years and West shift years. *Dashed line* denotes an average of differences in 12 weather observation stations between the two phases



**Fig. 7** Temporal variabilities of the 7 day running averaged rainfall for **a** East shift years (*solid line*) and **b** west shift years (*dotted line*), and the difference between the mean of East shift years and the mean of west shift years



to rise in mid-June before reaching its peak in early June and declining in late July in the east shift years. In the west shift years, on the other hand, rainfall increases in early June and decreases in late July. Although the summer rainy season is longer in the west shift years than in the east shift years, the amount of rainfall is about two times smaller. As for the autumn rainy season, rainfall starts to increase

in mid-August and decreases in early September in the east shift years, and this coincides with the climatological autumn rainy season. In contrast, in the west shift years, rainfall starts to increase in early August before dropping in early September. Similar to the previous case, the autumn rainy season is longer in the west shift years than in the east shift years, but the amount of rainfall is nearly two times

smaller. Thus, the difference of annual rainfall variation between the two groups is the largest in summer (Fig. 7b). In other words, the amount of rainfall between the months of June and August, except in mid- and late June, is considerably higher in the east shift years. However, in the other months of the year, there are no significant differences in the rainfall between the two groups because it is the cold season in Korea and no much rainfall.

#### 4.2 Large-scale environments

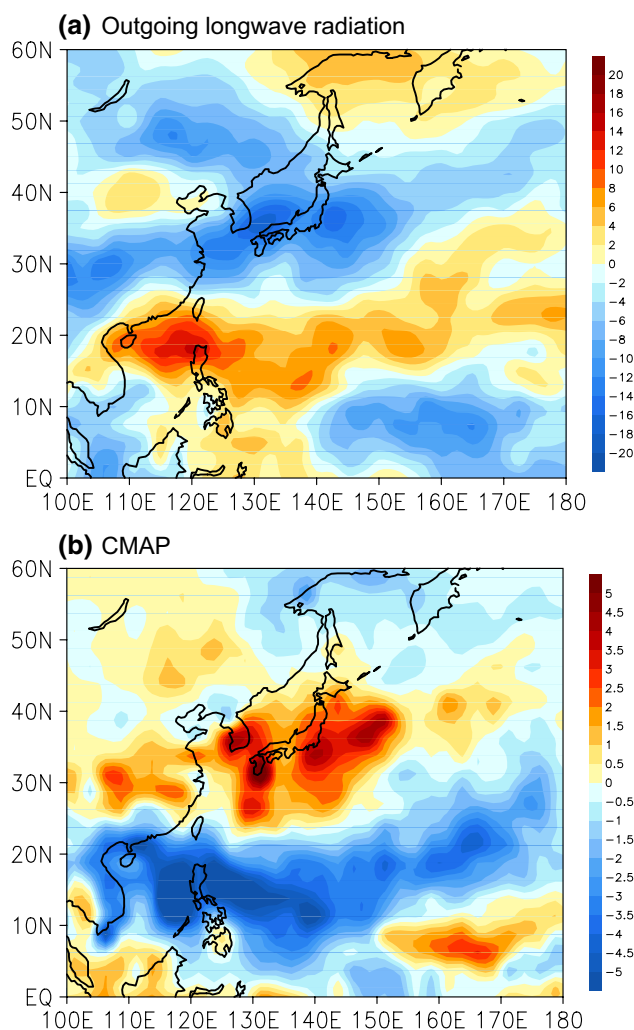
Figure 8a shows the OLR differences between the two groups. A negative anomaly was found across from the central region of China to the sea off the east coast of Japan, which covers Korea. This means that the convection was stronger in these regions in the east shift years. In contrast, a positive anomaly was found in the subtropical western North Pacific, indicating a weakened convection in these regions in the east shift years. Accordingly, there was a dipole pattern with respect to the OLR anomaly between the mid-latitude zones of East Asia and the subtropical western North Pacific. This means that while the East Asian summer monsoon developed in the east shift years, the western North Pacific summer monsoon weakened.

Due to the spatial distribution differences between the two groups with respect to the OLR, the opposite dipole pattern was observed in the CMAP (Fig. 8b). A positive anomaly was observed from central China to Korea and the sea off the east coast of Japan, where the convection was found to be steep in the OLR analysis results, and a negative anomaly was observed in the subtropical western North Pacific, where the convection was found to be weakened. These results well-reflect the positive correlation between the west–east shift of the SAH center and the summer rainfall in Korea.

