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Article

Precipitation Anomalies Around King Sejong Station, Antarctica Associated with El Niño/Southern Oscillation

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Abstract : Precipitation variability around King Sejong Station related with El Niño/Southern Oscillation (ENSO) is evaluated using the gauge-based monthly data of its neighboring stations. Though three Antarctic Stations of King Sejong (Korea), Frei (Chile), and Artigas (Uruguay) are all closely located within 10 km, their precipitation data show mostly insignificant positive or rather negative correlations among them in the annual, seasonal and monthly precipitation. This result indicates that there are locally large variations in the distribution of precipitation around King Sejong Station. The monthly data of Frei Station for 31 years (1970-2000) are analyzed for examining the ENSO signal in precipitation because of its longer precipitation record compared to other two stations. From the analysis of seasonal precipitation, it is seen that there is a tendency of less precipitation than the average during El Niño events. This dryness is more distinct in fall to spring seasons, in which the precipitation decreases down to about 30 % of seasonal mean precipitation. However, the precipitation signal related with La Niña events is not significant. From the analysis of monthly precipitation, it is found that there is a strong negative correlation during 1980s and in the late 1990s, and a weak positive correlation in the early 1990s between normalized monthly precipitation at Frei Station and Sea Surface Temperature (SST) anomalies in the NINO 3.4 region. However, this relation may be not applied over the region around King Sejong Station, but at only one station, Frei.

Key words : Antarctica, King Sejong Station, Frei Station, monthly precipitation, El Niño/Southern Oscillation.

1. Introduction

El Niño/Southern Oscillation (ENSO) is a complex phenomenon involving interactions between the atmosphere and the ocean typically in the tropical Pacific. Though it is centered in the tropical Pacific Ocean, the signals related with ENSO have been found in the far reaching regions of the globe, even in the Antarctic (Ropelewski and Halpert 1996; Smith and Stearns 1993; Kiladis and Diaz 1989; Angell 1981). In recent years ENSO has become evident as a dominant source of interannual climate variability around the world. Furthermore, the ENSO event has become one part of the predictable components of seasonal climate variability. At present, the basic process for transporting ENSO signals through the globe are understood as follows; changes in the tropical ocean impact the atmosphere and climate patterns around globe, in turn, changes in the atmosphere impact the ocean temperature and currents.

Smith and Stearns (1993) revealed significant correlations between Southern Oscillation Index (SOI) and the surface temperatures and pressures over the Antarctic. The ENSO signals have been also found in sea-ice (Simmonds and Jacka 1995; Gloersen 1995) and populations of marine life (Testa *et al.* 1991) over the south polar regions. There are also several studies showing the ENSO signals in the high latitudes of southern hemisphere; Antarctic circumpolar variability on ENSO time scales (White and Peterson 1996), increased frequency of the South Pacific blocking related to the ENSO warm phase (Renwick 1998), and

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wave-train patterns of climate anomaly linking southern low and high latitudes during the South Pacific warm and cold events (Houseago *et al.* 1998). Bromwich *et al.* (2000) and Cullather *et al.* (1996) reported the strong ENSO signals in West Antarctic precipitation from the analysis of net precipitation calculated by using the model operational and reanalyses dataset. The results showed that there are a close positive correlation between SOI and West Antarctic precipitation from the early 1980s to 1990, and a close negative correlation after 1990. In order to explain the influence of ENSO in the South Pole region, Vincent (1994) suggests using the work of several authors (Meehl 1987; Trenberth 1976) that the South Pacific convergence zone may be related to variations in the ENSO cycle and may be a conduit for the poleward propagation of ENSO signal.

Antarctic precipitation is one of major components in mass balance of the Antarctic ice sheet. It is a primary input to the hydrological budget over the Antarctic region. The Antarctic ice sheet is one of the largest reservoirs of fresh water available on earth. The variability of the Antarctic ice sheets, especially supply of fresh water, has the potential for affecting the global freshwater budget and ocean circulation at lower latitudes. Also, the change of the Antarctic ice sheets related with global warming could have a major impact on global sea level variations (Jacobs 1992). Therefore, precipitation over the Antarctic region is important for understanding the mass balance of the Antarctic ice sheet and then the variability of global freshwater budget and ocean circulation. However, measuring precipitation over the Antarctic region is a complicated matter. Along the coasts, the effect of wind on gauge collections is large; considerable biases frequently result from blowing snow from snow fields surrounding the measurement sites (Schwerdtfeger 1984; Woo *et al.* 1983). In the interior, precipitation rates are usually less than the minimum snow gauge resolution (Bromwich 1988). So the works on Antarctic precipitation have in part employed the model operational and reanalysis data.

King Sejong Station (62.2°S, 58.7°W) is located in the Barton Peninsula of King George Island; one of South Shetland Islands off the northern tip of the Antarctic Peninsula (Fig. 1). The station was built in the beginning of 1988 and has provided the meteorological records for about 15 years until now. It has been supplied valuable data for understanding the meteorological environment of King George Island. Also, The observatory of King Sejong as a meteorological station (Index No. 89251) of WMO (World Meteorological Organization) has made an

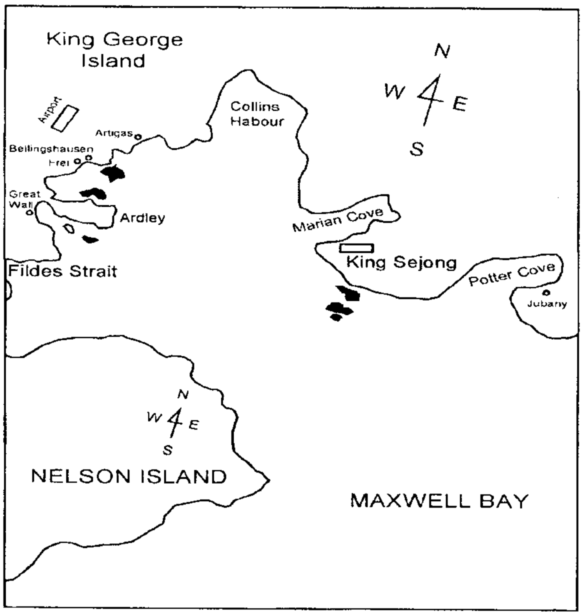

Fig. 1. Location map of King Sejong, Frei, and Artigas stations.

useful contribution for monitoring the variations of the Antarctic climate since 1988. Especially, the precipitation data of King Sejong Station will be able to be employed usefully for validating model precipitation output, investigating the accuracy of direct precipitation measurement, and also for understanding the variability of regional precipitation.

