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ARTICLE

Changed Relationships between El Niño-Southern Oscillation Events and Climate over the Democratic People's Republic of Korea since 1950

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ABSTRACT

The El Niño-Southern Oscillation (ENSO) is a dominant interannual climate mode influencing global weather patterns. This study investigates the evolving relationship between ENSO and seasonal climate over the Democratic People's Republic of Korea (DPRK) from 1950 to 2024. Using the Niño3.4 index alongside homogenized monthly temperature and precipitation records from 37 stations, we applied continuous wavelet analysis, Mann-Kendall abrupt change detection, and 21-year sliding correlation techniques. To isolate interannual ENSO signals, linear trends associated with global warming were removed from temperature data. Results indicate that 25 El Niño and 20 La Niña events occurred, with the Niño3.4 index exhibiting a dominant 1–5.7-year periodicity and a statistically significant regime shift in the late 1970s. Following detrending, the ENSO–winter temperature teleconnection weakened markedly after the late 1980s. Specifically, El Niño-induced DJF warming intensified by +0.45 °C ($p < 0.01$) in the 1991–2024 period compared to 1950–1990, whereas La Niña winters transitioned from anomalously warm to cold. Summer climate responses also shifted significantly: El Niño-related JJA precipitation decreased by 73.1 mm (from +20.7 to −52.4 mm, $p < 0.05$) in the DPRK, while La Niña summers exhibited opposite trends. These nonstationary relationships, driven by decadal reorganizations of Pacific-Asian atmospheric circulations, provide critical insights for improving seasonal climate prediction and informing regional climate adaptation strategies in the DPRK.

Keywords: ENSO; Decadal Shift; Climate Change; Korean Peninsula

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1. Introduction

El Niño is referred to as the sea surface temperature (SST) in the equatorial East Pacific (specifically, in the equatorial Pacific west of the Peruvian coast) lasting for the above few months or half a year by one of several years [1,2]. On the contrary, the opposite event is La Niña. Both El Niño and La Niña (or El Niño-Southern Oscillation; ENSO) events affect not only tropical atmosphere but also global atmosphere and ocean circulations, leading to abnormal climates on the Earth. The ENSO events occur as a result of macroscale interactions between atmosphere and ocean in the tropical Pacific.

So far, many countries have carried out numerous studies of the impacts of ENSO events on the climate and monsoon variations over different regions around the globe, against the background of global warming. Most of these studies were concerned with the teleconnection between ENSO events and local weather and climate [3–5]. Recent work has further emphasized the decadal modulation of these teleconnections by large-scale climate modes such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) [6,7], as well as the distinct regional impacts of different El Niño types (i.e., Eastern Pacific (EP) vs. Central Pacific (CP) El Niño) on East Asian climate [8,9]. Moreover, the nonstationary nature of the ENSO–East Asian winter monsoon(EAWM) relationship has been extensively evaluated in both observations and CMIP6 models [10,11].

The Democratic People's Republic of Korea (DPRK) is located in north of the East Asian monsoon (EAM) domain of 20°–45° N and 110°–140° E. As such, the weather and climate over the DPRK usually depend on the behavior of EAM, which is related to ENSO. But, as indicated by Jia and Ge [12], the relationship between the winter precipitation anomalies in southeastern China, ENSO, and EAWM at the end of the twentieth century was obviously weakened. Previously, He and Wang [13] also investigated the oscillations of the relationship between ENSO and EAWM and pointed out the weakening of the relationship between these. The winter surface air temperature over the DPRK in the late 1980s was abruptly changed in the late 1980s due to the weakened EAWM [14]. Sun et al. [15] found that ENSO's impact on eastern China summer precipitation has experienced two decadal shifts, one in the late 1970s and the other in the 1990s. Wang [16] showed the East Asian summer monsoon (EASM) in 1979–2005 compared to 1950–1978 was weakened. Meanwhile, Han and Wang [17] concluded that since the 1970s, the Western Pacific subtropical high (WPSH), the major circulation system of EASM, has been strengthened with the weakening of EASM. As many researchers have pointed out, under this background, both the relationship between ENSO and EASM, and the relationship between ENSO and summer precipitation in China, weakened [16,18–20].

With regard to the interdecadal variations in the atmosphere and oceans in the 1970s, when and how did the changes in temperature and precipitation over the DPRK occur during El Niño and La Niña? Also, did the ENSO events affect the entire region of the DPRK equally? Yet, these issues are not well understood over the study area, although there are many studies on the changed relationship between ENSO and climate in different parts of the world. Hence, this paper focuses on the identification of the changed relationships between ENSO events and climate over the DPRK during the period from 1950 to present.

2. Data and Methodology

2.1. Data

In this study, we use the Niño3.4 index for the period from 1950 to 2024 obtained at the website of the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (https://www.esrl.noaa.gov/psd/enso/ dashboard.html).

For the period mentioned above, monthly mean surface air temperature and monthly total precipitation data from 37 carefully selected meteorological stations over the DPRK were used. As demonstrated by Om et al. [21], these 37 stations provide high-quality, homogenized data with guaranteed accuracy, ensuring reliable long-term climate analysis. The distribution of the stations and detailed information are shown by Jong et al. [22].