In order to determine the causes behind the differences in the summer rainfall in Korea according to the west–east shift of the SAH center, the differences between the two groups with respect to the 850 hPa streamline were analyzed (Fig. 9a). The results showed an intensification of anomalous anticyclonic circulations in the subtropical western North Pacific, and an intensification of anomalous cyclonic circulations near Manchuria. In other words, the west-low and east-high anomalous pressure system pattern intensified, and this is the typical pressure system pattern observed in East Asia in summer. Thus, the areas near Korea are influenced by the anomalous southwesterlies forming between the two anomalous pressure systems. On the other hand, an analysis of the differences in terms of the 200 hPa streamline showed that anomalous anticyclonic circulations developed in the Northeast Asian continent, and anomalous cyclonic circulations was centered

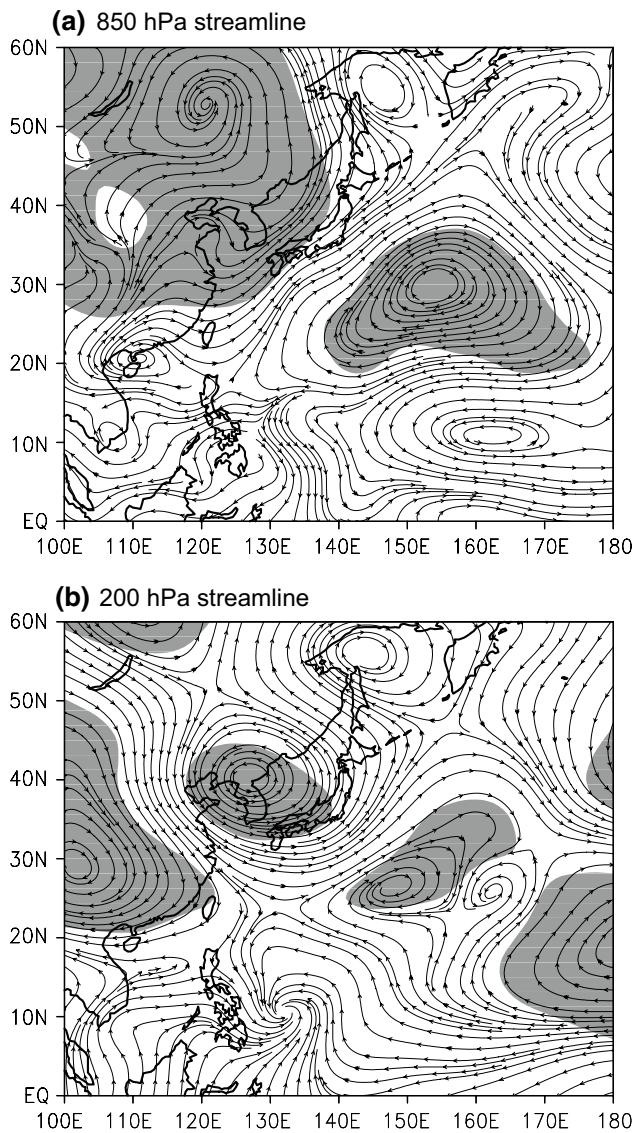
near 30°N, 100°E (Fig. 9b). Thus, Korea is influenced by the northwesterlies forming between these two anomalous circulations.

In Fig. 9, the anomalous anticyclonic circulations that developed in the subtropical western North Pacific at 850 hPa may be associated with the WNPSH, while the anomalous anticyclonic circulations that developed in the East Asian continent at 200 hPa may be associated with the development of the SAH. Thus, in order to examine this further, the degree of development of the SAH and WNPSH was analyzed with respect to the two groups (Fig. 10). Here, SAH and WNPSH were defined as zones with values >12,480 and 5870 gpm, respectively. In the east shift years, the SAH expanded eastward to about 145°E and at the same time, the WNPSH expanded westward to the areas near Taiwan (Fig. 10a). As shown in Fig. 9, this creates an environment that facilitates the intensification of the anomalous cold and dry northwesterly