Due to the recent discoveries of ENSO signals from the Antarctic model precipitation, the ENSO signal is evaluated using the gauge-based precipitation data around King Sejong Station. The following section describes the gauge-based monthly precipitation data used in this study as well as the SST anomalies of the tropical Pacific that were used for quantifying the ENSO phenomenon. The gauge-based monthly precipitation data were collected from the three stations located within 10 km around King Sejong Station. The collected data are compared each other to examine the spatial coherence of precipitation in section 3. Among the three stations, Chilean Antarctic Frei Station (62.4°S, 58.9°W, WMO Index No. 89056) has longer precipitation record compared to the other two stations. Because of its longer record, the precipitation data from Frei for 31 years (1970-2000) are analyzed for examining the ENSO signal in seasonal precipitation in section 4. Also in section 5, the detailed relation between precipitation and ENSO is evaluated in the moving period of 5 years using the monthly data. Conclusions regarding analyzed results are discussed in section 6.

2. Description of data

Though there are several meteorological stations around King Sejong Station, the gauge-based monthly precipitation data were collected only from the three stations because of the difficulty in obtaining the data from the other stations. The three Antarctic stations are fully-equipped in meteorological observatories; King Sejong (Korea), Frei (Chile), and Artigas (Uruguay; 62.2°S, 58.9°W). These are all located within 10 km one another. However, there are considerable differences in the geographical environment of the measurement sites. In general, these stations are surrounded by sea and low mountains. King Sejong station is located between sea to the north (Marian Cove; MC) and to the west (Maxwell Bay; MB) and low mountain to the east and to the south. However, Frei and Artigas are reversely located between low mountain to the west or the north and sea to the east (MB) or to the south (MB) (Fig. 1). Therefore, there could be considerable variations in their climates due to the difference of their geographic environment. The available monthly precipitation data are the records of 13, 31, and 8 years from King Sejong, Frei, and Artigas Stations, respectively. The climate of King Sejong Station exhibits relatively warm temperature and wet condition compared with those of the inland stations in Antarctica, which shows the characteristics of

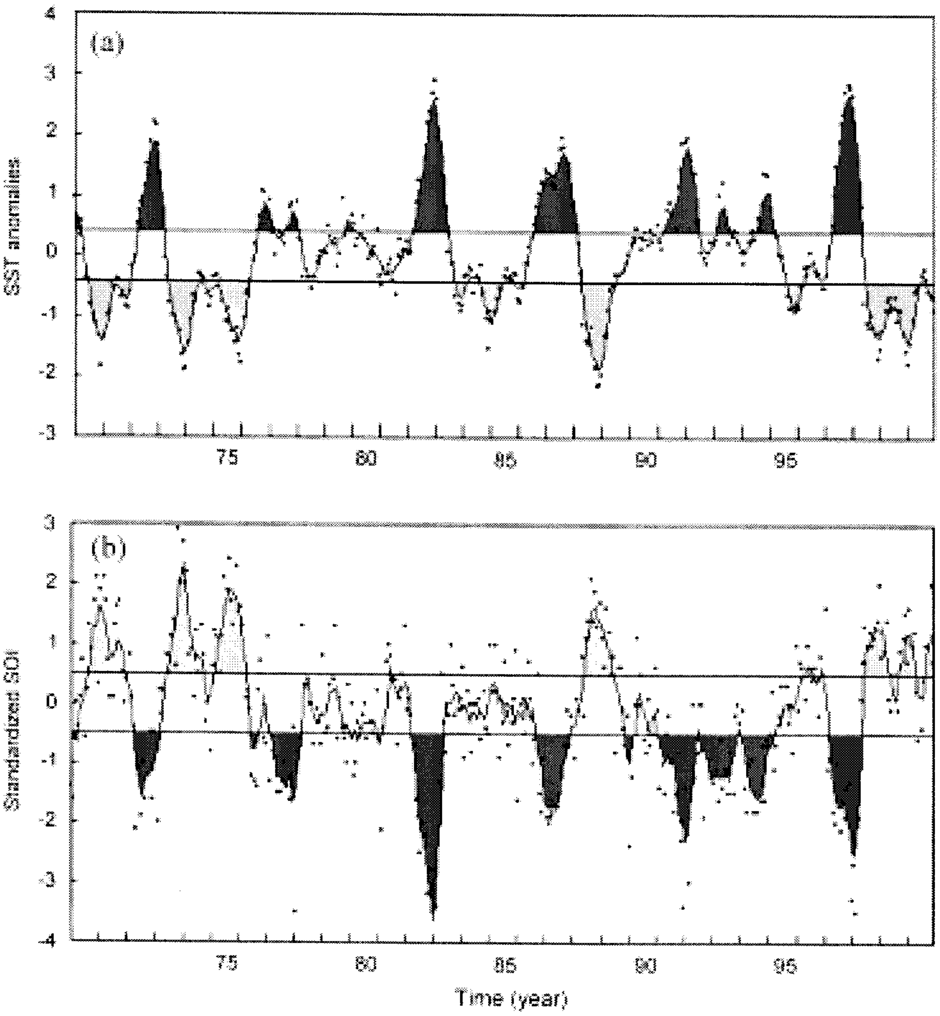

Fig. 2. Time series of (a) SST anomalies in the NINO 3.4 region and (b) SOI (Southern Oscillation Index). The shaded periods represent El Niño and La Niña events.

oceanic climate in polar region. Its annual mean values are -1.7 °C in surface air temperature, 8.0 ms^{-1} in surface wind speed, and about 90 % in relative humidity (Lee *et al.* 2000). The annual range of surface temperature is about 9 °C, which is far less than those of the inland stations in Antarctica. For the austral summer (December-February), the surface air temperature at the station is above freezing point and surface wind exhibits mostly northwesterlies. Meanwhile, strong southeasterlies are predominant in the austral winter (June-August) and these are frequently accompanied by severe blizzards (Lee *et al.* 1990; Lee and Nam 1991). Hence, the blowing snow accompanied by severe blizzards in the Antarctic winter may be one of the difficulties in measuring the accurate precipitation directly.

