

# The spatio-temporal characteristics of total rainfall during September in South Korea according to the variation of ENSO

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**Abstract** A significant negative correlation between the total rainfall averaged over South Korea and the Niño-3.4 index was found for the month of September. To find out the reason for this negative correlation, composite analyses were carried out for the highest and lowest 8 years of the Niño-3.4 index. During the strong El Niño year, an anomalous anticyclone occurs in the continental East Asia, while an anomalous cyclone emerges in the subtropical western Pacific. The resultant eastward pressure gradient force induces anomalous northerlies in most regions of East Asia, which produces anomalous cold and dry conditions throughout the troposphere between 120° and 140°E, reducing the Korean rainfall. It is also found that during El Niño year, tropical cyclones (TCs) tend to recurve far east offshore of Japan because the weakening of the western North Pacific subtropical high (WNPSH). During La Niña years, on the other hand, the strengthening and westward extension of the WNPSH render more TCs influencing the Korean peninsula. Therefore, the TC track

changes associated with El Niño-Southern Oscillation is another contributor to change of the Korean rainfall.

**Keywords** Korean rainfall · Western North Pacific subtropical high · ENSO

## 1 Introduction

Recently, abnormal weather phenomena such as abnormal high temperature, abnormal low temperature, floods and drought, and heavy snowfall have occurred frequently over the world. Since these phenomena cannot be explained by analysis on the weather condition of a specific region, the characteristics of the global-scale atmospheric circulation should be considered. In particular, since climate phenomena that appear in the mid-latitudes are closely related to climate changes in the tropics, many studies have been performed to find out the correlation about climate interaction between the tropics and the mid-latitudes. The El Niño-Southern Oscillation (ENSO) phenomenon, which gives a great influence on the global climate, is a typical climate phenomenon occurred in the tropics. ENSO has been known to be a major cause to generate extreme weather in the world. Also, ENSO is known to be the most important phenomenon to cause the interannual variation of the large-scale atmospheric circulation in the tropical Pacific, which accounts for more than one-third of the interannual variation of the large-scale atmospheric circulation in the tropical Pacific (Horel and Wallace 1981). The ENSO phenomenon is a climate pattern that does not occur intermittently but recurs between El Niño and La Niña periodically in every 2–7 years. Therefore, it is a right direction to understand the ENSO phenomenon as an effect on climate changes rather than as the main cause of the extreme weather or weather disasters.

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The studies on the global-scale influences with regard to ENSO have been focused mostly on rainfall changes. As for the study on the relationship between ENSO and rainfall in South Korea, Kang et al. (1992) showed that the sea surface temperature in the Pacific Ocean was the most important variable for the long-term forecast of rainfall in South Korea. Kim et al. (1995) indicated that more detailed studies were required due to no specific influence of ENSO found on rainfall changes in South Korea though there was a high correlation between El Niño and Asian monsoon in the year of 1988. Ahn and Park (1996) and Oh (1996) studied on the effects of variations in the large-scale atmospheric circulation due to El Niño on rainfall changes in South Korea using the general circulation model. Kang and Jeong (1996) showed that rainfall in Seoul tended to increase slightly in the years of El Niño. Kang (1998) showed that El Niño and rainfall in South Korea were related with each other in cycles of 5–7 years, and 3 years. In particular, they stressed that variations of the 3 year cycle were consistent with the inter-variation timescale between El Niño and the summer monsoon. Ahn et al. (1997) analyzed the correlation between monthly average rainfall in South Korea and the strength of El Niño. This paper presented that winter and summer rainfall anomaly in South Korea had a high correlation with the sea surface temperature in the equatorial Pacific 6 month ago. Cha et al. (1999) proved that while the onset and withdrawal dates of Changma were delayed and rainfall increased during this Changma period in the El Niño years, the onset date of Changma was similar to the one in the normal year and the withdrawal date was earlier than the one in the normal year thereby making the Changma period shorter and decreasing rainfall in that period. Cha et al. (2000) showed that based on a study on correlations between the large-scale atmospheric circulation due to El Niño in 1997/1998 and summer climate in 1998, the summer mean temperature in 1998 was lower than the one in the normal year, and in particular, low temperature in the Youngdong region of South Korea occurred due to the abnormal activity of the Okhotsk high. Also, they showed that rainfall was larger than the normal year due to heavy rainfall between the 31st of July and the 18th of August in 1998. Byun et al. (2001) found out that there was no significant correlation between the years of El Niño and La Niña, and drought and floods in the Asia region through contemporaneous and lagged correlation analysis. Kim et al. (2012) proved that based on the comparison results of winter rainfall in South Korea by dividing the El Niño years into the canonical El Niño years and the El Niño Modoki years, more rainfall occurred during the El Niño Modoki years than average one but showed no significant change of rainfall during the canonical El Niño years. As indicated above, there were many studies on correlation between

ENSO and rainfall in South Korea, but the mechanism between them is not fully understood.

Once Bjerknes (1969) interpreted the El Niño phenomenon as part of the global climate changes for the first time, a number of researchers have studied on the dynamics of El Niño (Neelin and Jin 1993; Kang and An 1998), correlation with the global climate system (Horel and Wallace 1981; Kang and Lau 1986), and prediction of El Niño (Zebiak and Cane 1987; Chen et al. 1997, Kirtman et al. 1997). As part of the overseas studies on correlation between the ENSO phenomenon and rainfall changes, correlations between the monsoon and El Niño have been studied many times. According to the study of Webster and Yang (1992) and Lau (1992), the Asian monsoon and El Niño had the highest correlation with time delay of approximately 9 months, and the strength of the monsoon weakened in general during the El Niño year. Accordingly, in the El Niño year, while rainfall in India showed a significant tendency to weaken, rainfall in the region of the Yangtze River in China increased but showed a tendency of decrease in the northern part of the Yellow River. Xie et al. (1997) discussed that the onset date of the East Asian summer monsoon was delayed in the El Niño year thereby showing a tendency of decreasing the summer rainfall. Wu and Wang (2002) showed that the convection change in the equatorial Pacific occurred in the late 1970s so that inverse relationship between ENSO and rainfall in the India region weakened. Ropelewski and Halpert (1987) and Halpert and Ropelewski (1992) discussed about characteristics of rainfall changes related to ENSO in terms of global and regional scales. Rasmusson and Carpenter (1982, 1983) and Shukla and Paolino (1983) studied on relationship between the sea surface temperature in the equatorial eastern Pacific and summer monsoon rainfall in India and Sri Lanka. Harger (1995) presented correlations between the ENSO change and drought occurrence in Indonesia and Philippines. Nigam (1994) discussed about the mechanism basis of relationship between the Asian summer monsoon rainfall and El Niño. Mujumdar et al. (2007) presented that the sea surface temperature in the western Pacific, not in the eastern Pacific, had a high correlation with the summer monsoon rainfall in the region of India. Also, Soman and Slingo (1997) and Ju and Slingo (1995) discussed about the relationship between ENSO and the Asian summer monsoon rainfall. In addition to these researches, there are some studies on the relationship between ENSO and East Asian climate (Wang et al. 2000; Wu et al. 2012a, b).

The relationship between changes in the sea surface temperature in the tropical Pacific and climate changes in Japan has been studied extensively in Japan too. Aoki (1985) showed that the summer rainfall decreased due to reduction of tropical cyclone (TC) genesis frequency in the tropical western Pacific during the El Niño year and

frequency of TCs that influence Japan. Miyazaki (1988, 1989) analyzed the typical fluctuation of rainfall change in Japan in the El Niño year while Nitta (1990) found out that the convective activity near the sea of Philippines which is a part of the tropical Pacific, had a great effect on the rainfall changes in Japan. In addition to these researches, there are some studies on the effect of mid-high latitude systems on the East Asian climate (Wu et al. 2009, 2010, 2011, 2012a, b; Li and Wu 2012).

As discussed in the previous studies, ENSO had a close correlation with not only climate changes in the tropical regions but also climate changes in the East Asian mid-latitude regions including South Korea and Japan. Though changes in the sea surface temperature in the tropical eastern Pacific, which is the index of ENSO, could influence rainfall changes in the mid-latitude region simultaneously, it could delay influence due to the non-linearity of the ENSO phenomenon. Therefore, since rainfall changes in the mid-latitude region due to the sea surface temperature in the tropical Pacific could be shown differently in the El Niño year, the rainfall forecast could be very difficult. Nonetheless, there have been few studies on relationship between ENSO and the mid-latitude rainfall in terms of not only lagged correlation but also contemporaneous correlation. In this study, we will analyze by focusing on the contemporaneous correlation between the two variables rather than on the time-delayed correlation.

In Sect. 2, data and analysis methodology used in this study are introduced. In Sect. 3, correlations between monthly total rainfall averaged over South Korea and the Niño-3.4 index will be studied. In Sect. 4, spatio-temporal characteristics of rainfall due to the change of the Niño-3.4 index and the large-scale atmospheric circulations that cause these characteristics will be analyzed. Finally, the results of this study are summarized in Sect. 5.

## 2 Data and methodology

### 2.1 Data

#### 2.1.1 Observation data

This study used the monthly total rainfall data between 1982 and 2011 (30 years), which was obtained from the 61 weather observation stations of the Korea Meteorological Administration (KMA). Also, the monthly total rainfall data in the same period from 160 weather observation stations in China excluding the western arid region of 90°E, 26 weather observation stations in North Korea and 51 weather observation stations in Japan was used. The rainfall data of these three nations are available from the

web sites of China Meteorological Administration (CMA, <http://www.cma.gov.cn>), KMA (<http://www.kma.go.kr>) and Japan Meteorological Agency (JMA, <http://www.jma.go.jp>) respectively.

#### 2.1.2 Reanalysis data

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) (Kalnay et al. 1996; Kistler et al. 2001) Reanalysis dataset in the same period with the observed rainfall data were used. The variables used were geopotential height (gpm), zonal and meridional winds ( $\text{m s}^{-1}$ ), vertical velocity ( $\text{m s}^{-1}$ ), air temperature ( $^{\circ}\text{C}$ ), relative humidity ( $\text{g kg}^{-1}$ ), velocity potential ( $\text{m}^2 \text{s}^{-1}$ ), precipitable water ( $\text{kg m}^{-2}$ ). These data are configured in spatial resolutions such as  $2.5^{\circ} \times 2.5^{\circ}$  (latitude  $\times$  longitude) and 17 vertical layers (except for precipitable water which is one layer only) and are available for the period from 1948 to present.