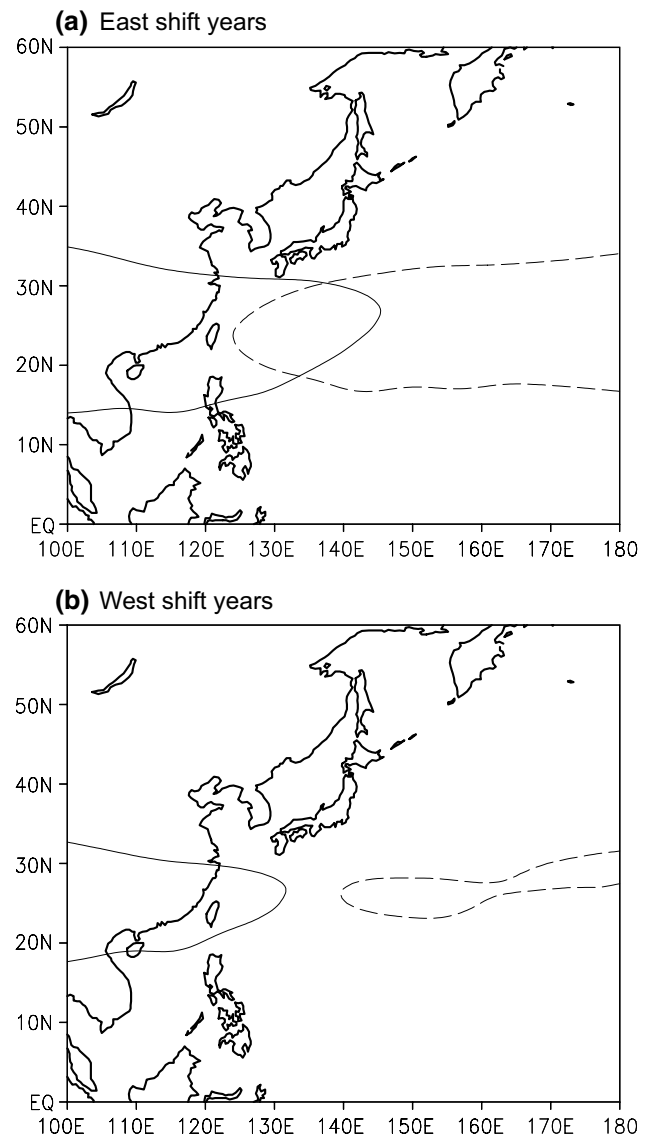
**Fig. 8** Differences in **a** outgoing longwave radiation (OLR) and **b** CMAP between East shift years and West shift years





**Fig. 9** Same as in Fig. 8 but for **a** 850 hPa and **b** 200 hPa streamlines. Shaded areas are significant at the 95 % confidence level

in the upper atmosphere in regions near Korea and the anomalous warm and humid southwesterly in the lower and middle atmosphere. It can be seen that both the SAH and WNPSH become developed in the east shift years. On the other hand, in the west shift years, the SAH weakened toward the west up to about 130°E, and the WNPSH contracted in both north–west and west–east directions (Fig. 10b). Such air pressure patterns in the upper, lower and middle atmosphere contribute to the creation of an environment with a negative effect on the increase in the summer rainfall near Korea. In the west shift years, both the SAH and WNPSH are weakened. It is important to note, however, that the reason for the simultaneous intensification and weakening of both pressure systems should be examined in future research.