In order to express quantitatively the ENSO phenomenon, it is often separately described by the atmospheric and oceanic components. The atmospheric component has been known as a seesaw of atmospheric pressure between the eastern equatorial Pacific and Indo-Australian areas. SOI is used to characterize the strength of this atmospheric phenomenon. It is based on the monthly average of the surface pressure differences between Tahiti and Darwin. The oceanic component consists of a periodic displacement of the normally cold water that upwells along the coasts of the South America and across the Pacific in a cold tongue due to the tropical easterlies. When the easterlies relax, upwelling weakens and warm water moves in from the west, extending across the equatorial Pacific, it is known as an El Niño. When SST conditions in the tropical central Pacific are anomalously cold, it is known as a La Niña. The oceanic phenomenon is simply quantified by large-scale changes in SST across the eastern tropical Pacific. In recent years, Trenberth (1997) reported that SST anomalies in the NINO 3.4 region (5°N-5°S, 120°-170°W) match the ENSO identified historically.

The time series of SOI and SST anomalies (dots), 5-month running mean values (lines), and El Niño and La Niña periods (shaded) are shown in fig. 2. Using SOI, El Niño and La Niña events are defined by Ropelewski and Jones (1987) as follows; if 5-month running means of SOI is less than -0.5 standard deviations for 5 months or longer, the period is defined as El Niño, and La Niña is defined conversely. Trenberth (1997) defined El Niño and La Niña events using SST anomalies in the NINO 3.4 region; if 5-month running means of SST anomalies exceed 0.4 °C for 6 months or longer, the period is defined as El Niño, and La Niña is defined conversely. In this study, because there is a strong negative correlation (-0.9) between SOI and SST anomalies (5-month running means) for 31 years (1970-2000), SST anomalies in the NINO 3.4 region is used for quantifying the intensity of ENSO phenomenon. A list of El Niño and La Niña events defined by SST in the NINO 3.4 region is shown in table 1.

Table 1. List of El Niño and La Niña events after 1970. These are defined by SST anomalies in the NINO 3.4 region.

El Niño events		La Niña events	
Begin	**End**	**Begin**	**End**
Jan. 1970	Mar. 1970	Jul. 1970	Jan. 1972
May 1972	Mar. 1973	Jun. 1973	Jul. 1974
Aug. 1976	Mar. 1977	Sep. 1974	Apr. 1976
Aug. 1977	Jan. 1978	Sep. 1984	Jun. 1985
Oct. 1979	Mar. 1980	May 1988	Jun. 1989
Apr. 1982	Jun. 1983	Sep. 1995	Mar. 1996
Aug. 1986	Feb. 1988	Jul. 1998	Jun. 2000
Mar. 1991	Jul. 1992		
Feb. 1993	Aug. 1993		
Jun. 1994	Mar. 1995		
Apr. 1997	Apr. 1998		

3. Examination of spatial coherence in precipitation

In order to examine the spatial variability of precipitation around King Sejong Station, the data collected from the three stations are compared each other for the same period (1988-2000). The data from Artigas, however, is available only for 8 years (1988-1995). First, a visual inspection on the time series of monthly precipitation (Fig. 3) is carried out. The results exhibit that in all three stations, the annual cycle is not clear, while the interannual variability is considerably large; also there seems to be a decreasing trend at Frei. Fig. 4 shows the distribution of the monthly mean and standard deviation calculated from monthly total precipitation for the three stations. The total mean annual precipitation of the three stations are similar one another, which are 450 (King Sejong), 485 (Frei), 496 (Artigas) mm/year, respectively. The precipitation at Frei is almost evenly distributed throughout the year, while the relatively larger amount of Antarctic summer/fall precipitation is found at King Sejong and Artigas. This result shows a large difference compared with the precipitation climatology obtained by Jaeger (1976): the precipitation in the Antarctic Peninsula shows larger values during the Antarctic winter than during the summer. The standard deviation of monthly precipitation for the entire period amounts to 50-60 % of the annual

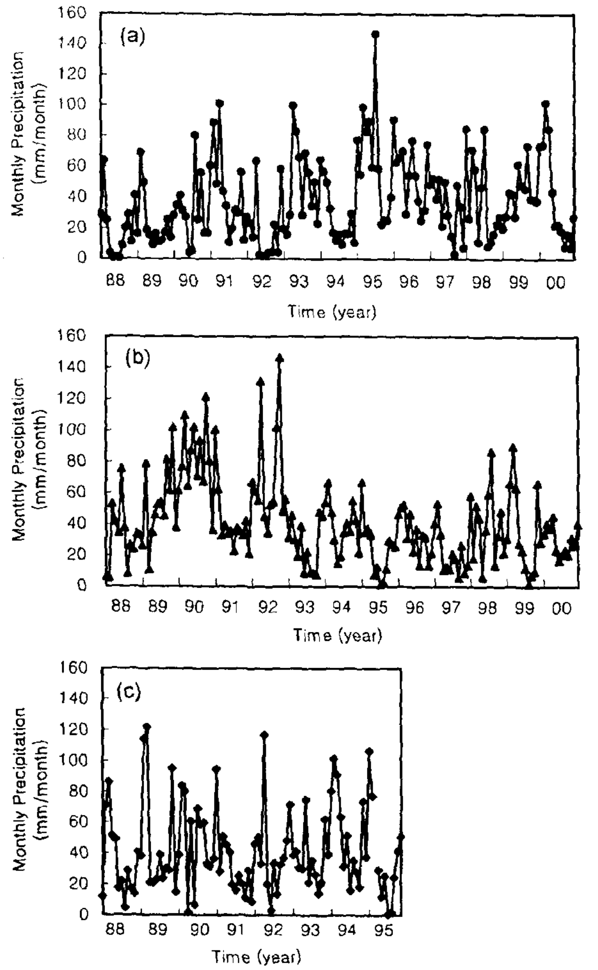

Fig. 3. Monthly Precipitation records at three Antarctic stations of (a) King Sejong, (b) Frei, and (c) Artigas.