Also, NOAA interpolated outgoing longwave radiation (OLR) data which was retrieved from the NOAA satellite series was used. This data between 1974 and the present is available in the Climate Diagnosis Center (CDC) though it has missing data between March and December of 1978. For more information about the OLR data, refer to the study results of Liebmann and Smith (1996) or the CDC website (<http://www.cdc.noaa.gov>).

Extended reconstructed monthly sea surface temperature (SST) data that constructed using the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) SST data was used to analyze large-scale oceanic environments. The data have a spatial resolution of  $2.0^{\circ} \times 2.0^{\circ}$  and are available from 1854 to present (Reynolds et al. 2002).

#### 2.1.3 Tropical cyclone (TC) data

This study used the TC best track archives provided by Regional Specialized Meteorological Center (RSMC), Tokyo Typhoon Center in order to find out the effect of TCs on the monthly total rainfall averaged over South Korea. This data included information such as the name of TC, latitude and longitude location, minimum surface central pressures, and maximum sustained wind speeds (10-min average maximum winds to the nearest 5 kts) at 6 h intervals. Generally, TCs are graded into 4 grades based on the maximum sustained wind speed (MSWS): tropical depression ( $\text{MSWS} < 17 \text{ m s}^{-1}$ ), tropical storms ( $17 \text{ m s}^{-1} \leq \text{MSWS} \leq 24 \text{ m s}^{-1}$ ), severe tropical storms ( $25 \text{ m s}^{-1} \leq \text{MSWS} \leq 32 \text{ m s}^{-1}$ ), and typhoons ( $\text{MSWS} \geq 33 \text{ m s}^{-1}$ ). Currently, this study used the data of TCs which have these 4 grades of intensity.

## 2.2 Methodology

A classification of high, low, and normal Niño-3.4 index years from the SST anomalies (SSTA) over the Niño-3.4 region (5°S–5°N, 170°W–120°W) is determined by the following criteria:

High :  $SSTA \geq 0.5$  °C

Low :  $SSTA \leq -0.5$  °C

Normal :  $-0.5$  °C  $\leq SSTA \leq 0.5$  °C

To obtain the SSTA, the climatological mean SST for 30 years averaged over the Niño-3.4 region was used. In addition, in this study, a statistical method called Student's *t* test was applied for the significance test. For more information about this statistical method, refer to Wilks (1995).

## 3 Correlation between monthly total rainfall in South Korea and Niño-3.4 index

Table 1 shows the correlation between monthly total rainfall in South Korea and the Niño-3.4 index. The Niño-3.4 indices during winter (January and February) and early spring (March) showed a positive correlation of more than 0.47 with April total rainfall at the 99 % confidence level. Also, the Niño-3.4 indices during winter (January and February) and spring (March and April) showed a negative correlation of more than  $-0.36$  with June total rainfall at the 95 % confidence level. Furthermore, it was analyzed that the Niño-3.4 indices from summer showed a high correlation with rainfall after summer in South Korea. The Niño-3.4 indices during summer (June–August) and early autumn (September) showed a negative correlation of more than  $-0.46$  with September total rainfall at the 99 % confidence level. In particular, the Niño-3.4 indices showed the highest correlation with total rainfall in September after summer. This indicates that the SST in the Niño-3.4 region started to increase from spring (correlations between the Niño-3.4 indices of April and May, and the September total rainfall were  $-0.07$  and  $-0.22$  respectively), and in September, in which the SST reached to the highest in the tropical Pacific all the year round, reduction of rainfall was most prominent. The correlation between the September Niño-3.4 index and September total rainfall is a strong negative contemporaneous correlation of  $-0.54$ . The Niño-3.4 indices during summer (July and August) and autumn (September and October) showed a positive correlation of more than 0.45 with November total rainfall at the 99 % confidence level. Also, the Niño-3.4 indices during summer (Jun–August), autumn (September–November) and winter (December) showed a positive correlation of more than

0.39 at the confidence level of more than 95 %. In particular, it showed that as the Niño-3.4 index is closer to winter, a correlation with the total rainfall is higher. The December Niño-3.4 index showed a high positive correlation of 0.52 with the December total rainfall.

As discussed above, it showed a unusual relationship that while a positive correlation was shown between monthly total rainfall from late autumn through winter to early spring in South Korea and the Niño-3.4 indices, a negative correlation was shown between monthly total rainfall from early summer to early autumn and the Niño-3.4 indices.

Figure 1 showed the time series of the September Niño-3.4 index (dotted line with open circles) and the September total rainfall (solid line with closed circles) in South Korea, which showed the highest correlation between the two variables in the recent 30 years. As explained above, apparent out of phase relationship was shown between the two variables. However, if we eliminate trends from the two variables, correlation between them can be different. While the trend of September total rainfall was shown little change (thick solid line), the trend of the September Niño-3.4 index was shown to be decreased slowly (thick dashed line). Therefore, even though trends were eliminated from the two variables respectively, a negative correlation between the two variables was not changed significantly (Corr =  $-0.53$  at the 99 % confidence level).

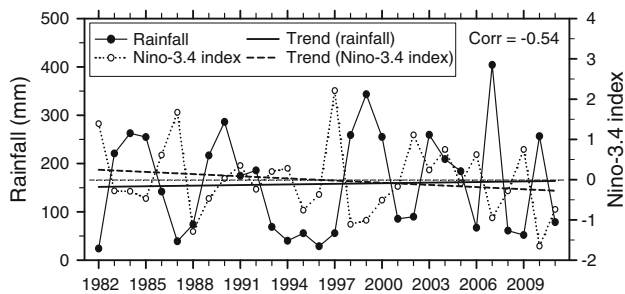
Analysis on the correlation between the September total rainfall in South Korea and the September Niño-3.4 index was performed on the weather observation stations in South Korea and its spatial distribution was reviewed (Fig. 2). Most of the regions in South Korea showed that the correlation between the two variables was significant at the 90 % confidence level. Other than a few weather observation stations, most places showed the negative correlation of more than  $-0.3$ . Also, places shown the negative correlation of more than  $-0.3$  were not limited to any specific region but to all areas distributed evenly in South Korea.

The correlation between the September total rainfall and the September Niño-3.4 index was analyzed extensively in the region of East Asia (Fig. 3). Overall, a negative correlation was shown in most regions of East Asia except Manchuria, southern parts of China, and south-west areas of Japan. In addition, some regions of North Korea also showed a significant correlation in the west coast area at the 90 % confidence level. Therefore, a correlation between the monthly total precipitation averaged over North Korea and the monthly Niño-3.4 index was studied (Table 2). Overall, a high correlation was not shown at the 99 % confidence level. Although a correlation between the two variables was not shown as high as in South Korea, seasonal variability of the correlation between the two

**Table 1** Correlation coefficients between monthly total rainfall in South Korea and Niño-3.4 index

| Niño-3.4 index | Monthly total rainfall |      |      |             |       |       |       |      |              |       |             |             |
|----------------|------------------------|------|------|-------------|-------|-------|-------|------|--------------|-------|-------------|-------------|
|                | Jan                    | Feb  | Mar  | Apr         | May   | Jun   | Jul   | Aug  | Sep          | Oct   | Nov         | Dec         |
| Jan            | −0.10                  | 0.11 | 0.19 | <b>0.47</b> | −0.01 | −0.37 | −0.12 | 0.26 | 0.13         | −0.18 | −0.29       | −0.09       |
| Feb            |                        | 0.14 | 0.12 | <b>0.51</b> | −0.03 | −0.36 | −0.08 | 0.28 | 0.12         | −0.21 | −0.24       | −0.08       |
| Mar            |                        |      | 0.12 | <b>0.47</b> | −0.02 | −0.36 | −0.12 | 0.28 | 0.07         | −0.19 | −0.23       | −0.07       |
| Apr            |                        |      |      | 0.33        | 0.02  | −0.37 | −0.11 | 0.27 | −0.07        | −0.24 | −0.09       | 0.10        |
| May            |                        |      |      |             | 0.10  | −0.25 | −0.04 | 0.22 | −0.22        | −0.18 | 0.18        | 0.24        |
| Jun            |                        |      |      |             |       | −0.28 | 0.11  | 0.13 | <b>−0.46</b> | −0.16 | 0.34        | <i>0.39</i> |
| Jul            |                        |      |      |             |       |       | 0.18  | 0.07 | <b>−0.48</b> | −0.18 | <b>0.45</b> | <i>0.43</i> |
| Aug            |                        |      |      |             |       |       |       | 0.02 | <b>−0.49</b> | −0.12 | <b>0.45</b> | <i>0.40</i> |
| Sep            |                        |      |      |             |       |       |       |      | <b>−0.54</b> | −0.15 | <b>0.50</b> | <i>0.39</i> |
| Oct            |                        |      |      |             |       |       |       |      |              | −0.09 | <b>0.48</b> | <b>0.45</b> |
| Nov            |                        |      |      |             |       |       |       |      |              |       | <i>0.44</i> | <b>0.49</b> |
| Dec            |                        |      |      |             |       |       |       |      |              |       |             | <b>0.52</b> |

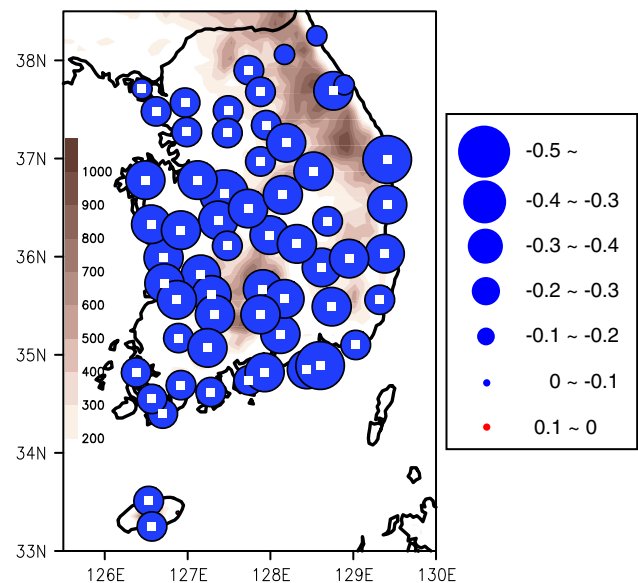
Bold and Italicised values are significant at the 99 and 95 % confidence levels, respectively



**Fig. 1** Time series of September total rainfall in South Korea (solid line with closed circles) and September Niño-3.4 index (dotted line with open circles)

variables was shown similar as in South Korea. The Niño-3.4 indices during February and March showed a high correlation of more than 0.39 with the April total rainfall at the 95 % confidence level. Also, the Niño-3.4 indices in September and December showed a negative contemporaneous correlation of  $-0.40$  with the September total rainfall and a positive contemporaneous correlation of  $0.38$  with the December total rainfall respectively at the 95 % confidence level. Therefore, in this study, characteristics of changes in the September total rainfall, which showed not only the highest correlation between the monthly total rainfall in South Korea and North Korea and the Niño-3.4 index, but also a contemporaneous correlation, were focused to be analyzed.