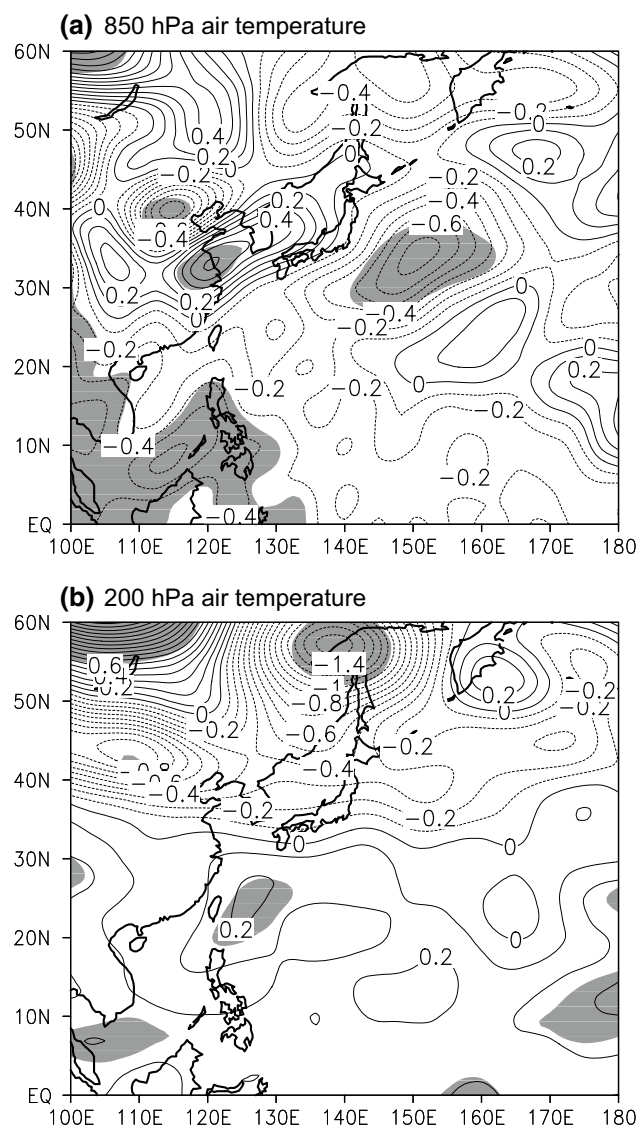
**Fig. 10** South Asian highs (solid line, 12,480 gpm) and western North Pacific subtropical highs (dashed line, 5870 gpm) in **a** East shift years and **b** West shift years

In order to examine whether the degree of the SAH and WNPSH development with respect to the two groups, shown in Fig. 10, actually has an impact on the air temperature of the regions near Korea, the air temperature differences between the two groups were examined (Fig. 11). In the east shift years, the warm anomaly intensified from eastern China to Korea and the East Sea due to the impact of the anomalous southwesterlies, which developed in the western periphery of the WNPSH, as shown in Fig. 9a (Fig. 11a). On the other hand, at 200 hPa, the cold anomaly was shown to have been intensified in the latitudes north of 35°N, which includes Korea, as the areas near Korea were influenced by the anomalous northwesterlies, as shown in Fig. 9b. As such, in the regions near Korea, the presence of

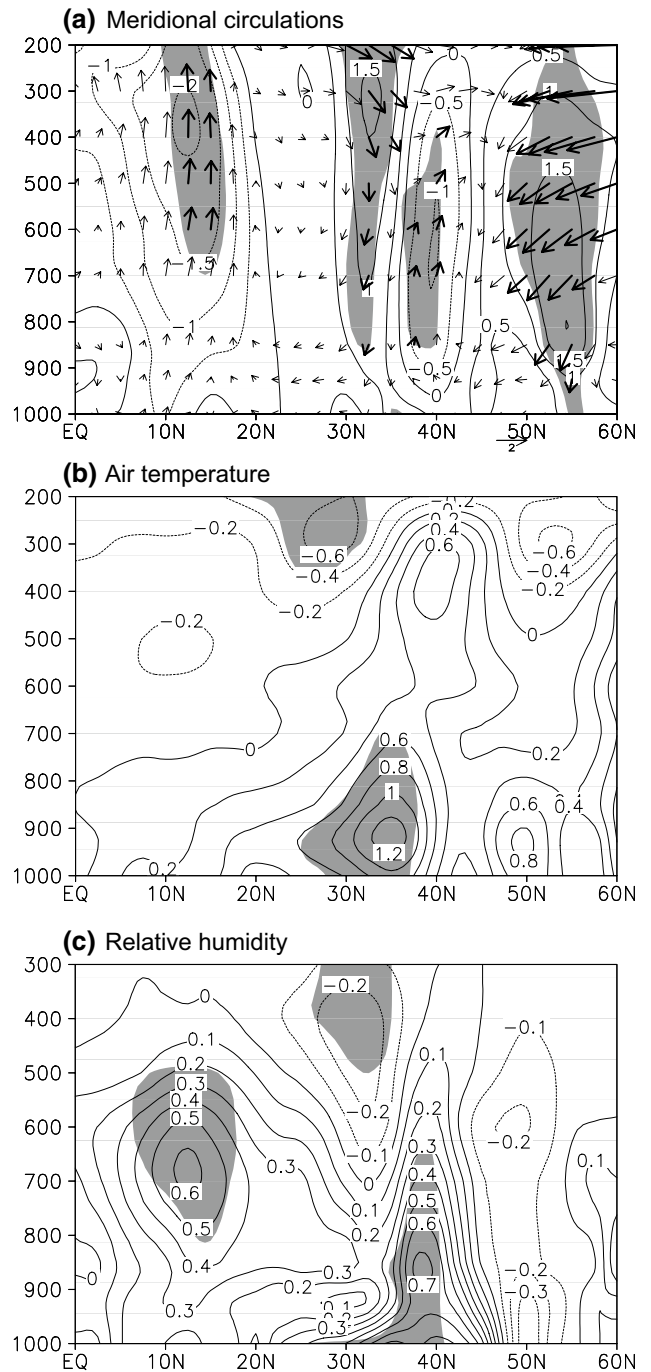
warm air temperature anomaly in the lower atmosphere and the cold air temperature anomaly in the upper atmosphere forms vertical thermal instability, and this can result in conditions that can contribute to the formation of precipitation.