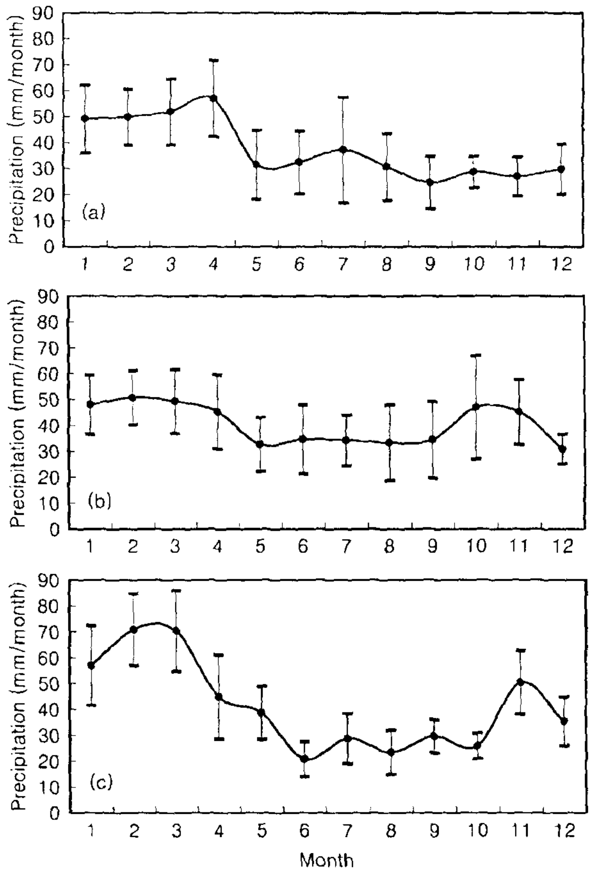

Fig. 4. Monthly mean and standard deviation of monthly total precipitation at (a) King Sejong and (b) Frei for 13 years (1988-2000), and (c) Artigas for about 8 years (1988-1995).

mean precipitation at the three stations. At Frei, the standard deviation of monthly precipitation for each month of the year is similar to or larger than annual precipitation range. Hence, the Frei precipitation can be characterized by that the interannual variability is larger than the annual variability.

The annual precipitation records at King Sejong and at Frei are compared in order to assess the spatial coherence of precipitation around King Sejong except for Artigas having short record of data. However, because the long-term trends are found in the annual precipitation (a decreasing trend with correlation of −0.48 at Frei and an increasing trend with correlation of 0.49 at King Sejong), first, the data are detrended to separate the long-term and short-term variabilities. Then, the correlation of annual precipitation between King Sejong and Frei is examined using both original and detrended data. Fig. 5 shows negative correlations in both cases of original (−0.52) and detrended data (−0.37). The negative correlation in the original data is significant at the level of 5 %. For further study, the correlation analysis was performed for the seasonal mean precipitation at the three stations; King Sejong, Frei, and Artigas (Table 2). In general, the seasonal correlations are mostly not significant with some negative correlations. Also, as the detrended data were used for the comparison of King Sejong and Frei, it is shown that the differences of the results are negligible. Hence, the above results can be summarized by that the relations in precipitation among measurement sites around King Sejong are not closely positive, but in some cases, rather negative. However, it should be noted that the data period used in the study is very short. The correlation between King Sejong and Frei is further examined on the

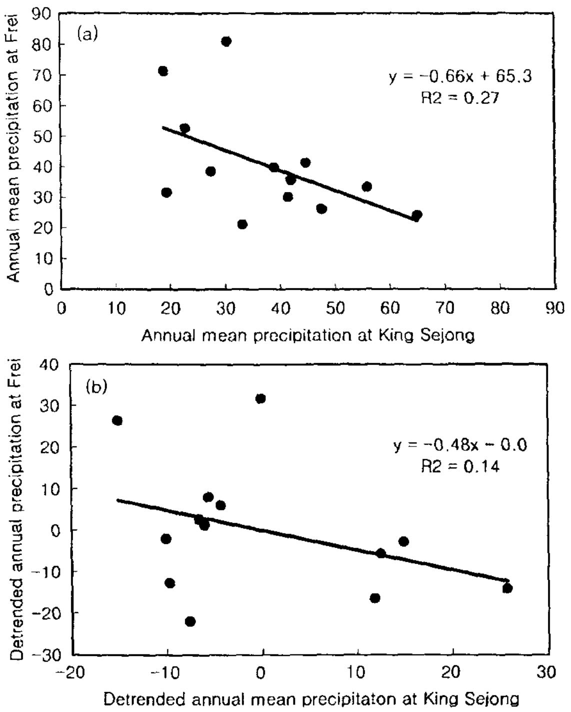

Fig. 5. Correlations of (a) annual mean precipitation (mm/month) and (b) detrended annual mean precipitation between King Sejong and Frei.

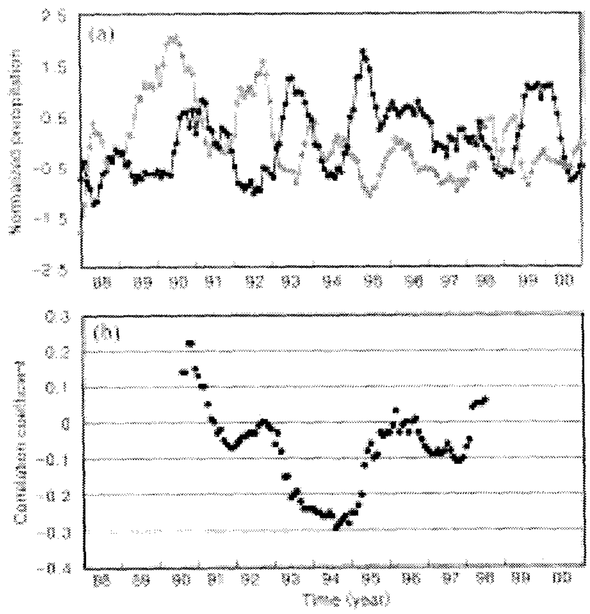

Fig. 6. Comparison of King Sejong and Frei precipitation. (a) 5-month running mean of normalized monthly precipitation [King Sejong (black line) and Frei (gray line)] and (b) correlation coefficient between normalized monthly values for 5-year moving period.

Table 2. Correlation coefficients between seasonal mean precipitation at King Sejong, Frei, and Artigas Stations. The values in the parenthesis are obtained from the detrended data. The correlations significant at the 95 % level are shaded.

	Summer	Fall	Winter	Spring
King Sejong-Frei	−0.16 (0.14)	−0.40 (−0.33)	−0.45 (−0.29)	−0.33 (−0.36)
King Sejong-Artigas	0.75	−0.81	−0.23	−0.38
Frei-Artigas	−0.26	−0.10	0.67	0.59

monthly precipitation data by a 5-year moving average. The purpose of this examination is to find the relation of monthly precipitation between King Sejong and Frei in ENSO time scales. The time period of 5 years is chosen for taking account of the precipitation variability related with ENSO and also eliminating the influence by long-term variability of precipitation. In order to do this, the monthly precipitation data are at first normalized to remove the annual variability (variations of monthly mean and variance through the year) of precipitation which might dominate the correlation. The normalization is achieved by dividing the departure from the average of monthly mean precipitation by the standard deviation of the values for that month. Then, the correlations are obtained from the 62 pairs (5-year data) of normalized monthly precipitation for the 5-year moving period (Fig. 6b). It shows that King Sejong precipitation is not closely related with that of Frei for most of the entire period except in the early of 1990, which shows even significant negative correlation (critical correlation coefficient for the 5 % significance level is −0.21). For the visual inspection, the 5-month running means of normalized precipitation are shown in fig. 6a.