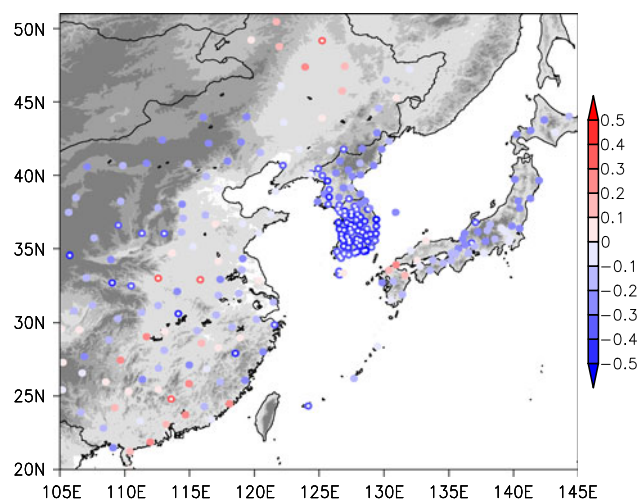
In contrast with summer rainfall, rainfall in September caused a big flood often with the second Changma which comes with TCs. Therefore, let alone summer rainfall, a study on finding out the characteristics of rainfall in September which showed the second peak of rainfall in South Korea is valuable as much as studies on the complex



**Fig. 2** Spatial distribution of correlation coefficient between September total rainfall and September Niño-3.4 index over South Korea. Small white dots are significant at the 90 % confidence level

phenomenon of rainfall in South Korea which is related to heavy rainfall or TCs during summer.

The time series of the September total rainfall (solid line with closed circles) in North Korea and the September Niño-3.4 index (dotted line with open circles) for recent 30 years were analyzed (Fig. 4). Weaker out of phase relationship between the two variables was found compared to the one in South Korea. The trend of the September total rainfall in North Korea showed little change as shown in South Korea (thick solid line). Therefore, even if the trends of the two variables were removed from the time



**Fig. 3** Same as in Fig. 2, but for East Asia

series, the relationship between the two variables was not changed greatly compared to the previous one ( $\text{Corr} = -0.39$  at the 95 % confidence level).

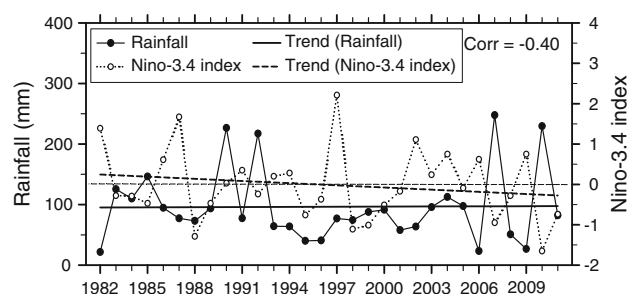
#### 4 Differences between high and low Niño-3.4 index years in September

##### 4.1 Spatial distribution of rainfall

In order to study the spatio-temporal characteristics of the September total rainfall due to the changes of the Niño-3.4 index and the characteristics of the large-scale atmospheric circulations that cause the spatio-temporal characteristics of the September total rainfall, 8 years of having the highest and lowest Niño-3.4 indices during recent 30 years were selected (Table 3). The climatological average of the September total rainfall in South Korea was 157.8 mm.

**Table 2** Same as in Table 1, but for North Korea

| Niño-3.4 index | Monthly total rainfall |      |      |      |      |      |       |       |       |       |      |      |
|----------------|------------------------|------|------|------|------|------|-------|-------|-------|-------|------|------|
|                | Jan                    | Feb  | Mar  | Apr  | May  | Jun  | Jul   | Aug   | Sep   | Oct   | Nov  | Dec  |
| Jan            | -0.12                  | 0.20 | 0.19 | 0.34 | 0.18 | 0.13 | 0.02  | 0.18  | 0.32  | -0.18 | 0.00 | 0.06 |
| Feb            |                        | 0.25 | 0.22 | 0.40 | 0.13 | 0.20 | 0.02  | 0.09  | 0.32  | -0.17 | 0.04 | 0.13 |
| Mar            |                        |      | 0.24 | 0.39 | 0.17 | 0.26 | 0.00  | 0.11  | 0.33  | -0.15 | 0.03 | 0.12 |
| Apr            |                        |      |      | 0.34 | 0.26 | 0.30 | -0.11 | 0.00  | 0.26  | -0.09 | 0.08 | 0.24 |
| May            |                        |      |      |      | 0.30 | 0.19 | -0.19 | -0.14 | 0.04  | -0.02 | 0.18 | 0.34 |
| Jun            |                        |      |      |      |      | 0.03 | -0.16 | -0.12 | -0.19 | 0.08  | 0.17 | 0.23 |
| Jul            |                        |      |      |      |      |      | -0.15 | -0.19 | -0.26 | 0.09  | 0.20 | 0.24 |
| Aug            |                        |      |      |      |      |      |       | -0.14 | -0.30 | 0.10  | 0.14 | 0.21 |
| Sep            |                        |      |      |      |      |      |       |       | -0.40 | 0.04  | 0.17 | 0.20 |
| Oct            |                        |      |      |      |      |      |       |       |       | 0.11  | 0.20 | 0.26 |
| Nov            |                        |      |      |      |      |      |       |       |       |       | 0.21 | 0.31 |
| Dec            |                        |      |      |      |      |      |       |       |       |       |      | 0.38 |



**Fig. 4** Same as in Fig. 1, but for North Korea

**Table 3** Statistics on low and high Niño-3.4 index years in South Korea

| High Niño-3.4 index years | Rainfall (mm) | Low Niño-3.4 index years | Rainfall (mm) |
|---------------------------|---------------|--------------------------|---------------|
| 1982                      | 24.0          | 1988                     | 74.0          |
| 1986                      | 141.9         | 1995                     | 55.7          |
| 1987                      | 39.1          | 1998                     | 258.9         |
| 1997                      | 55.9          | 1999                     | 343.2         |
| 2002                      | 89.8          | 2000                     | 255.1         |
| 2004                      | 209.0         | 2007                     | 404.1         |
| 2006                      | 67.1          | 2010                     | 256.4         |
| 2009                      | 52.0          | 2011                     | 78.7          |
| Average                   | 84.8          | Average                  | 215.8         |
| Climatology               | 157.8         | Climatology              | 157.8         |

The September total rainfalls in the high Niño-3.4 index years were all lower than the climatological average rainfall except the year of 2004. The average rainfall of these years was 84.8 mm which is nearly a half of the climatological average rainfall (the difference between the two average rainfalls was significant at the 95 % confidence level). In the low Niño-3.4 index years, except three years

(1988, 1995, and 2011) of them, all the years showed more rainfall than the climatological average rainfall. The average rainfall of these years was 215.8 mm which is close to 1.5 times of the climatological average rainfall (the difference between the two average rainfalls was significant at the 90 % confidence level). Consequently, the average rainfall in the high Niño-3.4 index years was 2.5 times less than the average rainfall in the low Niño-3.4 index years (the difference between the two average rainfalls was significant at the 99 % confidence level).

As for North Korea, the climatological average of the September total rainfall was 96.4 mm (Table 4). The September total rainfalls in the high Niño-3.4 index years were all lower than the climatological average rainfall except the year of 2004 as shown in South Korea. The average rainfall of these years was 62.1 mm which is 1.5 times less than the climatological average rainfall (the difference between the two average rainfalls was significant at the 90 % confidence level). In the low Niño-3.4 index years, except two years (2007 and 2010) of them, all the years showed less rainfall than the climatological average rainfall. The average rainfall of these years was 115.8 mm, which is 1.2 times more than the climatological average rainfall, but the difference between these two average rainfalls was not significant statistically. Consequently, the average rainfall in the high Niño-3.4 index years was approximately 2 times less than the average rainfall in the low Niño-3.4 index years (the difference between the two average rainfalls was significant at the 95 % confidence level).