The differences between the two groups were examined with respect to the meridional circulations, air temperature, and relative humidity in the averaged latitude–pressure cross-section between 120°E and 180°E, which is the longitudinal zone in which Korea is located, in order to examine the atmospheric conditions in the troposphere of the regions near Korea (Fig. 12). In the analysis of the meridional circulations, the results showed an intensification of anomalous downward flows in the upper atmosphere and anomalous upward flows in the lower atmosphere between

30°N and 40°N, the latitudinal zone in which Korea is located (Fig. 12a). This resulted in an environment that promoted thermal instability, as mentioned above, due to



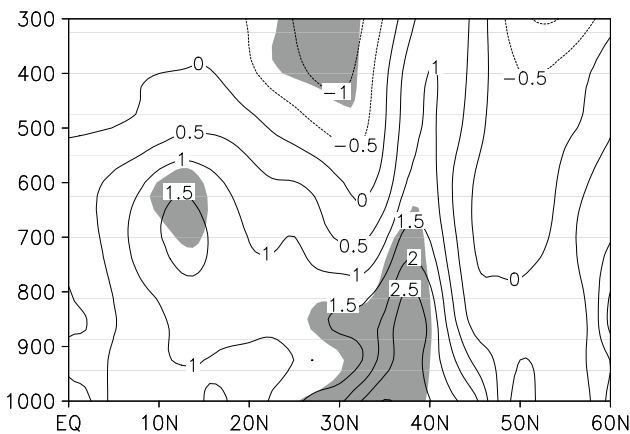
**Fig. 11** Same as in Fig. 8 but for **a** 850 hPa and **b** 200 hPa air temperatures. Contour interval is 0.1 °C. Shaded areas are significant at the 95 % confidence level



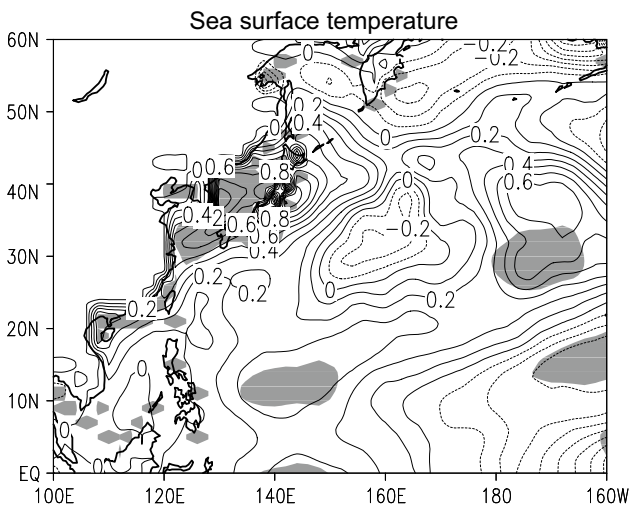
**Fig. 12** Composite differences of latitude–pressure cross section of **a** vertical velocity (contours) and meridional circulations (vectors), **b** air temperature, and **c** relative humidity averaged along 120°–130°N between East shift years and West shift years for June–August. The values of vertical velocity are multiplied by  $-100$ . Shaded areas are significant at the 95 % confidence level. Contour intervals are  $0.5^{-2}$  hPa  $s^{-1}$ , 0.2 °C for air temperature, and 0.1 % for relative humidity

the presence of a cold anomaly in the upper atmosphere and a warm anomaly in the lower atmosphere in the 30–40°N latitudinal zone, with respect to air temperature (Fig. 12b). As for relative humidity, there was an intensification of a dry anomaly in the upper atmosphere and a humid anomaly in the lower atmosphere (Fig. 12c), which showed that there was a good atmospheric vertical structure that could contribute to an increase in the summer rainfall near Korea.