2.2. Methodology

The indices used to quantify the intensity of El Niño and La Niña events include the Niño1+2 (10° S–0°, 90°–80° W) index, Niño3 (5° S–5° N, 150°–90° W), Niño3.4 (5° S–5° N, 170°–120° W), and Niño4 (5° S–5° N, 160° E–150° W), and so on [23]. The Niño index used in our study is the Niño3.4 index.

In order to confirm the periodicity of El Niño and La Niña events between 1950 and 2024, a continuous wavelet analysis, a powerful mathematical tool for non-stationary random signals, was performed on the Niño3.4 index time series. Also, the Mann-Kendall rank test, a non-parametric trend test, was used to detect an abrupt change point in the index time series mentioned above. This method does not assume any particular probability distribution of the data series. The null hypothesis is that there is no trend in the series. The test generates two statistical series: U-Forward statistics (UF: progressive) and U-Backward statistics (UB: retrograde). An abrupt change point is identified when the UF and UB curves intersect within the confidence limits (e.g., at the 95% confidence level), indicating a statistically significant shift in the time series. A more detailed description of the wavelet analysis and the Mann-Kendall test is given by Zhu et al.[5].

To investigate the temporal evolution of the relationship between ENSO and the climate over the DPRK, a sliding window correlation analysis was performed. A 21-year window (with a 1-year step) was used to calculate the correlation coefficient between the detrended seasonal mean temperature (and seasonal total precipitation) averaged over the DPRK and the Niño3.4 index. The significance of the correlation coefficients was assessed at the 95% confidence level using a two-tailed t-test. This approach allows identification of periods when the ENSO–climate relationship strengthened or weakened.

For composite analysis, we assessed statistical significance using Student's t-test applied to regional-mean time series averaged over 37 stations, following established practice in teleconnection research[6,10]. This approach enhances the signal-to-noise ratio for detecting large-scale ENSO impacts that may be obscured by local variability at individual stations.

To isolate the ENSO-related climate variability from the long-term global warming trend, we removed the linear trend from the original temperature time series. For each season and each station, a linear regression was fitted to the temperature data over the entire study period (1950–2024), and the fitted trend was subtracted to obtain detrended temperature anomalies. This approach allows us to focus on interannual variability associated with ENSO by removing the influence of secular warming.

In this study, the onset of El Niño (and La Niña) is defined as the beginning month when a region-averaged SST anomaly of +0.5 °C (−0.5 °C) or more (below) occurs in the Niño 3.4 region and it lasts for at least 5 months[2]. And if, during the period of the El Niño (La Niña) event, the value of +0.5 °C (−0.5 °C) or less (more) is present for 1 to 3 months and the sign does not change, it is considered that the event persists. This definition allows the inclusion of relatively short-lived ENSO events, which can also exert significant climatic impacts over the study area.

3. Result

3.1. Occurrence Characteristics of El Niño and La Niña

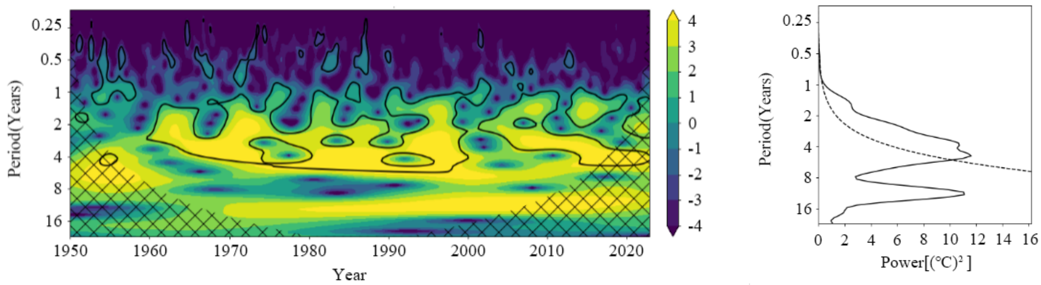
3.1.1. Periodicity of Niño3.4 Index Time Series

A total of 25 cases of El Niño were observed during the study period, which was approximately once every 3 years. This is consistent with the fact in Ahrens and Henson's study[1] that El Niño occurs mostly once every 2 to 7 years. The El Niño intensity showed a rather linear increasing trend from 1950 to 2024, but the statistical significance was low. During this period, La Niña events occurred 20 times, corresponding to a frequency of approximately once every 3.7 years.

In order to further confirm the periodicity of El Niño and La Niña events between 1950 and 2024, a continuous wavelet analysis was performed on the Niño3.4 index time series. **Figure 1a** illustrates the analysis results of the Niño3.4 index time series. The continuous wavelet spectrum for the case of the Niño3.4 index time series shows that the significant (confidence level of 95%) Niño3.4 index is approximately uniformly distributed over the 1–5 years during the study period. **Figure 1b** also illustrates the corresponding global wavelet spectrum. When the wavelet spectrum exceeds the dashed line, it shows that the corresponding period is at 95% confidence level of verification. **Figure 1b** shows that the Niño3.4 index time series has a significant period at time scales of 1–5.7 years. In other words, during the 75-year period, the change in the Niño 3.4 index time series is predominant with the 1–5.7-year period change.