The spatial coherence of precipitation around King Sejong was examined by comparing the data collected from the three stations; King Sejong, Frei and Artigas. The precipitation records show mostly insignificant positive or rather negative correlations among the three stations in the annual, seasonal and monthly precipitation data. Even though the period of record used in this study is short, the results can be summarized that there is considerable spatial variability within the small region of about 10 km distance around King Sejong. So, when the temporal variability of precipitation is investigated around King Sejong, careful consideration is required on whether one station can represent the given region in precipitation.

4. Seasonal precipitation anomaly related with El Niño/La Niña

Among the three stations, Frei, Chile has longer precipitation record compared to the other two stations. Because of its longer record, the precipitation data from Frei for 31 years (1970-2000) are analyzed for examining the seasonal precipitation variability associated with El Niño/La Niña. Fig. 7 shows the time series of seasonal precipitation at Frei. Significant decreasing trends (at the level of 1 %) are found in Antarctic fall, winter and spring, but no significant trend in summer. This results agree well with the decreasing trend of 13-year annual precipitation in the previous section. From visual inspection of fig. 7, it is also easy to find the precipitation variability related with El Niño. The ENSO related variability of seasonal precipitation is examined by comparing the precipitation anomalies associated with El Niño and La Niña. A list of El Niño and La Niña is given in table 1. The anomalies are calculated from the original data and the detrended data, respectively. Then, the precipitation distributions, for the periods of El Niño, La Niña, and of the total, are compared quantitatively, based on these anomalies.

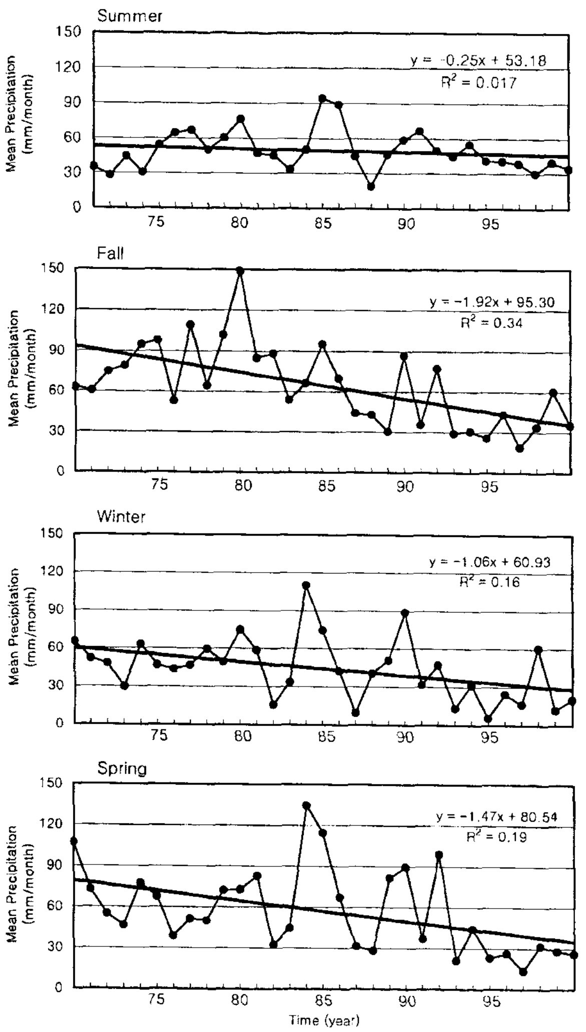

Fig. 7. Distribution of seasonal mean precipitation at Frei and their trend.

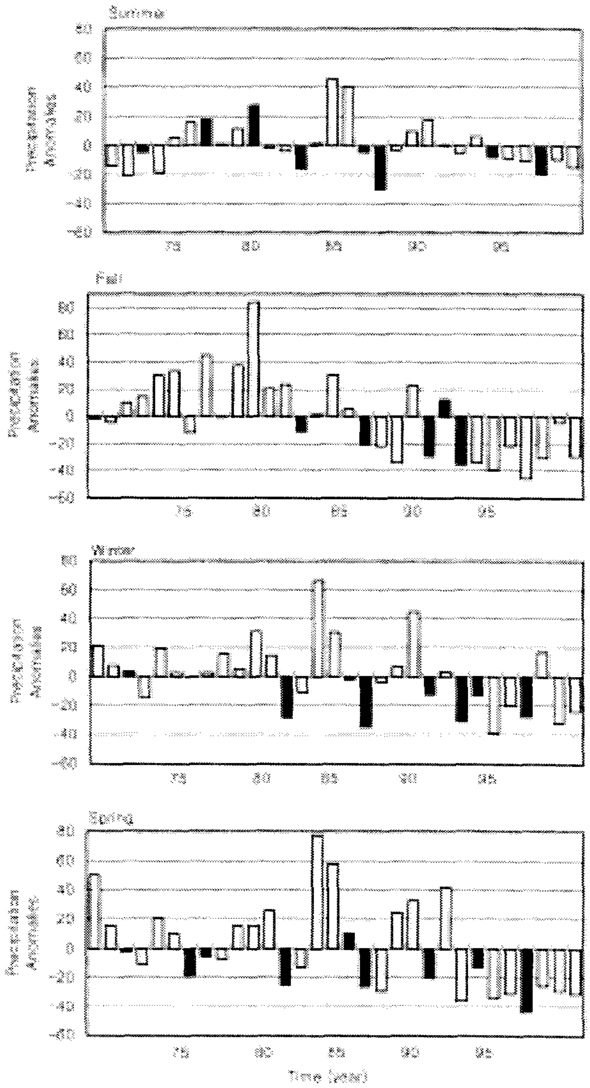

Fig. 8. Distribution of seasonal precipitation anomalies (mm/month) at Frei. The El Niño periods are shaded.