In order to examine whether thermal instability in east shift years is strengthened around Korea, the difference in equivalent potential temperature between the two groups is analyzed (Fig. 13). The positive anomaly is positioned at the lower atmosphere between 30°N and 40°N where Korea is located, but negative anomaly at the upper atmosphere.



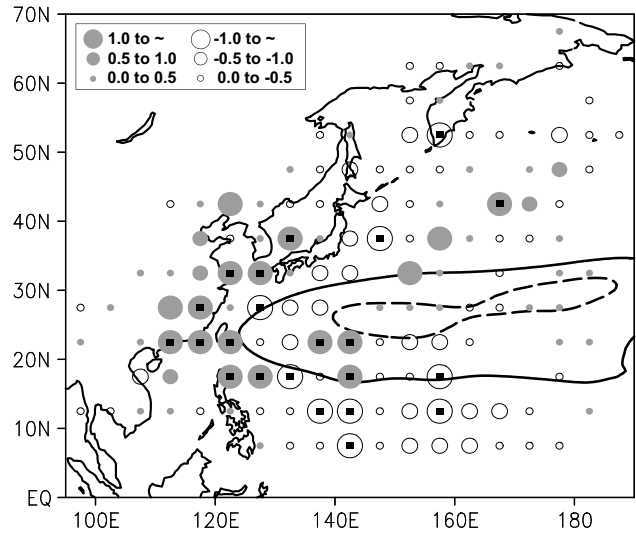
**Fig. 13** Same as in Fig. 12, but for equivalent potential temperature. Contour interval is 0.5 g kg<sup>-1</sup>. Shaded areas are significant at the 95 % confidence level



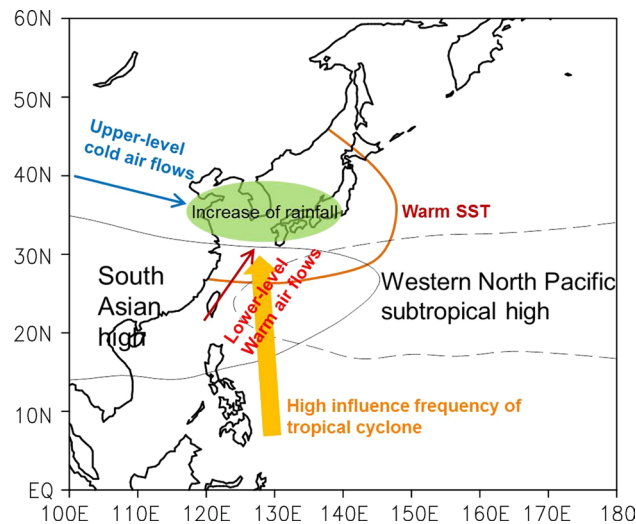
**Fig. 14** Same as in Fig. 8 but for SST. Contour interval is 0.1 °C. Shaded areas are significant at the 95 % confidence level

As mentioned above, thermal instability in east shift years is strengthened around Korea.

SST can also cause stability or instability in the atmosphere by exerting a thermal effect on the lower troposphere. Thus, the group differences in the SST were also analyzed in this study (Fig. 14). The results showed the presence of a warm SST anomaly, which was significant at a 95 % confidence level, in the waters in the mid-latitude zones of East Asia (30°–40°N, 120°–150°E). But, cold SST anomaly is shown in the subtropical western North Pacific (0°–20°N,



**Fig. 15** Difference in TC passage frequency between East shift years and low shift years. Small squares inside the circles indicate that the differences are significant at the 95 % confidence level. Solid and dashed lines represent 5870 gpm contours in East shift years and West shift years, respectively



**Fig. 16** Schematic illustration of anomalous atmospheric circulation patterns for East shift years of South Asian high

160°–180°E). A warm SST anomaly not only heats the lower troposphere, but also supplies water vapor, thereby increasing thermal instability and creating a good condition for an increase in the summer precipitation near Korea.