On the other hand, the spectral analysis by the discrete

Fourier transform[24] shows that the first significant period of Niño3.4 index time series variation is 12 months (1 year), the second significant period is 42 months (3.5 years), and the third significant period is 56 months (4.7 years).



(**a**) Nino3.4 index wavelet power spectrum (Morlet).

(**b**) Global wavelet spectrum.

Figure 1. The continuous wavelet power spectrum and the global wavelet spectrum of the Niño3.4 index time series since 1950.

3.1.2. Abrupt Change of Niño3.4 Index Time Series

So far, numerous studies have investigated abrupt changes in regional temperature and precipitation[14,25,26], as well as in atmospheric circulation indices[27–29]. However, research on abrupt changes in the Niño index time series itself remains scarce.

The Mann-Kendall abrupt change test identifies a statistically significant regime shift in the Niño3.4 index around the late 1970s (>95% confidence; **Figure 2**). This timing precedes the late-1980s climate shift over the DPRK by approximately one decade, providing a physical basis for the P1/P2 subperiod division.

On the other hand, the seasonal climate over the DPRK also underwent a statistically significant abrupt change, but approximately one decade later (see Section 3.2 for the basis of the subperiod division).

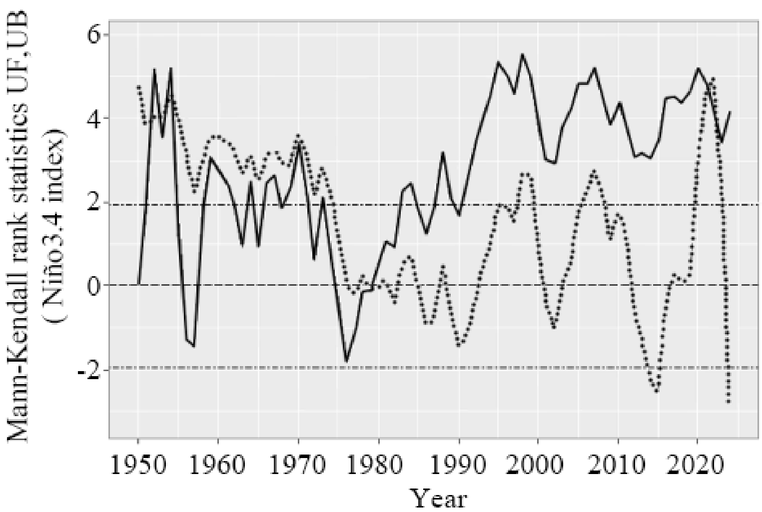


Figure 2. The abrupt change in Niño3.4 index time series during the period from 1950 to 2020.

Note: The black solid line denotes the progressive series (Mann-Kendall UF-statistic); dotted line denotes the retrograde series (UB-statistic); horizontal dashed & dotted lines are the confidence limits (0.05).

3.1.3. Beginning, End and Duration of El Niño and La Niña Events

As shown in **Table 1**, a total of 25 El Niño events were observed during the study period. Among these, El Niño events that occurred in boreal summer (June–July–August; JJA) accounted for 12 cases (48% of the total), while those starting in boreal autumn (September–October–November; SON) accounted for 8 cases (32%). The mean duration of El Niño during the study period was 8.9 months, with the longest event lasting 20 months (October 2014–May 2016).

Table 1. The onset, end and duration of El Niño and La Niña events occurring between 1950 and 2024.

No.	Onset (Year. Month)	End (Year. Month)	Duration (Months)
		El Niño	
1	1951. 6	1952. 1	8
2	1953. 2	1954. 2	13
3	1957. 4	1958. 7	16
4	1958. 11	1959. 2	5
5	1963. 6	1964. 2	9
6	1965. 5	1966. 4	12
7	1968. 10	1969. 5	8
8	1969. 8	1970. 1	5
9	1972. 5	1976. 3	11
10	1976. 9	1977. 2	6
11	1977. 9	1978. 1	5
12	1979. 10	1980.2	5
13	1982. 4	1983. 6	15
14	1986. 9	1988. 2	18
15	1991. 5	1992. 6	12
16	1994. 9	1995. 3	7
17	1997. 5	1998. 5	13
18	2002. 6	2003. 2	9
19	2004. 7	2005. 2	8
20	2006. 9	2007. 1	5
21	2009. 7	2010. 3	9
22	2014. 10	2016. 5	20
23	2018. 9	2019. 6	10
24	2019. 11	2020. 3	5
25	2023. 5	2024. 5	13
		La Niña	
1	1950. 1	1950. 7	7
2	1954. 5	1956. 9	29
3	1964. 5	1965. 1	9
4	1970. 7	1972. 1	19
5	1973. 5	1974. 7	15
6	1974. 10	1976. 4	19
7	1983. 9	1984. 1	5
8	1984. 10	1985. 8	11
9	1988. 5	1989. 5	13
10	1995. 8	1996. 3	8
11	1998. 7	2001. 2	32
12	2005. 11	2006. 3	5
13	2007. 6	2008. 6	13
14	2008. 11	2009. 3	5
15	2010. 6	2011. 5	12
16	2011. 8	2012. 3	8
17	2016. 8	2016. 12	5
18	2017. 10	2018. 3	6
19	2020. 8	2021. 4	9
20	2021. 9	2023. 1	17