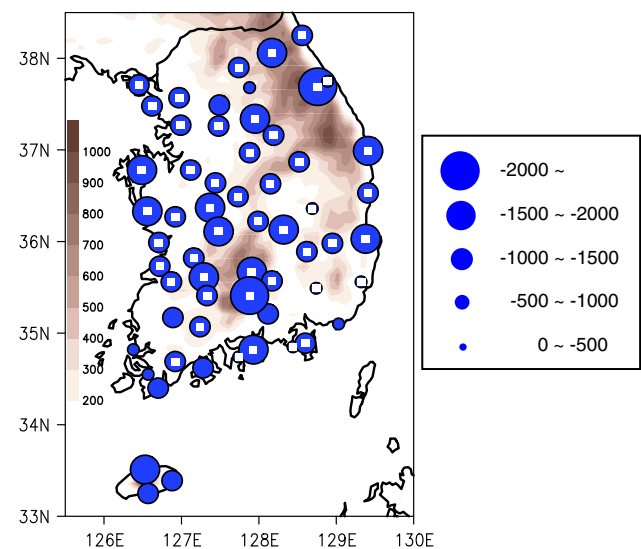
The difference of the September total rainfall between the two groups was applied to every weather observation station in South Korea to find out the spatial distribution (Fig. 5). Overall, except Jeju Island, most of the regions showed significant difference at the 90 % confidence level and above. The largest difference was found in Jiri

**Table 4** Same as in Table 3, but for North Korea

| High Niño-3.4 index years | Rainfall (mm) | Low Niño-3.4 index years | Rainfall (mm) |
|---------------------------|---------------|--------------------------|---------------|
| 1982                      | 21.7          | 1988                     | 73.2          |
| 1986                      | 94.7          | 1995                     | 40.1          |
| 1987                      | 77.3          | 1998                     | 74.4          |
| 1997                      | 76.9          | 1999                     | 87.8          |
| 2002                      | 63.6          | 2000                     | 91.5          |
| 2004                      | 112.6         | 2007                     | 247.8         |
| 2006                      | 23.4          | 2010                     | 229.5         |
| 2009                      | 26.7          | 2011                     | 82.4          |
| Average                   | 62.1          | Average                  | 115.8         |
| Climatology               | 96.4          | Climatology              | 96.4          |

Mountain area located in the Sobaek mountain range and the east coast region located in the east of the Taebaek mountain range. This indicates that the geographical effect also contributed to the difference of the September total rainfall between the two groups.

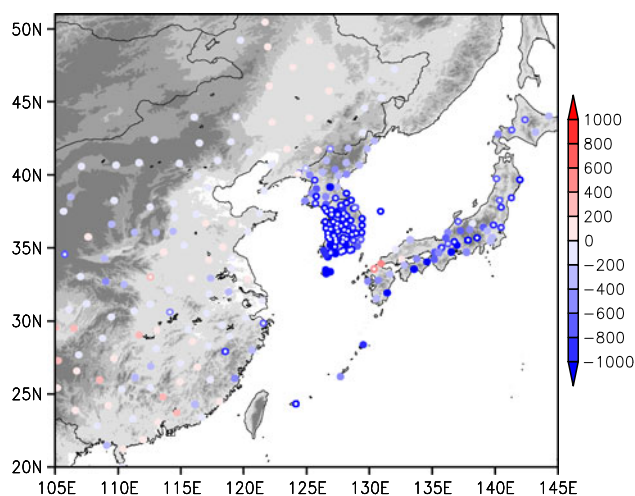
The difference of the September total rainfall between the two groups was analyzed extensively in the regions of East Asia (Fig. 6). Overall, the spatial distribution showed a negative value in most regions, except Manchuria, a part of southern China and the south-west region in Japan, as similar as shown in the correlation distribution. However, a difference of the September total rainfall between the two groups in most of these regions showed no significance statistically. In particular, regions that showed the clearest difference among the East Asia regions were found in South Korea and the middle-north areas of Japan. Also, all the weather observation stations in North Korea showed a negative value, and near the border line between South Korea and North Korea, a significant difference was shown at the 90 % confidence level. Therefore, a negative correlation between the September total rainfall and the September Niño-3.4 index, and a negative value of difference of the September total rainfall between the two groups were not limited to South Korea, but also they can be found commonly in most regions of East Asia. These results were similar to the studies of Lau (1992), Webster and Yang (1992), and Xie et al. (1997) in which the strength of the East Asian summer monsoon weakened in the El Niño year thereby decreasing summer monsoon rainfall in the East Asia regions.



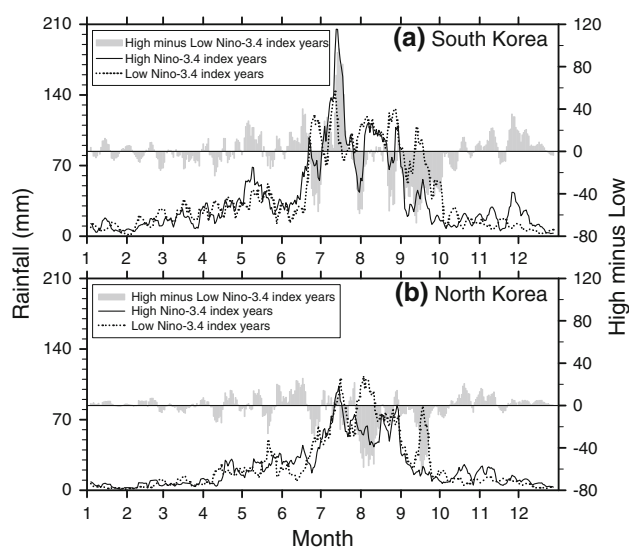
**Fig. 5** Spatial distribution of the difference in September total rainfall between high Niño-3.4 index years and low Niño-3.4 index years over South Korea. Small white dots are significant at the 90 % confidence level

## 4.2 Seasonal variation of rainfall

In order to compare variation of rainfall in South and North Korea between the two groups during the season other than September, the seasonal variation of rainfall was analyzed (Fig. 7). In this study, 7-day running averaged rainfall was used to analyze seasonal variation of rainfall. Ha et al. (2009) showed successfully that a climate regime shift was present in variance of August rainfall in South Korea after the time of the late 1960s using the 7-day running averaged rainfall data.



**Fig. 6** Same as in Fig. 5, but for over East Asia



**Fig. 7** Temporal variability of the 7-day running averaged rainfall for high Niño-3.4 index years (solid line) and low Niño-3.4 index years (dotted line), and the difference (gray bar graph) between high Niño-3.4 index years and low Niño-3.4 index years **a** in South Korea and **b** North Korea

Climatologically, the rainy season in South Korea is largely divided into three periods such as Spring Rainy Season (from early April to middle of May), Changma (from late June to late July), and second Changma or early Autumn Rainy Season (hereafter, second Changma; from middle of August to early September). These three rainy seasons were defined as the hydro-meteorological summer monsoon (Byun and Lee 2002).

As for South Korea, in the high Niño-3.4 index years, rainfall increased from early May and decreased by late May (solid line in Fig. 7a). Although this period might be defined as Spring Rainy Season, it occurred approximately one month and 15 days later than the onset and withdrawal dates of the climatological average Spring Rainy Season respectively. After this period, rainfall started to increase rapidly again at middle of June, and reached the highest peak by the middle of July. This period was defined as Changma, and it continued approximately 1 month, which was similar to the climatological average Changma period, but the onset and withdrawal dates of this period occurred approximately 15 days earlier than the ones of the climatological average Changma respectively. Rainfall increased again from early August, and decreased rapidly at late August. This one month period was the second Changma. The onset and withdrawal dates of this period occurred approximately a week earlier than the ones of the climatological average second Changma, respectively. Then, rainfall in September become much smaller than the one in Spring Rainy Season even though the season was very important because the second peak (the first peak occurred during Changma) of the yearly rainfall occurred due to the effects of TCs along with the second Changma as discussed earlier. It was a cold season in South Korea after September, thus variance of rainfall was smaller. However, in the high Niño-3.4 index years, variance of rainfall was much higher from the middle of November to December.

In the low Niño-3.4 index years, rainfall increased steadily from the middle of February, and then decreased at late May (dotted line in Fig. 7a). Therefore, in the low Niño-3.4 index years, it was difficult to define the period of Spring Rainy Season due to inclusion of February which was a month of winter. Then, rainfall started to increase from late June and then reached to the first peak at the middle of July. This period was Changma season and its onset time was similar to the one in the climatological average Changma but its withdrawal time was approximately 15 days earlier than the one in the climatological average Changma. In particular, rainfall at the first peak was as little as a half of the rainfall at the first peak in the high Niño-3.4 index years. Rainfall started to increase from late July again, and then decreased at late August. This was the second Changma, and its onset and withdrawal times occurred approximately 15 days earlier and a week earlier

than the ones in the climatological average second Changma respectively, but the period was longer than the climatological average second Changma. In the low Niño-3.4 index years, it was shown that rainfall in September was not little. The peak of rainfall in September in these years was as much as two times of the rainfall in the high Niño-3.4 index years. This explained well the strong negative correlation between the September total rainfall in South Korea and the September Niño-3.4 index.

Regarding the difference between the two groups, Changma was started a little earlier in the high Niño-3.4 index years, and more rainfall occurred at the first peak thereby producing more rainfall during Changma period except the end of June. On the other hand, in the low Niño-3.4 index years, since the second Changma started earlier and September rainfall was much higher, more rainfall was found in these years from August to September (bar graph in Fig. 7a).

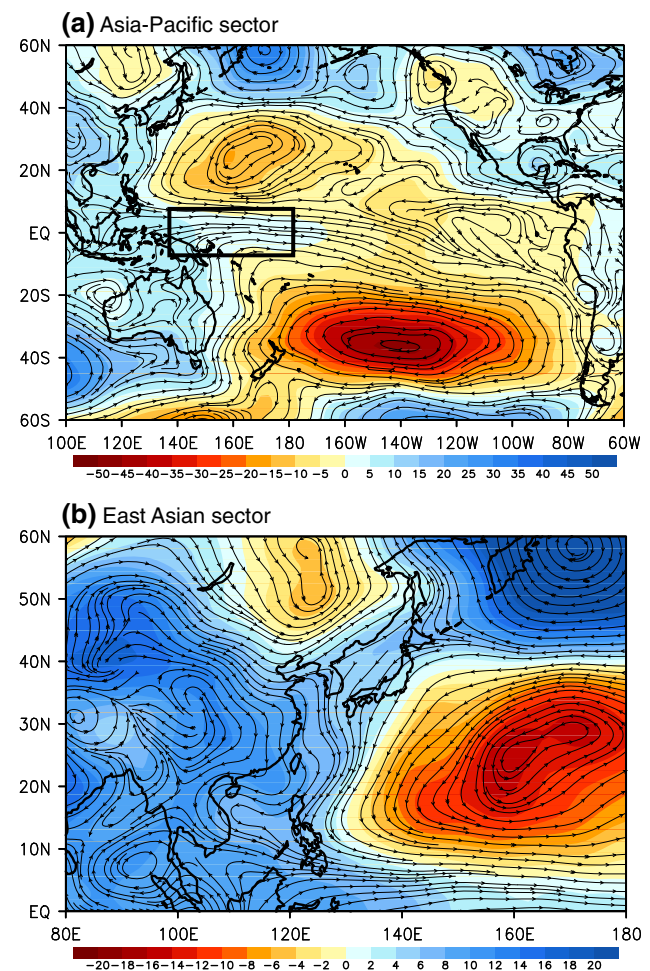
As for North Korea, overall, the two groups had less rainfall than the one in South Korea (Fig. 7b). In the high Niño-3.4 index years, rainfall increased steadily from the middle of April to the middle of June (solid line in Fig. 7b). However, since June which is a month of summer was included, it was difficult to define this period as Spring Rainy Season. Again, rainfall started to increase rapidly from the end of June, and reached to the first peak at the middle of July. In these years, the onset of Changma was similar to the one in the climatological average Changma, but the withdrawal was approximately 15 days earlier than the one in the climatological average Changma. Then, rainfall increased again from the middle of August and decreased at the end of August. This period was defined as the second Changma but the withdrawal time was 1 week earlier than the one in the climatological average second Changma.