Fig. 8 shows the time series of actual (not detrended) precipitation anomalies. The anomalies related with El Niño are shaded in the figure. For El Niño, most events are associated with negative anomalies; 22 of 29 events (when all of the seasonal events are counted) are associated with negative anomalies. In spring, 8 of 9 are negative, 6 of 7 in winter, 4 of 5 in fall, 6 of 9 in summer, respectively. Especially, for three seasons of fall, winter and spring, the average of the seasonal anomalies for El Niño period is −20 mm/month, which amounts to 35 % of seasonal mean precipitation. Also, in order to take into account the case that seasonal precipitation may not be normally distributed, the anomalies are obtained by taking the departure from the median of seasonal precipitation. When both of mean-based anomalies and median-based anomalies were employed, however, the difference between the seasonal precipitation anomalies for El Niño period is not large. For fall-spring, average of the median-based anomalies for El Niño period is −17 mm/month and 33 % of the seasonal median precipitation (Table 3).

Table 4 shows the summary of detrended precipitation anomalies associated with El Niño. The detrending procedure is applied in order to remove long-term trends in seasonal precipitation that might influence the above results related with El Niño. The detrended anomalies are analyzed only for fall-spring seasons which show significant decreasing trends in precipitation. For fall-spring, 18 of 21 El Niño events are associated with negative anomalies. The average duration of the seasonal anomalies for El Niño period is −14 mm/month and it amounts to 27 % of the seasonal mean precipitation. Hence, it can be summarized from the above analysis that El Niño events are in general associated with negative anomalies, in particular the seasons of fall-spring show the decrease of 14-20 mm/month in the average precipitation for El Niño period and it amounts to 27-35 % of seasonal mean precipitation.

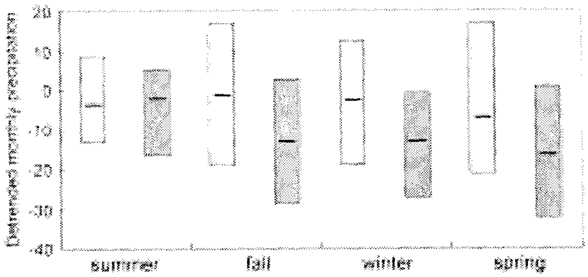

Fig. 9. Detrended monthly precipitation anomalies at 25th, 50th, 75th percentiles for the El Niño period (shaded box) and the total period. The upper and lower ends of the box are drawn at the quartiles. The bar through the box is drawn at the median.

Fig. 9 further compared the distributions of seasonal precipitation for El Niño period and total period. Due to shortness of the record, the distributions are obtained from monthly anomalies instead of seasonal anomalies. For example, for a given season of the year three monthly anomalies are used. To do this, it is assumed that there is not a large difference within a season in the distribution of precipitation anomalies for each month of the year. The anomalies are also calculated through the detrending procedure. The results show that the precipitation distribution

Table 3. Seasonal precipitation anomalies in the El Niño periods.

Season	Precipitation anomalies (mm/month)	Precipitation anomalies (%)	Mean (median) precipitation (mm/month)	Number of season (dry/total)
Summer	−6.0	−12.3	48.9 (45.7)	6/9
Fall	−19.1	−28.6	66.6 (62.8)	4/5
Winter	−20.8	−47.2	44.0 (46.5)	6/7
Spring	−18.8	−33.0	56.0 (50.0)	8/9
Average	−16.2	−30.0	54.1 (51.3)	24/30

Table 4. Seasonal anomalies of detrended precipitation in the El Niño periods.

Season	Precipitation anomalies (mm/month)	Precipitation anomalies (%)	Mean precipitation (mm/month)	Number of season (dry/total)
Fall	−8.4	−12.6	66.6	4/5
Winter	−17.1	−38.8	44.0	7/7
Spring	−16.4	−29.3	56.0	7/9
Average	−14.0	−26.9	55.5	18/21

associated with El Niño is shifted toward negative anomalies compared with the one for the total period in the seasons of fall, winter and spring, while they are similar in

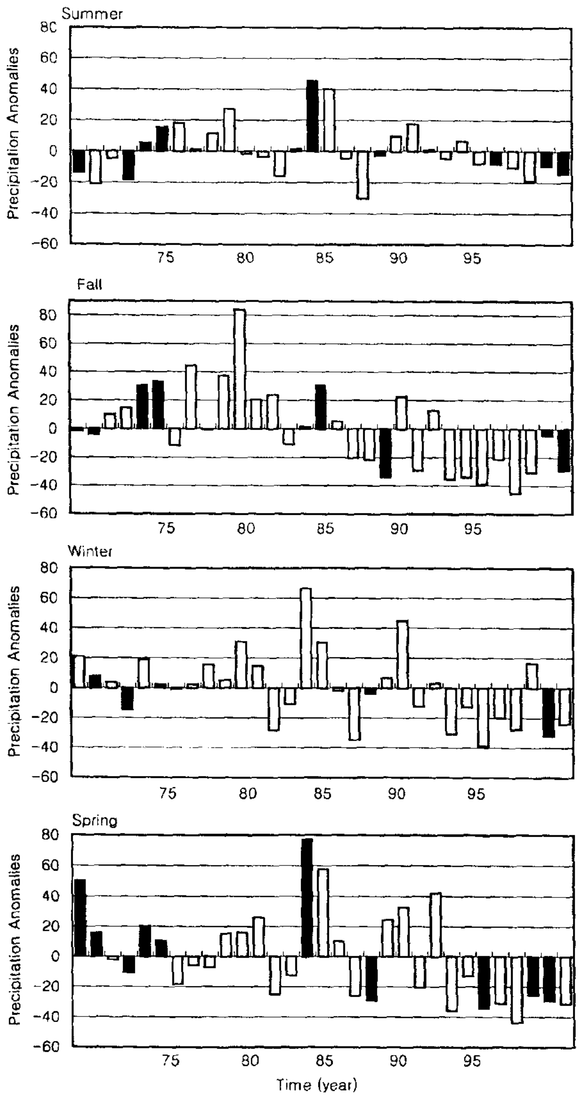

Fig. 10. Distribution of seasonal precipitation anomalies (mm/month) at Frei. The La Niña periods are shaded.

summer. In the seasons of fall-spring, the El Niño associated values at the 25th and 50th (median) percentile are near the 50th and 75th percentile values for the total period. Hence, this results also indicate that El Niño events are associated with negative precipitation anomalies, especially for fall-spring season.