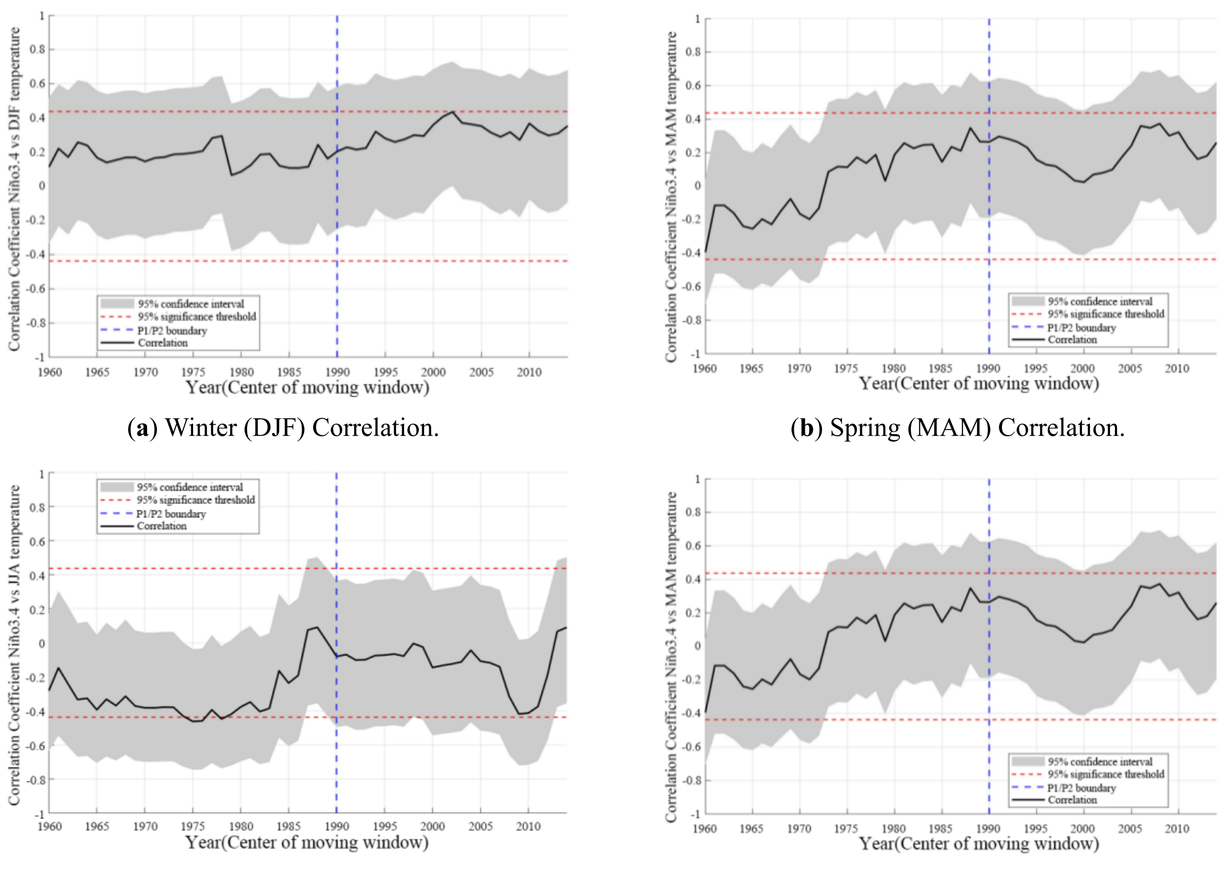
A total of 20 La Niña events occurred during the study period (**Table 1**). The mean duration of La Niña was 12.7 months, with the longest event lasting 32 months (July 1998–February 2001). The inclusion of short-lived events (5–6 months duration) under our 5-month criterion accounts for the higher frequency and shorter average duration compared to previous studies that applied a stricter 6-month threshold.

3.2. Sliding Correlation between ENSO and DPRK Climate

According to the Mann-Kendall rank test, the seasonal mean air temperature and seasonal total precipitation time series over the DPRK experienced a statistically significant abrupt change in the late 1980s, about 10 years later than the Niño3.4 index time series in almost all seasons, for example, as indicated by Jong et al.[14] for winter surface air temperature. On this basis, the study period was divided into two subperiods: P1 (1950–1990; 41 years) and P2 (1991–2024; 34 years). To examine the temporal evolution of the ENSO–climate relationship across these periods, a 21-year sliding correlation analysis was performed.