In the low Niño-3.4 index years, rainfall started to increase from early April, and it continued up to the end of May (dotted line in Fig. 7b). This period was defined as Spring Rainy Season and its withdrawal time was 1 week later than the one in the climatological Spring Rainy Season. Rainfall started to increase rapidly from the middle of June, and reached to the first peak at the middle of July. This period was defined as Changma, and its period was approximately 1 month but its onset and withdrawal times were 1 week earlier than the ones in climatological average Changma respectively. Rainfall started to increase again from the end of July and reached to the highest peak at early August. Then it decreased but slightly increased again at the end of August. This period was the second Changma, and its period was longer than the one in the climatological average second Changma. Also, in September, the third peak of rainfall occurred so that it created a negative correlation between the September total rainfall in North Korea and the September Niño-3.4 index.

Regarding the difference between the two groups, there were no large difference between them up to July, but due to the little longer second Changma and the third peak of rainfall in September in the low Niño-3.4 index years, these years had more rainfall from August to September (bar graph in Fig. 7b). Therefore, there was a common result that the low Niño-3.4 index years produced more rainfall in both South and North Korea from August to September after Changma.

#### 4.3 Large-scale atmospheric circulations

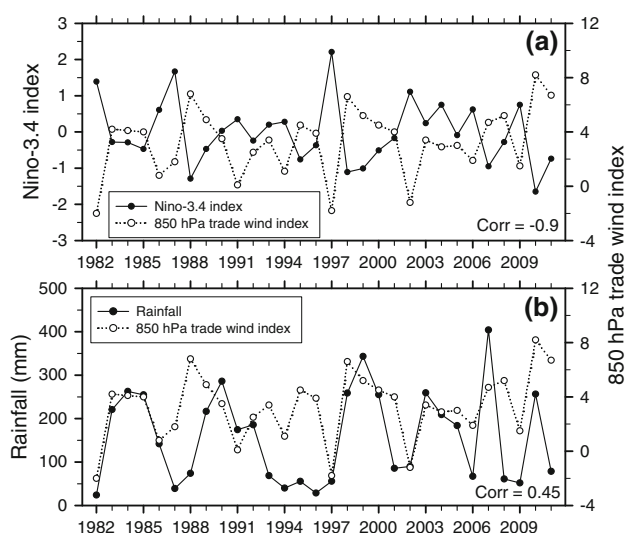
As described earlier, 850 hPa stream flows in September were analyzed to find out the reason for causing the difference in the September total rainfall in South Korea between the two groups (Fig. 8a). The huge anomalous cyclonic circulations were formed in the Pacific Ocean in the both hemispheres. Due to the placement of these anomalous pressure systems, anomalous equatorial



**Fig. 8** Differences in 850 hPa stream flow and geopotential height (shading) between high Niño-3.4 index years and low Niño-3.4 index years in September in **a** Asia-Pacific sector and **b** East Asian sector

westerlies were strengthened in the equatorial Pacific. The strengthening of these anomalous equatorial westerlies was related to the weakening of the trade wind in the high Niño-3.4 years. Instead, in East Asia, the Maritime continent, and Australia, which were located in the west of approximately  $140^{\circ}\text{E}$ , the anomalous anticyclonic circulations were evident. These characteristics were the patterns of typical anomalous large-scale atmospheric circulations in the El Niño years. In addition, as for East Asia, whereas the anomalous cyclonic circulation was strengthened in the east region of  $130^{\circ}\text{E}$ , that is, the region of the subtropical western Pacific, the anomalous anticyclonic circulation was strengthened in the continent of East Asia except Manchuria (Fig. 8b). This indicates that continental anticyclone was strengthened in the East Asia continent but the subtropical western North Pacific high (SWNPH) was weakened in the subtropical western Pacific. The placement of the west-high and east-low type anomalous pressure system was a typical pressure system pattern discovered in winter season in East Asia. Therefore, the anomalous northerlies were strengthened in most regions of the East Asia continent except Manchuria. As a result, due to these anomalous flows, as discussed earlier, in most regions of East Asia including South and North Korea except Manchuria, the September total rainfall had a negative correlation with the September Niño-3.4 index. Also, negative values were found in most regions of East Asia except Manchuria in the difference of the September total rainfall between the two groups.

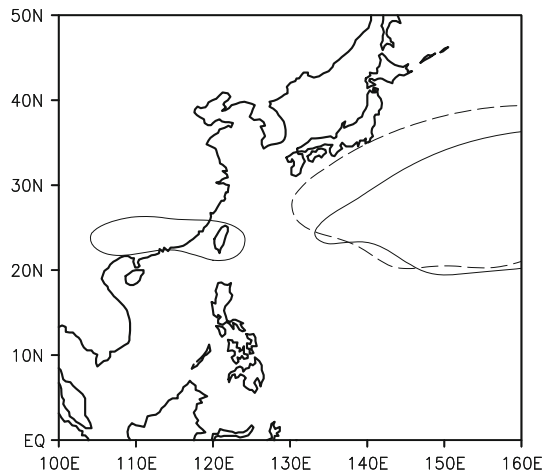
Earlier, it was referred that the trade wind was weakened in the equatorial Pacific in the high Niño-3.4 years. In order to find the strength of the trade wind, the September 850 hPa zonal wind averaged over the south western Pacific region (solid line box in Fig. 8a:  $5^{\circ}\text{S}$ – $5^{\circ}\text{N}$ ,  $135^{\circ}$ – $180^{\circ}\text{E}$ ) was examined. The strength of the trade wind may be related to not only the strength of ENSO but also the strength of the SWNPH because the south western Pacific region was located near the southern periphery of the SWNPH. As above, correlation between the September 850 hPa trade wind index for this region and the September Niño-3.4 index was studied (Fig. 9a). It was found that there was a high negative correlation of  $-0.9$  between the two variables at the 99 % confidence level. This indicates that as the September 850 hPa trade wind became weaken in this region, the September SST increased (El Niño strengthened) in the Niño-3.4 region. On the other hand, the weakening of the 850 hPa trade wind in the south western Pacific region was followed by the strength of the anomalous equatorial westerlies. Also, the strength of the anomalous equatorial westerlies in this region may be related to the weakening of the SWNPH. This was in general due to strong equatorial or subtropical easterlies near the southern periphery of the SWNPH. The SWNPH



**Fig. 9** Time series of **a** Niño-3.4 index (solid line with closed circles) and 850 hPa trade wind index (dotted line with open circles), and **b** September total rainfall in South Korea (solid line with closed circles) and 850 hPa trade wind index (dotted line with open circles)

plays an important role to cause rainfall by supplying water vapor and heat from the low-latitudes to the mid-latitudes of East Asia including Korea. Therefore, a correlation between the September 850 hPa trade wind index in the south western Pacific region, which can represent the development degree of the SWNPH, and the September total rainfall in South Korea was studied (Fig. 9b). There was a positive correlation of 0.45 between the two variables at the 99 % confidence level. This indicates that if the September 850 hPa trade wind was strengthened (weakened) in the south western Pacific region, then the September total rainfall in South Korea increased (decreased). Also, the strengthening of the 850 hPa trade wind in the south western Pacific region was followed by the strengthening of equatorial easterlies and this in turn related with the strength of the SWNPH. That is, the weakening of the 850 hPa trade wind in the high Niño-3.4 years, which was analyzed in this study, indicates rather the strengthening of anomalous equatorial westerlies in return (El Niño strengthened), and the strengthening of anomalous equatorial westerlies was followed by the weakening of the SWNPH thereby reducing the September total rainfall in most regions of the East Asia including South Korea.

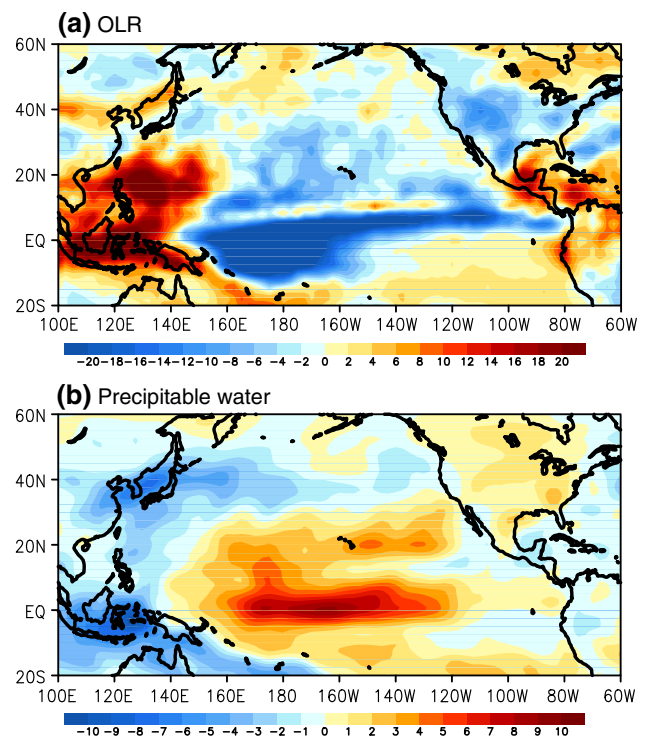
In order to find out the actual relationship of strengthening of anomalous equatorial westerlies with the weakening of the SWNPH, the development degree of the SWNPH in September for the two groups were studied (Fig. 10). The SWNPH in this study was defined as a region having more than 5,875 gpm at 500 hPa level. As shown in the figure, the SWNPH in the high Niño-3.4 index years was located farther south-east than the SWNPH in



**Fig. 10** 5875 geopotential height meter (gpm) at 500 hPa level in the high Niño-3.4 index years (solid line) and low Niño-3.4 index years (dotted line)

the low Niño-3.4 index years. Therefore, in the high (low) Niño-3.4 index years, when South Korea was little farther (closer) to the SWNPH, the September total rainfall in East Asia including South Korea was found to be decreased (increased). This result is consistent with the one in Miyazaki (1989) which showed reduction of the summer rainfall in the East Asia regions due to the migration of the center of the SWNPH to the south-east in the summer of the El Niño year by not developing enough into the East Asia regions compared to phenomena during the normal year.