Tropical cyclones (TCs) can also have a significant impact on the summer rainfall variability in Korea. Thus, the group differences in the TC track were analyzed (Fig. 15). In the east shift years, the WNPSH developed westward to the regions near Taiwan and the TCs in those years showed a pattern of moving from the sea off the northeast coast of the Philippines toward the south-central region of China and ultimately landing in Korea and Japan. In contrast, in the west shift years, due to the contraction of the WNPSH, the TCs mainly moved from the sea far off the south coast of the Philippines, past the East China Sea and toward the sea off the east coast of Japan. Thus, as explained earlier, in the east shift years, the SAH and WNPSH led to the thermal instability in the atmosphere, and the TCs also had an impact on the increased rainfall in Korea in summer.

## 5 Summary and conclusions

In this study, the correlation between the north–south, west–east, southwest–northeast, and southeast–northwest shifts of the South Asian High (SAH) and the summer (June–August) rainfall variability in Korea over the course of 45 years (1958–2002) was examined. The highest correlation was observed between the summer rainfall variability in Korea and the west–east shift, out of all four directions. However, the correlation between the summer rainfall variability in Korea and the shifts in other directions was much less significant, and this showed that the east–west shift of the SAH center had a significant impact on the summer rainfall variability in Korea. Accordingly, analyses were carried out to examine the summer rainfall variability in Korea resulting from the east shift years and the west shift years, centering on the SAH, and the large-scale environments that cause the variability. In other words, the differences between the mean values of the east and west shift years were determined.

An analysis of the spatial distribution of the rainfall showed that the amount of rainfall was higher in the northern region of Korea than the southern region in the east shift years. It is deemed that further research using regional numerical modeling is necessary to determine the cause of this phenomenon. Also, an analysis of the annual rainfall variations showed the absence of a spring rainy season in the east shift years, but the amount of rainfall in the summer and autumn rainy seasons of the east shift years was almost double of the amount of rainfall in the summer and autumn rainy seasons of the west shift years.

In order to examine the cause behind the differences between the two groups with respect to the amount of rainfall in summer, their differences in terms of the 850 hPa streamline were analyzed. The results showed that an anomalous cyclone and an anomalous anticyclone (western North Pacific subtropical high) were intensified in the East Asian continent and the western North Pacific, respectively; Korea, situated between these two pressure systems, was affected by the anomalous southwesterlies and the warm and humid air was supplied to the regions near Korea. On the other hand, with respect to the differences in the 200 hPa streamline, an anomalous cyclone intensified near Korea and there was a supply of cold and dry air to the upper atmosphere near Korea. This was possible due to the expansion of the SAH toward the east, near the southern part of Korea, which in turn caused the intensification of the northwesterlies.

As such, the properties of the air masses in the upper and lower atmosphere near Korea were determined based on the differences between the two groups with respect to the meridional circulations, air temperature, and relative humidity in the average latitude–pressure cross-section between 120°E and 180°E, which is the longitudinal zone in which Korea is located. In the latitudinal zone in which Korea is located, there were warm and humid anomalous upward flows in the lower atmosphere and cold and dry anomalous downward flows in the upper atmosphere. As such, the cold and dry air masses present in the upper and humid and warm air masses in lower atmosphere near Korea caused thermal instability, and this was analyzed to be a major factor that could potentially increase the amount rainfall in Korea in summer in the east shift years. Also, a warm SST anomaly formed in the waters of the mid-latitude zones of East Asia heated the lower troposphere and supplied water vapor, thereby intensifying the thermal instability even further. Furthermore, TCs frequently had an impact on Korea in the east shift years, and were another factor that caused the increased rainfall in summer. A schematic illustration of the above explanation is shown in Fig. 16.

It was noted earlier that the development and weakening of SAH and WNPSH occurred simultaneously. However, the cause of this phenomenon has not yet been revealed, and there are plans to investigate into the relationship between these two pressure systems in the future. The reason for this is that both the SAH and WNPSH are important factors that affect the summer rainfall variability in Korea.

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