Figure 3 shows the 21-year sliding correlation between the Niño3.4 index and the detrended seasonal mean temperature over the DPRK. During the period 1960–1990 (roughly corresponding to P1), the winter (DJF) correlation was positive and statistically significant. After the early 1990s, the correlation weakened considerably and became statistically insignificant. Summer (JJA) correlations remained weak throughout the entire period. This indicates a fundamental change in the ENSO–winter temperature relationship around the late 1980s, consistent with the abrupt change detected in the Niño3.4 index itself.

For precipitation (**Figure 4**), the sliding correlation shows a different behavior. Summer (JJA) precipitation exhibited a significant positive correlation with ENSO during the 1970s and 1980s, but this relationship weakened in the 1990s and reversed sign in the 2000s, though not statistically significant. Winter (DJF) precipitation correlations remained weak overall.

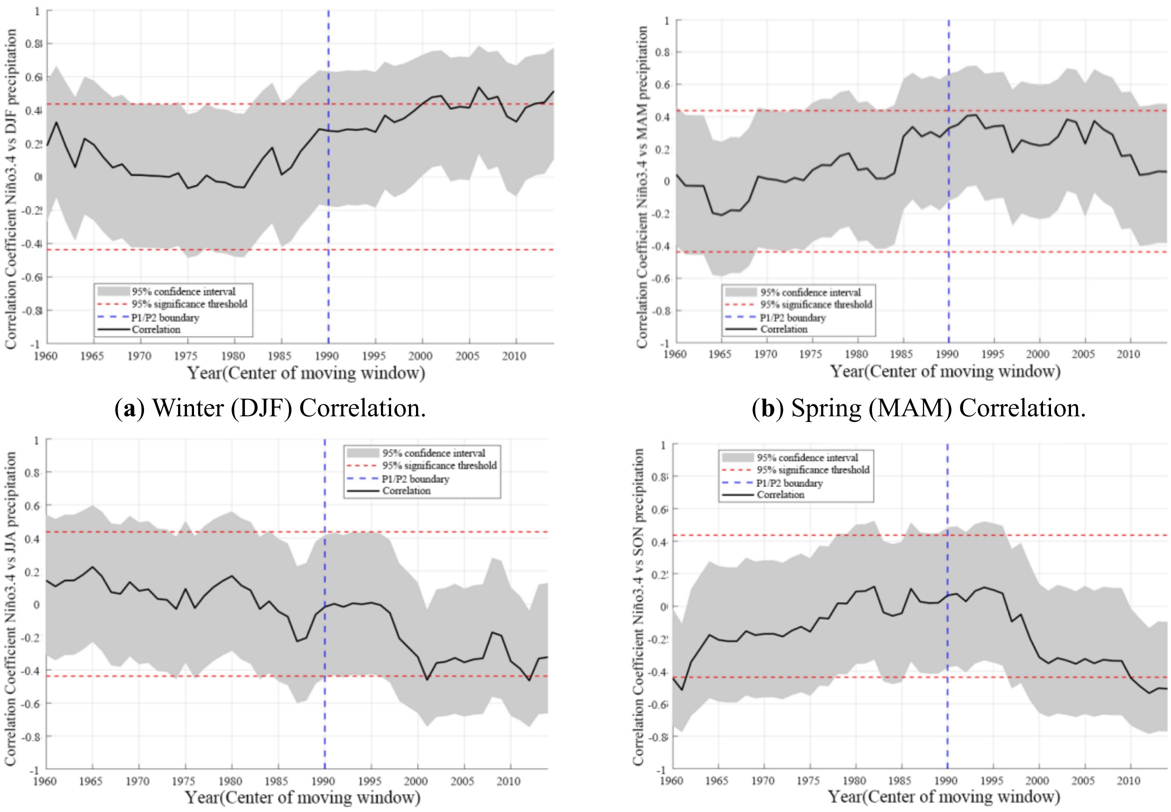


(**a**) Winter (DJF) Correlation. (**b**) Spring (MAM) Correlation.

(**c**) Summer (JJA) Correlation. (**d**) Autumn (SON) Correlation.

Figure 3. Sliding correlation between the Niño3.4 index and seasonal mean temperature over the DPRK.

Note: A 21-year sliding window was applied. The upper panel shows winter and spring and the lower panel shows summer and autumn. The horizontal dashed line indicates the 95% confidence level. Note the marked weakening of the winter correlation after the window centered around 1990.



(**a**) Winter (DJF) Correlation.

(**b**) Spring (MAM) Correlation.

(**c**) Summer (JJA) Correlation.

(**d**) Autumn (SON) Correlation.

Figure 4. Sliding correlation between Niño3.4 index and seasonal total precipitation over the DPRK.

Note: A 21-year sliding window was applied. The upper panel shows winter and spring and the lower panel shows summer and autumn. The horizontal dashed line indicates the 95% confidence level. Note the marked weakening of the winter correlation after the window centered around 1990.

3.3. Relationship of ENSO Events to the Seasonal Mean Air Temperature and Total Precipitation over the DPRK

To isolate ENSO-related variability from the long-term global warming trend, we removed the linear trend from the original temperature data. **Tables 2** and **3** summarize the seasonal mean temperature and precipitation anomalies for winter (DJF) and summer (JJA) during El Niño and La Niña events, respectively, after detrending. The full event-wise data for all seasons, including spring (MAM) and autumn (SON), are provided in **Tables S1–S4**. Statistical significance of the differences between P1 and P2 was tested using Student's *t*-test at the 95% confidence level.