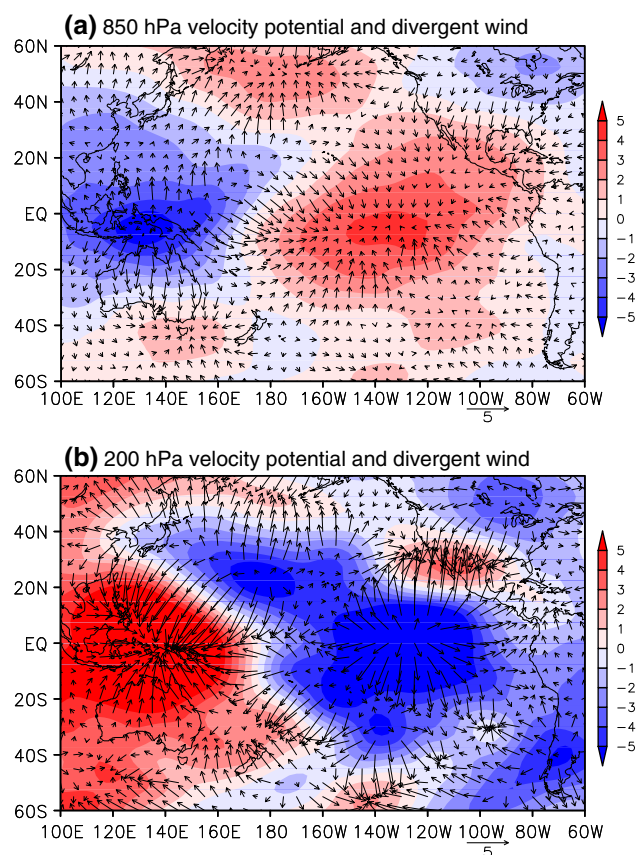
The development degree of the SWNPH in the tropical or subtropical Pacific can influence the convection in not only the tropical or subtropical Pacific but also the mid-latitude regions. Therefore, in order to find out the difference of convective activity between the two groups, the OLR difference in September between the two groups was analyzed (Fig. 11a). The lower the OLR value is, the stronger the convective activity is. From 140°E to the coast of Peru along the Equator, strong convection was formed. Also, strong convection was formed in the tropical Pacific in the Southern Hemisphere, and the central and eastern Pacific in the Northern Hemisphere. In particular, the strengthening convection in the central Pacific in the Northern Hemisphere meant the weakening of the SWNPH in the high Niño-3.4 index years. On the other hand, along the line of the East Asia continent of 45°N south, the subtropical western Pacific, the Maritime Continent and Australia, convection was shown to weaken. This might be a result due to the strengthening of anomalous equatorial westerlies as explained above. This characteristic of the OLR can be explained well by the difference of precipitable water between the two groups (Fig. 11b). Anomalous



**Fig. 11** Same as in Fig. 8, but for **a** OLR and **b** precipitable water

high precipitable water was shown in the region where convection was formed along the equator from 140°E to the coast of Peru. Also, positive anomaly was formed in the tropical Pacific in the Southern Hemisphere, the central and eastern Pacific in the Northern Hemisphere. On the other hand, negative anomaly was distributed from the East Asia continent and the mid-latitude western Pacific through the Maritime Continent to Australia. The center of the negative anomaly was located in the Korean Peninsula among East Asia and in the Maritime Continent. In particular, the negative anomaly in the mid-latitude western Pacific indicates that the WNPSH was not developed in the high Niño-3.4 index years.

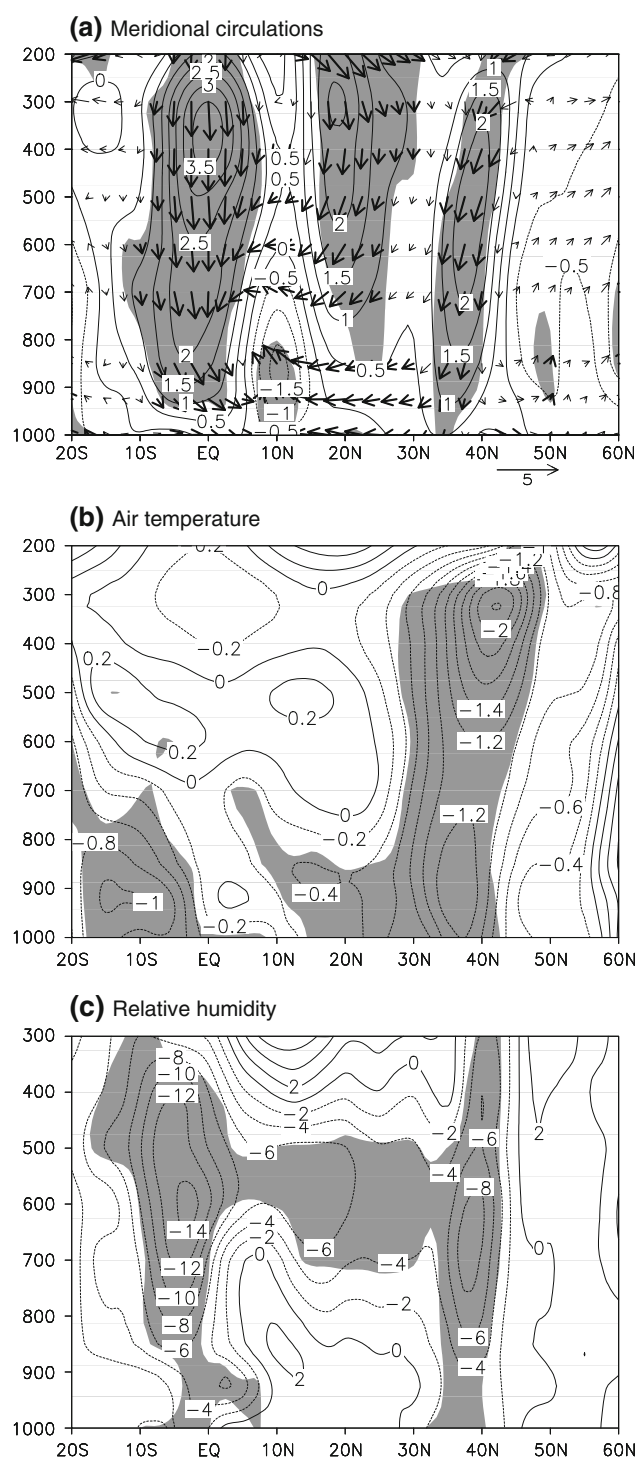
The convective activity in the Pacific Rim can be verified by the differences of the September velocity potential and the divergent wind between the two groups (Fig. 12). At the 850 hPa velocity potential and divergent wind, the center of the anomalous divergence was located in the Maritime Continent, and the center of the anomalous convergence was located in the equatorial central and eastern Pacific and the high latitudes of northern Pacific (Fig. 12a). The East Asia regions including the Korean Peninsula were included in the region of weak anomalous divergence. While the center of the anomalous convergence at the 200 hPa velocity potential and divergent wind was located in the Maritime Continent where anomalous divergence was strengthened at 850 hPa level, the center of



**Fig. 12** Differences in divergent wind (vector) and velocity potential (shading) at **a** 850 hPa level and **b** 200 hPa level between the high Niño-3.4 index years and the low Niño-3.4 index years. The unit of velocity potential is  $10^6 \text{ m}^2 \text{ s}^{-1}$

the anomalous divergence was located in the equatorial central and eastern Pacific where anomalous convergence was strengthened at 850 hPa level (Fig. 12b). That is, it indicates that the structure of the vertical zonal atmospheric circulation that airflows which were lifted from the equatorial central and eastern Pacific were fallen at the Maritime Continent. This was the typical Walker Circulation which was occurred in the El Niño years. Also, the East Asia regions including the Korean Peninsula was included in the anomalous divergence region at 200 hPa level.