However, the analysis associated with La Niña events suggests that there is no close relation between precipitation at Frei and La Niña events. Fig. 10 shows seasonal precipitation anomalies related with La Niña. Over all seasons, 13 of 31 La Niña events are positive anomalies and 18 of 31 negative anomalies. No significant anomalies associated with La Niña is found in any one season. Average of seasonal mean anomalies for La Niña period is very small (0.7 mm/month) and negligible compared with seasonal mean precipitation (Table 5). Also the analysis of the detrended anomalies shows similar results with the previous one in fall and spring, but not in winter (Table 6). Exceptionally, La Niña winters are associated closely with negative anomalies (5 of 5 La Niña events are negative anomalies). However, the comparison of precipitation distributions for La Niña period and the total period shows that there is no significant shift in the distribution during winter season (The figure is not shown here). Therefore, it may be summarized that the precipitation signal related with La Niña events is not significant.

5. Relationship between monthly precipitation and SST anomaly

The monthly precipitation at Frei is characterized by the large interannual variability that is similar to or larger than its annual precipitation range. In order to find out the obvious periodicities from the interannual variation, the spectral analysis was applied to the normalized monthly precipitation data for 31 years at Frei. Fig. 11 shows the resulting periodogram, which has distinct peaks at 31- and 5.2- year periods. The relative powers of the above two periods are 13.0 % and 8.1 %, respectively. These relative powers are much larger than the relative power of 3.7 %

Table 5. Seasonal precipitation anomalies in the La Niña periods.

Season	Precipitation anomalies (mm/month)	Precipitation anomalies (%)	Mean precipitation (mm/month)	Number of season (wet/total)
Summer	0.0	0.0	48.9	3/9
Fall	3.2	0.0	66.6	3/7
Winter	⇔5.0	⇔1.4	44.0	2/5
Spring	4.6	8.2	56.0	5/10
Average	0.7	⇔0.8	54.1	13/31

Table 6. Seasonal anomalies of detrended precipitation in the La Niña periods.

Season	Precipitation anomalies (mm/month)	Precipitation anomalies (%)	Mean precipitation (mm/month)	Number of season (wet/total)
Fall	2.7	4.1	66.6	4/7
Winter	-12.0	-27.3	44.0	0/5
Spring	1.18	2.1	56.0	3/10
Average	-2.7	-7.0	55.5	7/22

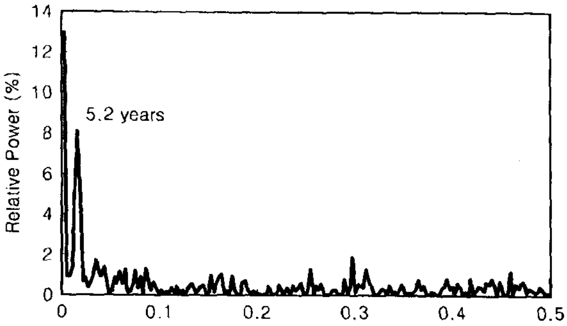

Fig. 11. A portion of the periodogram of normalized monthly precipitation.

corresponding to the significant level of 0.1 % with the assumption of white noise process and Chi-square distribution (Shumway 1988). The period of 31 years may be related with the significant decreasing trend which was already found in annual and seasonal precipitation. The period of 5.2 years agrees well with ENSO period (2-7 years). Hence, it may be interpreted that a large part of interannual precipitation variability at Frei consists of a long-term decreasing trend and ENSO related variation.

In order to investigate the ENSO related variation from the monthly precipitation data at Frei, the normalized monthly precipitation and the SST anomalies in the NINO 3.4 region are directly compared (Fig. 12). From the figure, it is shown that for the 1990s, dry periods (normalized monthly precipitation is less than -1) are dominant, while for the 1970s, wet events (normalized value is greater than 1) are more frequent than dry events; and for the 1980s, severe dry and wet periods appear alternately and the variation of these periods are closely related with the variation of the SST anomaly. By a visual examination, the long-term decreasing variation and the ENSO related variation in the monthly precipitation can be easily found. Therefore, for investigating the relation between monthly precipitation and SST anomaly, there is a need to remove the long-term variation from the normalized monthly precipitation of Frei.

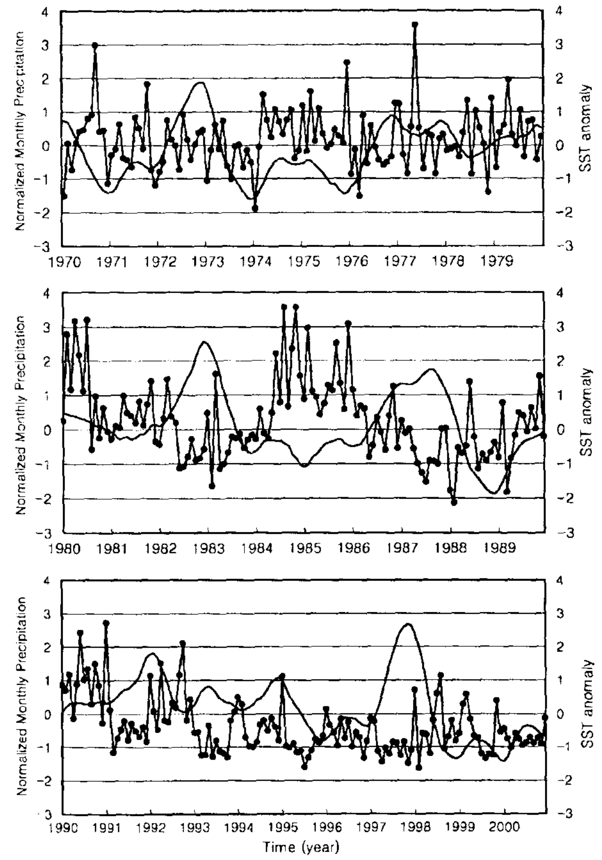

Fig. 12. SST anomaly (solid line) and normalized monthly precipitation (line with dots) at Frei for 31 years (1970-2000). The SST anomalies are five-month moving averages.