Table 2. Summary of seasonal mean temperature anomalies (°C) over the DPRK during ENSO events for P1 and P2.

ENSO Phase	Season	P1 Mean	P2 Mean	Difference	*p*-Value
El Niño	DJF	+0.23	+0.68	+0.45	<0.01
	JJA	−0.145	−0.14	0.005	<0.05
La Niña	DJF	+0.4	−0.6	−1	n.s.
	JJA	+0.2	−0.1	−0.3	n.s.

Note: n.s. = not significant ($p > 0.05$). Full seasonal data (MAM, SON) are provided in **Tables S1** and **S2**.

Table 3. Summary of seasonal total precipitation anomalies (mm) over the DPRK during ENSO events for P1 and P2.

ENSO Phase	Season	P1 Mean	P2 Mean	Difference	*p*-Value
El Niño	DJF	+1.8	+7.4	+5.6	n.s.
	JJA	+20.7	−52.4	−73.1	<0.05
La Niña	DJF	+0.2	−10.1	−10.3	<0.05
	JJA	−48.1	+65.0	+113.1	n.s.

Note: n.s. = not significant ($p > 0.05$). Full seasonal data (MAM, SON) are provided in **Tables S3** and **S4**.

For El Niño events (**Table 2**), the detrended DJF temperature anomaly increased significantly from +0.23 °C in P1 to +0.68 °C in P2, a difference of +0.45 °C ($p < 0.01$). The JJA temperature anomaly also showed a statistically significant change ($p < 0.05$), though the magnitude of change was small. Detailed event-wise temperature data for El Niño, including MAM and SON, are given in **Table S1**.

For La Niña events (**Table 2**), the detrended DJF temperature anomaly changed from +0.39 °C in P1 to −0.60 °C in P2, but this difference was not statistically significant ($p > 0.05$). Full La Niña temperature data, including other seasons, are available in **Table S2**.

Regarding precipitation anomalies (**Table 3**; full data in **Tables S3** and **S4**), statistically significant changes were found in different seasons for El Niño and La Niña. For El Niño (**Table 3**), JJA precipitation anomalies shifted significantly from +20.7 mm in P1 to −52.4 mm in P2 ($p < 0.05$), indicating that El Niño summers have become significantly drier in recent decades. However, DJF precipitation changes were not statistically significant ($p > 0.05$). For La Niña (**Table 3**), DJF precipitation anomalies showed a statistically significant change from +0.2 mm in P1 to −10.1 mm in P2 ($p < 0.05$), while JJA precipitation changes were not significant ($p > 0.05$).

These results confirm that the observed changes in seasonal temperatures and precipitation between P1 and P2 are not solely attributable to global warming but reflect genuine shifts in the relationship between ENSO events and the climate over the DPRK, with varying statistical confidence depending on the season and ENSO phase.

To comprehensively examine the spatial patterns of ENSO–climate relationships, we constructed composite maps of seasonal mean air temperature and total precipitation for P1 and P2 periods during El Niño and La Niña events (**Figures 5–8**). Each figure presents six panels: (**a–c**) temperature composites for P1, P2, and P2–P1 difference; (**d–f**) precipitation composites for P1, P2, and P2–P1 difference.

For El Niño events, the DJF temperature composites (**Figure 5a–c**) show a warming signal from P1 to P2 over the majority of the DPRK, particularly in the central and southern regions, while a slight cooling trend is observed over the northern inland area. This pattern is consistent with the statistically significant increase in the regional mean reported in **Table 2** ($p < 0.01$). The JJA precipitation composites (**Figure 6d–f**) reveal a shift from wetter conditions in P1 to drier conditions in P2, particularly in the central south, aligning with the significant regional mean change ($p < 0.05$, **Table 3**; see also **Table S3** for event-wise details).

For La Niña events, the DJF precipitation composites (**Figure 7d–f**) show a statistically significant shift in the regional mean from slightly positive anomalies in P1 to negative anomalies in P2 ($p < 0.05$, **Table 3**; full data in **Table S4**). During La Niña summers (**Figure 8**), neither precipitation nor temperature composites show statistically significant changes at the regional scale ($p > 0.05$ for both, **Tables 2** and **3**), and the spatial patterns exhibit considerable heterogeneity.