The difference between the two groups with regard to the September vertical meridional circulation averaged over  $120^\circ\text{--}140^\circ\text{E}$  which is the longitude band that includes South and North Korea was obtained (Fig. 13a). The anomalous downward flows were shown to be strengthened in all the latitude regions except the  $45^\circ\text{N}$  northern region and the  $10^\circ\text{N}$  band. In particular, as shown earlier in the difference of the velocity potential and the divergent wind, at the latitude band ( $10^\circ\text{S}\text{--}0^\circ$ ) of the Maritime Continent where anomalous divergence was strengthened at 850 hPa level, and anomalous convergence was strengthened at



**Fig. 13** Composite differences of latitude-pressure cross-section of **a** meridional circulations (vectors) and vertical velocity (contours), **b** air temperature, and **c** relative humidity averaged along  $120^\circ\text{--}140^\circ\text{E}$  between high and low Niño-3.4 index years in September. The values of vertical velocity are multiplied by  $-100$ . Thick arrows and shaded areas are significant at the 95 % confidence level. Contour intervals are  $0.5 \text{ hPa s}^{-1}$  for vertical velocity,  $0.2^\circ\text{C}$  for air temperature, and  $2 \text{ g kg}^{-1}$  for relative humidity

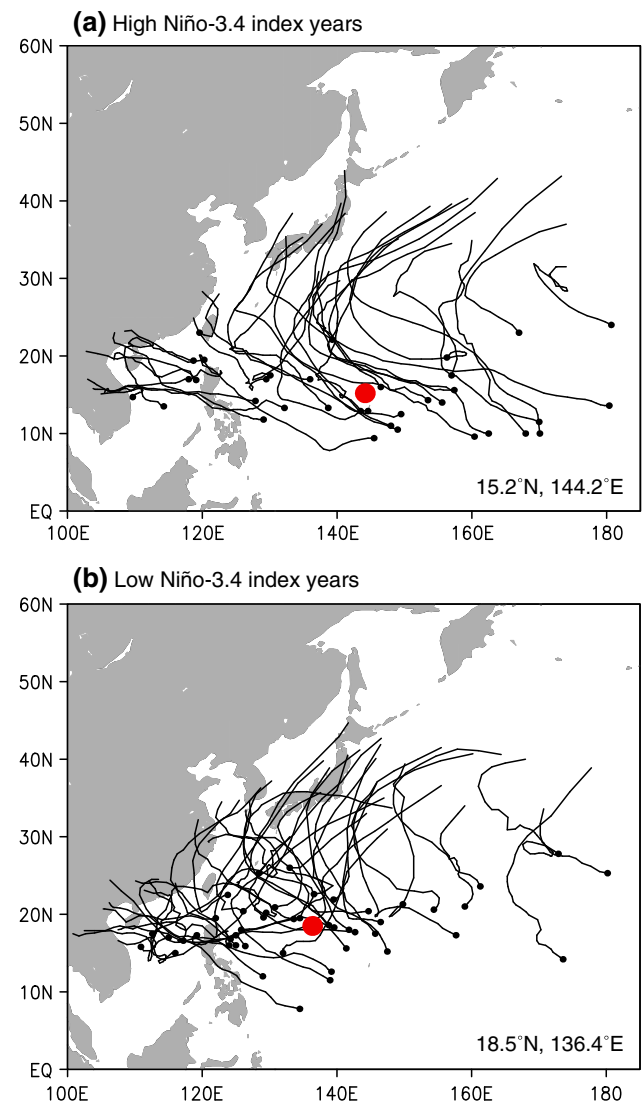
200 hPa level, anomalous downward flows were developed most strongly. Also at 30°–40°N where South and North Korea are located, anomalous downward flows were strengthened through all the tropospheric layers. In order to find out the properties of the anomalous vertical meridional circulation flows, the vertical distribution difference of the September meridional air temperature and relative humidity averaged over 120°–140°E which is the longitude band that includes South and North Korea were observed (Figs. 13b and 13c). As a result, anomalous low air temperature is found in all the latitude regions except the middle level between 20°S and 20°N, and its center was located at 30°–40°N where South and North Korea are located (Fig. 13b). Regarding relative humidity, anomalous low relative humidity was found in all latitude regions except low level of 10°–30°N and regions over 50°N (Fig. 13c) and its center was located in 10°S–0° where the Maritime Continent is located and 30°–40°N where South and North Korea are located. Therefore, regarding the difference between the two groups about the September 850 hPa stream flow as analyzed earlier, the properties of the anomalous northerlies which were strengthened in the most East Asia regions were anomalous cold and dry so that they created an unfavorable environment for rainfall in the high Niño-3.4 index years.

#### 4.4 TC activity

The season, which influences Korea the most by TCs, is August followed by September in which one or two TCs were approached in average (Choi and Kim 2007). Therefore, the effect of TCs on the September rainfall variability cannot be ignored. In this study, the tracks of TCs occurred in September for the two groups were analyzed (Fig. 14).

First, the numbers of frequency of TCs generated in the high Niño-3.4 index years and low Niño-3.4 index years were 35 and 46 respectively. The result showed that more frequent TCs occurred in the low Niño-3.4 index years but their difference was not significant statistically. Regarding the place that formed TCs, it showed a tendency that TCs were formed a little farther to the south-east in the subtropical western Pacific in the high Niño-3.4 index years compared to the low Niño-3.4 index years. This east–west difference of TC generation place can be explained by the frequency difference of TCs generated in the eastern waters of 150°E at the two groups. While 13 TCs were generated at the eastern waters of 150°E in the high Niño-3.4 index years, only 7 TCs were generated in the low Niño-3.4 index years. Therefore, regarding the longitude of the average generation place, while it was 144.2°E in the high Niño-3.4 index years, it was 136.4°E in the low Niño-3.4 index years. The longitude difference of the average TC

generation place between these two groups was significant at the 95 % CI. Next, regarding the south–north difference of the TC generation place can be explained by the frequency difference of TCs generated in the southern waters of 15°N at the two groups. While 20 TCs were generated at the southern waters of 15°N in the high Niño-3.4 index years, only 5 TCs were generated in the low Niño-3.4 index years. Therefore, regarding the latitude of the average generation place, while it was 15.2°N in the high Niño-3.4 index years, it was 18.5°N in the low Niño-3.4 index years. The latitude difference of the average TC generation place between these two groups was significant at the 90 % CI.



**Fig. 14** TC tracks in September in **a** high Niño-3.4 index years and **b** low Niño-3.4 index years. Small black dots denote TC genesis locations in each of Niño-3.4 index years. Big red dots indicate mean TC genesis locations in each of Niño-3.4 index years (high Niño-3.4 index years: 15.2°N, 144.2°E, low Niño-3.4 index years: 18.5°N, 136.4°E)

Regarding the moving path of TCs, while TCs moved through the far eastern waters of Japan in the high Niño-3.4 index years, TCs in the low Niño-3.4 index years moved through South China Sea or landed in the mid-latitude nations in East Asia. Therefore, while no TC was landed in South Korea or northern region of China in the high Niño-3.4 index years, a little high frequency of TCs were landed on these areas in the low Niño-3.4 index years. Also, high frequency difference of TCs which was landed on Japan was found between the two groups. This was also explained as described above, that the SWNPH was not extended to the East Asia regions in the high Niño-3.4 index years, so that TCs were formed in the south-east waters of the subtropical western Pacific to move to the far eastern waters of Japan without influencing the mid-latitude nations in East Asia. On the other hand, in the low Niño-3.4 index years, due to the further developed SWNPH in the mid-latitude regions in East Asia, TCs were formed in the north-west regions of the subtropical western Pacific and influenced the mid-latitude regions in East Asia (Wang and Chan 2002). Therefore, it was understood that in the high (low) Niño-3.4 index years, the low (high) landing frequency of TCs in the mid-latitude regions in East Asia influenced on reduction (increase) of the September total rainfall in these years. This result was similar with the study of Aoki (1985) in which summer rainfall was reduced due to reduction of the frequency which affected Japan in the El Niño year.

## 5 Summary and conclusion

In this study, it was analyzed that a high negative correlation was found between the September total rainfall averaged over South Korea and the same month Niño-3.4 index. North Korea also showed a negative correlation between the two variables although it was statistically lower significance than one in South Korea. Most of regions in East Asia also showed a negative correlation except some areas. In order to find out the reason for this negative correlation between these two variables, 8 years of having the highest Niño-3.4 index (high Niño-3.4 index years) and 8 years of having the lowest Niño-3.4 index (low Niño-3.4 index years) out of recent 30 years (1982–2011) were selected and then average difference between the two groups was analyzed.

In the high Niño-3.4 index years, reduction of the September total rainfall was shown most clearly in South Korea among the East Asia regions, and followed by the north-east area of Japan and North Korea. The rest of the regions showed also a tendency of reduction although it was not significant statistically. This meant that reduction of the September total rainfall in the high Niño-3.4 index

years was not limited in South Korea, but also shown in most regions of East Asia commonly.

Through analysis on seasonal variation of rainfall between the two groups, it was found that the high Niño-3.4 index years showed a tendency of more rainfall during Changma in both South and North Korea. However, after Changma to September, the low Niño-3.4 index years showed more rainfall due to earlier second Changma onset and the third peak of rainfall in September.

As described above, in order to find out the reason for reduction of the September total rainfall in most regions of East Asia including South and North Korea, the difference of 850 hPa stream flow between the two groups were analyzed. In the high Niño-3.4 index years, while huge anomalous cyclonic circulations were strengthened in the Pacific Ocean in the both hemispheres, anomalous anticyclonic circulations were strengthened at the regions from the middle-latitudes in East Asia through the Maritime Continent to Australia. Through the results of analysis of velocity potential and divergent wind, these circulations were confirmed as a typical Walk Circulation in the El Niño years, which was airflow lifted from the equatorial central and eastern Pacific and then fell down at the Maritime Continent. As for the East Asia regions, since the anomalous anticyclonic circulation and anomalous cyclonic circulation were strengthened in the East Asia continent and in the subtropical western Pacific respectively, the west-high east-low type anomalous pressure system pattern, which was a typical pressure system placement in winter, was shown so that anomalous northerlies were strengthened in most regions of East Asia thereby reducing the September total rainfall in the high Niño-3.4 index years. Through the difference of meridional vertical cross-section between the two groups on air temperature and relative humidity averaged over 120°–140°E, which is the longitude band that includes South and North Korea, these anomalous northerlies were found to have the properties of anomalous cold and dry in the all tropospheric layers. Due to the placement of these large-scale anomalous pressure systems, the trade wind (anomalous equatorial westerlies) was weakened (strengthened) in the equatorial Pacific. The weakening (strengthening) of the trade wind was related to the weakening (strengthening) of the WNPSH. This was confirmed by the 850 hPa trade wind index in the south western Pacific region, which showed the strengths of ENSO and the WNPSH. That is, the September 850 hPa trade wind index showed a strong negative correlation of -0.9 with the September Niño-3.4 index, and a positive correlation of 0.45 with the September total rainfall in South Korea. Therefore, in the high Niño-3.4 index years, the WNPSH was located farther away from the East Asia continent than in the low Niño-3.4 index years, thereby not supplying sufficiently water vapor and heat from the low-latitudes to the mid-latitudes of East Asia, which in turn reduced the September total rainfall.