Also, in order to evaluate in detail the relation between precipitation and SST anomaly, the SST anomalies in the NINO 3.4 region are correlated with normalized monthly precipitation at Frei. Correlation analyses are performed over the moving period of 5 years (Fig. 13), which is the period of ENSO time-scale variation found from the spectral analysis. The short time period such as 5 years is used in order to reduce the effect of long-term variation on the above correlation, instead of removing the long-term variation. For 1970-1977, the SST-Frei precipitation

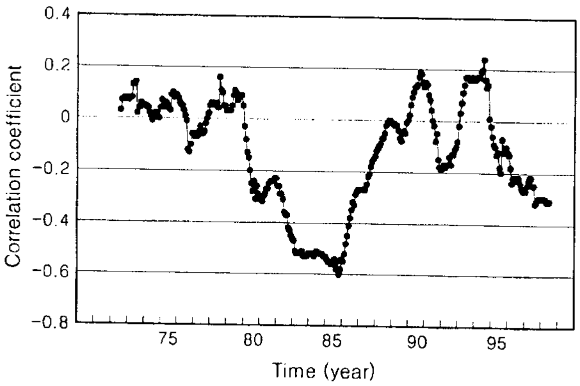

Fig. 13. Correlation coefficient between normalized monthly precipitation of Frei and SST anomalies in the 5-year moving periods.

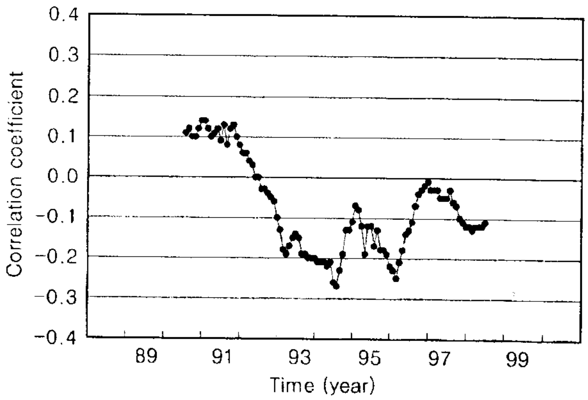

Fig. 14. Correlation coefficient between normalized monthly precipitation of King Sejong and SST anomalies in the 5-year moving periods.

correlations are almost close to 0, so not significant. For 1978-1989, most of correlation coefficients are less than <0.21, which is significant at the level of 5 % (one-tailed test). The negative correlation means that decreases in the SST anomaly are matched with increases in monthly precipitation, while increases in the SST anomaly are related with dryer periods. This result is coincident with decrease of precipitation for El Niño period in the previous section. For 1990-2000, in the early 1990s positive correlations are prevalent, even though these are not statistically significant, and in the late 1990s significant negative correlations are dominant. In conclusion, the main features of correlation analyses are as follows: there are a strong negative correlation between Frei monthly precipitation and SST anomalies in the NINO 3.4 regions for the periods of the 1980s and after 1994 and on the other hand a weak positive correlation in the early 1990s.

However, the above ENSO signal in Frei monthly precipitation may not be expected over all regions around King Sejong. Among three stations around King Sejong, correlations are mostly not significant or negative in the annual, seasonal and monthly precipitation. Probably there could be considerable difference among the SST-precipitation relations at King Sejong, Frei, and Artigas. Because of a shorter period of precipitation record, to analyse the ENSO related seasonal precipitation anomaly is not adequate at King Sejong and Artigas. For King Sejong having longer record than Artigas, the correlation analyses are performed over the moving period of 5 years (Fig. 14). The SST-King Sejong precipitation correlations are positive in the early 1990s and negative in the mid and late 1990s, which are mostly not statistically significant.

Comparing the correlations at King Sejong and at Frei, in general the magnitude of correlation coefficient is smaller at King Sejong than at Frei. The distribution pattern of correlation coefficient at King Sejong is similar with that of Frei.

6. Summary

This study evaluates a detailed relation between ENSO and precipitation around King Sejong using the gauge-based precipitation data. To do this, monthly precipitation data are collected from three stations which are all located within 10 km; King Sejong (Korea; 1988-2000), Frei (Chile; 1970-2000), and Artigas (Uruguay; 1988-1995). For examining ENSO signal in the precipitation around King Sejong, the analysis focused on the 31 years data from Frei, due to the relatively longer period of the record.

The precipitation data of the three stations are compared one another in order to examine the spatial coherence of precipitation. The comparison shows that there are mostly insignificant positive or rather negative correlations among them in the annual, seasonal, and monthly precipitation. It means that there is a considerable spatial variability around King Sejong. Understanding the characteristics of precipitation around King Sejong, therefore, requires further detailed study with longer and more data. Moreover, owing to the large spatial variability, the ENSO signal obtained from Frei precipitation may not be expected over the region around King Sejong.

Seasonal precipitation at Frei shows the significant decreasing trends in the Antarctic fall, winter, and spring. From the analysis of both original data and detrended data (after removing decreasing trends), it is revealed El Niño events are mostly related with negative anomalies in seasonal precipitation. This dryness is more distinct in fall to spring seasons, in which 18 of 21 El Niño events are associated with negative anomalies. Average of the precipitation decrease is 14-20 mm/month and amounts to 27-35 % of seasonal mean precipitation. It is also shown that the precipitation anomaly distribution associated with El Niño is shifted toward negative anomalies: there is shifts on the order of 20 percentile points, that is, from the median to the 30th percentile. However, it is found that the precipitation signal related with La Niña events is not significant.

Monthly precipitation at Frei is characterized by the large interannual variability that is similar to or larger than its annual precipitation range. From the spectral analysis of normalized monthly precipitation data, it may be interpreted that a large part of interannual variability at Frei consists of a long-term decreasing trend and 5.2-year variation of ENSO time-scale. For evaluating in detail the relation between ENSO and monthly precipitation of Frei, the SST anomalies in the NINO 3.4 region are correlated with normalized monthly precipitation over the moving period of 5 years. It is found that there are a strong negative correlation between Frei normalized monthly precipitation and SST anomalies in the NINO 3.4 region for the periods of the 1980s and after 1994 and on the other hand a weak positive correlation in the early 1990s.

Recently, Bromwich *et al.* (2000) and Cullather *et al.* (1996) reported a strong ENSO signal and a significant upward trend in West Antarctic precipitation (precipitation-evaporation/sublimation) from the analysis of the model operational and reanalysis dataset. The results showed that there is a close positive correlation between SOI and West Antarctic precipitation from the early 1980s to 1990, and a close negative correlation after 1990. These results are in good agreement with the correlation pattern in this study between SST anomaly and Frei precipitation except for the period of the late 1990s. Hence, the ENSO signal in Frei precipitation is supported by the results of West Antarctic precipitation. However, a significant upward trend in West Antarctic precipitation are conflicting with a significant decreasing trend in Frei precipitation. Even the precipitation at Frei and King Sejong also exhibit the opposite trend. Therefore, to confirm the ENSO related variability and interannual trend in precipitation around King Sejong, the further exploration of the spatial precipitation variability needs to be done.

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