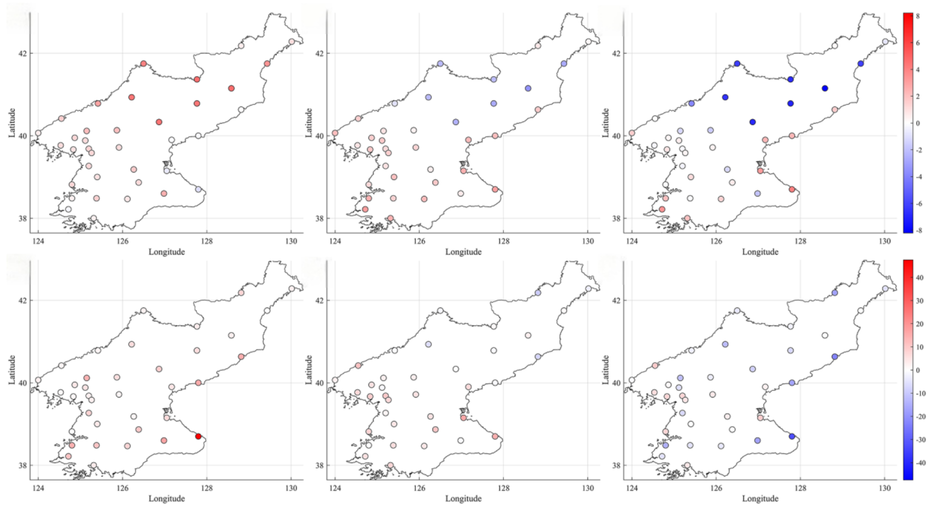


Figure 5. Composite maps of seasonal mean air temperature (°C) and seasonal total precipitation (mm) over the DPRK during El Niño events in winter (DJF). Upper panels (**a–c**): temperature; lower panels (**d–f**): precipitation. Panels (**a,d**): P1 (1950–1990); (**b,e**): P2 (1991–2024); (**c,f**): P2 minus P1 difference.

Note: Color scales indicate anomaly values relative to the 1950–2024 baseline.

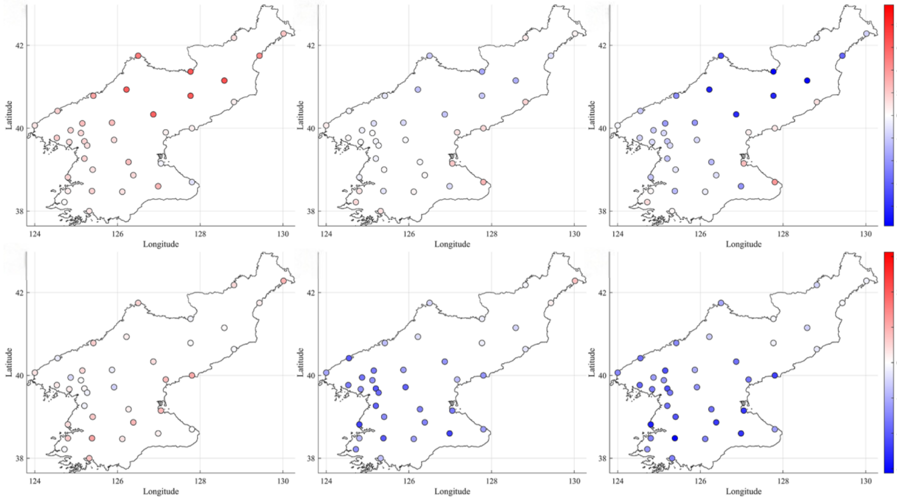


Figure 6. Composite maps of seasonal mean air temperature (°C) and seasonal total precipitation (mm) over the DPRK during El Niño events in summer (JJA). Panel layout and color scales are identical to **Figure 5**.

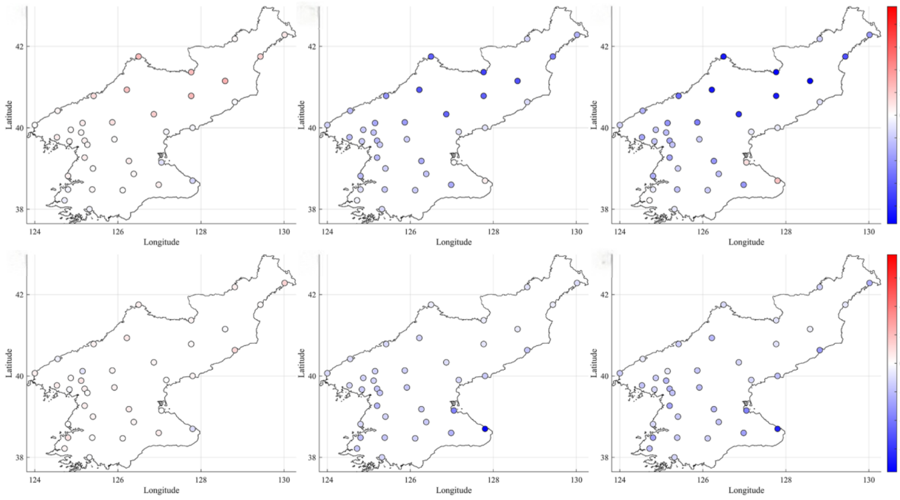


Figure 7. Composite maps of seasonal mean air temperature (°C) and seasonal total precipitation (mm) over the DPRK during La Niña events in winter (DJF). Panel layout and color scales are identical to **Figure 5**.