Since September is the second highest month influenced by TCs after August, TC tracks for the two groups were analyzed to find out the effects of TCs on variance in the September total rainfall in South Korea. In average, while TCs were mostly formed in the south-east of the subtropical western Pacific in the high Niño-3.4 index years, TCs were formed in the north-west in the low Niño-3.4 index years. As for the TC track, the WNPSH was not developed into the mid-latitude regions in East Asia so that TCs were moved through the far eastern sea of Japan in the high Niño-3.4 index years. On the other hand, in the low Niño-3.4 index years, the WNPSH was developed further into the mid-latitude regions of East Asia so that frequency of TCs which affected the regions was high. Therefore, it can be concluded that the low frequency of TCs in the mid-latitude regions in East Asia in the high Niño-3.4 index years also contributed to reduction of the September total rainfall in the East Asia regions.

In this study, September was focused because it showed not only the highest correlation but also contemporaneous correlation between the monthly total rainfall averaged over South Korea and the Niño-3.4 index. However, as explained earlier, the September total rainfall in South Korea showed a high negative correlation already from June. Further, the summer Niño-3.4 index showed a high correlation with the winter total rainfall in South Korea. Therefore, in the future, we will study by focusing on a lagged correlation between the monthly total rainfall and the Niño-3.4 index.

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## References

- Ahn JB, Park HS (1996) Application of continuous dynamic grid adaption (CDGA) to heat-induced tropical circulation with latent heat release. *J Korean Meteorol Soc* 32:363–372
- Ahn JB, Ryu JH, Cho EH, Park JY, Ryoo SB (1997) A study of correlations between air-temperature and precipitation in Korea and SST over the tropical Pacific. *J Korean Meteorol Soc* 33:487–495
- Aoki T (1985) A climatological study of typhoon formation and typhoon visit to Japan. *Pap Meteorol Geophys* 36:61–118
- Bjerknes J (1969) Atmospheric teleconnections from the equatorial Pacific. *Mon Weather Rev* 97:163–172
- Byun HR, Lee DK (2002) Defining three rainy seasons and hydrological summer monsoon in Korea using available water resources index. *J Meteorol Soc Jpn* 80:33–44
- Byun HR, Kang KA, Kim KH (2001) Correlations between Niño-3 anomalies and Asian drought flood. *J Korean Meteorol Soc* 37:453–464
- Cha EJ, Jhun JG, Chung HS (1999) A study on characteristics of climate in South Korea for El Niño/La Niña years. *J Korean Meteorol Soc* 35:98–117
- Cha EJ, Choi YJ, Oh JH (2000) 1997/98 El Niño and analysis of unusual climate in summer 1998. *J Korean Meteorol Soc* 36:269–283
- Chen D, Zebiak SE, Cane MA, Busalacchi AJ (1997) Initialization and predictability of a coupled ENSO forecast model. *Mon Weather Rev* 125:773–788
- Choi KS, Kim BJ (2007) Climatological characteristics of tropical cyclones making landfall over the Korean Peninsula. *J Korean Meteorol Soc* 43:97–109
- Ha KJ, Yun KS, Jhun JG, Li JP (2009) Circulation changes associated with the interdecadal shift of Korean August rainfall around late 1960s. *J Geophys Res* 114:D04115. doi:10.1029/2008JD011287
- Halpert MS, Ropelewski CF (1992) Surface temperature patterns associated with the Southern Oscillation. *J Clim* 5:577–593
- Harger JRE (1995) ENSO variations and drought occurrence in Indonesia and the Philippines. *Atmos Environ* 29:1943–1955
- Horel JD, Wallace JM (1981) Planetary scale atmospheric phenomena associated with the Southern Oscillation. *Mon Weather Rev* 109:819–829
- Ju J, Slingo JM (1995) The Asian summer monsoon and ENSO. *Q J R Meteorol Soc* 121:1133–1168
- Kalnay E et al (1996) The NCEP/NCAR 40-Year reanalysis project. *Bull Am Meteorol Soc* 77:437–471
- Kang IS (1998) Relationship between El-Niño and Korean climate variability. *J Korean Meteorol Soc* 34:390–396
- Kang IS, An SI (1998) Kevin and Rossby wave contributions to the SST oscillation of ENSO. *J Clim* 11:2461–2469
- Kang IS, Jeong YK (1996) Association of interannual variations of temperature and precipitation in Seoul with principal modes of Pacific SST. *J Korean Meteorol Soc* 32:339–345
- Kang IS, Lau NC (1986) Principal modes of atmospheric variability in model atmospheres with and without anomalous sea surface temperature forcing in the tropical Pacific. *J Atmos Sci* 43:2719–2735
- Kang IS, Ho CH, Min KD (1992) Long-range forecast of summer precipitation in Korea. *J Korean Meteorol Soc* 28:283–292
- Kim JW, Cho HG, Lee SM, Lee TY, Lee KH, Ha KJ (1995) Research on the parameterized processes in climate models: V. A general circulation model study of influence of sea surface temperature anomaly on the evolution of Asian summer monsoon. *J Korean Meteorol Soc* 31:439–452
- Kim DW, Choi KS, Byun HR (2012) Effects of El Niño Modoki on winter precipitation in Korea. *Clim Dyn* 38:1313–1324
- Kirtman BP, Shukla J, Huang B, Zhu Z, Schneider EK (1997) Multiseasonal predictions with a coupled tropical ocean global atmospheric system. *Mon Weather Rev* 125:789–808
- Kistler R et al (2001) The NCEP/NCAR 50-year reanalysis. *Bull Am Meteorol Soc* 82:247–267
- Lau KM (1992) East Asia summer monsoon rainfall variability and climate teleconnection. *J Meteorol Soc Jpn* 70:211–242
- Li J, Wu Z (2012) Importance of autumn Arctic sea ice to northern winter snowfall. *Proc Natl Acad Sci USA* 109:1899–1900. doi:10.1073/pnas.1205075109
- Liebmann B, Smith CA (1996) Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull Am Meteorol Soc* 77:1275–1277
- Miyazaki Y (1988) Characteristics of the weather over Japan in El Niño years. *J Meteorol Soc Jpn* 36:15–22
- Miyazaki Y (1989) The relationship between tropical convection and winter weather over Japan. *J Meteorol Soc Jpn* 67:863–875
- Mujumdar M, Kumar V, Krishnan R (2007) The Indian summer monsoon drought of 2002 and its linkage with tropical convective activity over northwest Pacific. *Clim Dyn* 28:743–758
- Neelin JD, Jin FF (1993) Mode of interannual tropical ocean-atmosphere interaction-A unified view. Part II: analytical results in a weak coupling limit. *J Atmos Sci* 50:3504–3522
- Nigam S (1994) On the dynamical basis for the Asian summer monsoon rainfall—El Niño relationship. *J Clim* 7:1750–1771

- Nitta T (1990) Unusual summer weather over Japan in 1988 and its relationship to the Tropics. *J Meteor Soc Jpn* 68:575–588
- Oh JH (1996) Radiative transfer model for climate studies. *J Korean Meteorol Soc* 32:471–484
- Rasmusson EM, Carpenter TH (1982) Variation in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon Weather Rev* 110:354–384
- Rasmusson EM, Carpenter TH (1983) The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon Weather Rev* 111:517–528
- Reynolds RW, Rayner NA, Smith TM, Stokes DC, Wang W (2002) An improved in situ and satellite SST analysis for climate. *J Clim* 15:1609–1625
- Ropelewski CF, Halpert MS (1987) Global and regional scale precipitation patterns associated with El Niño/Southern Oscillation. *Mon Weather Rev* 115:1606–1626
- Shukla J, Paolino DA (1983) The southern oscillation and long-range forecasting of the summer monsoon rainfall over India. *Mon Weather Rev* 111:1830–1837
- Soman MK, Slingo J (1997) Sensitivity of the Asian summer monsoon to aspects of sea-surface temperature anomalies in the tropical Pacific Ocean. *Q J R Meteorol Soc* 123:309–336
- Wang B, Chan JCL (2002) How strong ENSO affect tropical storm activity over the western North Pacific. *J Clim* 15:1643–1658
- Wang B, Wu R, Fu X (2000) Pacific-East Asia teleconnection: how does ENSO affect East Asian climate? *J Clim* 13:1517–1536
- Wang B, Wu Z, Liu J, Chang CP, Li J, Zhou TJ (2010) Another look at climate variations of the East Asian winter monsoon: northern and southern temperature modes. *J Clim* 23:1495–1512
- Webster PJ, Yang S (1992) Monsoon and ENSO: selectively interactive systems. *Q J R Meteorol Soc* 118:877–926
- Wilks DS (1995) Statistical methods in the atmospheric sciences. Academic Press, New York, p 467
- Wu R, Wang B (2002) A contrast of the East Asian summer-ENSO relationship between 1962–1977 and 1978–1993. *J Clim* 15:3266–3279
- Wu Z, Wang B, Li J, Jin FF (2009) An empirical seasonal prediction model of the East Asian summer monsoon using ENSO and NAO. *J Geophys Res* 114:D18120. doi:[10.1029/2009JD011733](https://doi.org/10.1029/2009JD011733)
- Wu Z, Li J, Jiang Z, He J (2011) Predictable climate dynamics of abnormal East Asian winter monsoon: once-in-a-century snowstorms in 2007/2008 winter. *Clim Dyn* 37:1661–1669
- Wu Z, Li J, Jiang Z, He J, Zhu X (2012a) Possible effects of the North Atlantic Oscillation on the strengthening relationship between the East Asian summer monsoon and ENSO. *Int J Climatol* 32:794–800. doi:[10.1002/joc.2309](https://doi.org/10.1002/joc.2309)
- Wu Z, Li J, Jiang Z, Ma T (2012b) Modulation of the Tibetan Plateau snow cover on the ENSO teleconnections: from the East Asian summer monsoon perspective. *J Clim* 25:2481–2489
- Xie A, Chung YS, Liu X, Ye Q (1997) On the international variations of the summer monsoon onset over the South China Sea. *J Korean Meteorol Soc* 33:553–567
- Zebiak SE, Cane MA (1987) A model El-Niño-Southern oscillation. *Mon Weather Rev* 115:2262–2278