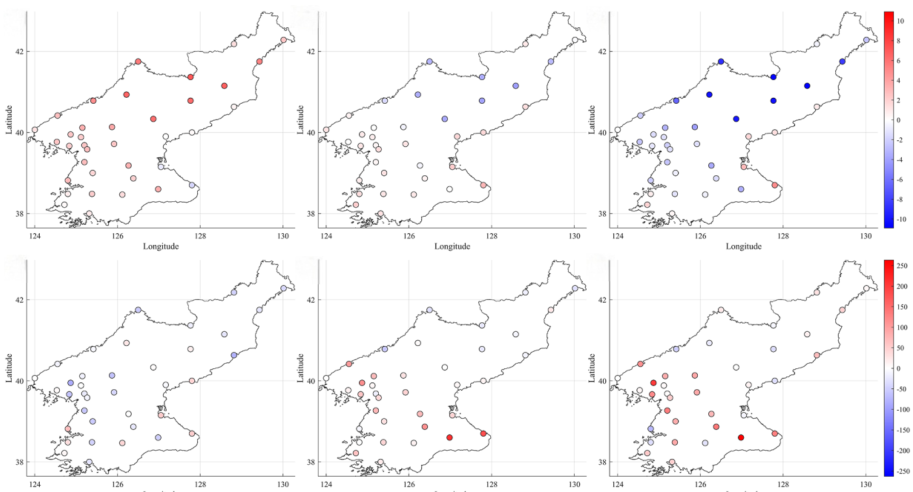


Figure 8. Composite maps of seasonal mean air temperature (°C) and seasonal total precipitation (mm) over the DPRK during La Niña events in summer (JJA). Panel layout and color scales are identical to **Figure 5**.

These composite analyses, based on all ENSO events in each period rather than single sample years, provide robust evidence that the relationship between ENSO and climate over the DPRK has genuinely changed between P1 and P2.

It should be noted that ENSO teleconnections operate at large spatial scales, and their climatic impacts are often more detectable in regional averages than at individual station levels due to the signal-to-noise ratio. To properly evaluate statistical significance, we therefore applied a two-tiered approach. First, point-wise Student's *t*-tests were conducted at each of the 37 stations, which generally yielded non-significant results ($p > 0.05$) because high local variability masks the large-scale ENSO signal. Second, we constructed DPRK-wide regional mean anomaly time series for each ENSO phase and season, and applied Student's *t*-tests to these aggregated series. This regional-mean approach revealed statistically significant P1–P2 differences for key combinations (e.g., El Niño DJF temperature: $\Delta = +0.45$ °C, $p < 0.01$; El Niño JJA precipitation: $\Delta = -73.1$ mm, $p < 0.05$), consistent with established practices in teleconnection studies [6,8,10]. Accordingly, the *p*-values reported in **Tables 2** and **3** reflect the regional-mean response, which is the appropriate metric for assessing large-scale ENSO–DPRK relationships. The composite maps (**Figures 5–8**) illustrate the spatial heterogeneity of these changes, while the statistical significance in the tables confirms their robustness at the regional scale.

4. Discussion

The aim of this study was to analyze and evaluate several indicators related to the occurrence of El Niño and La Niña, and to investigate the changed relationship of the ENSO events around the late 1980s with the seasonal mean air temperature and the seasonal total precipitation over the DPRK.

Many studies have determined El Niño and La Niña years on the basis of the Niño3.4 index [3–5]. Furthermore, the distinct climate impacts of EP and CP El Niño events have been increasingly recognized [8,9], along with their modulation of tropical cyclone activity and the western North Pacific subtropical high [30–33]. The El Niño and La Niña periods presented in this study are generally consistent with previous work, though some differences arise from our inclusion of short-duration events (≥5 months) under the definition described in Section 2.2. For example, the 2015/16 strong El Niño period considered in Yang et al. [4] is included as Event No. 22 in **Table 1** (October 2014–May 2016). According to Xue et al. [32], a major El Niño event was reported in 2006/07; this event lasted only 5 months (September 2006–January 2007) and is included as Event No. 20 in **Table 1** under our 5-month criterion. The slight discrepancies with some previous studies are likely due to differences in the sliding smoothing period, data processing, or the specific definition of El Niño intensity. The data in **Table 1** of Zhao and Wang [33] in which the El Niño and La Niña years for the period 1979–1997 were recorded are in agreement with **Table 1** in this study. Ahrens and Henson [1] quoted that the three strongest El Niño events since 1950 were in 1982/83, 1997/98, and 2014/16, which is in complete agreement with our results. On the other hand, according to Jien et al. [3], 1993 is designated as the El Niño year, but **Table 1** shows that there is no El Niño event in that year. A detailed analysis of the Niño3.4 index time series shows that during the entire 1993 period, positive phases of Niño3.4 indices are observed, with a positive phase of more than +0.5 only in April and May, although the positive phases are overwhelmingly dominant. This cannot be considered an El Niño period by the definition presented in this study. According to Xue et al. [32], a major El Niño event was also reported in 2006/07. However, this event started in September 2006 and ended in January 2007, with a duration of only 5 months, which is consistent with our El Niño definition. The slight discrepancy is probably due to differences in the sliding smoothing period, the data processing statistics period, or the definition of El Niño intensity when obtaining the index time series. Nevertheless, we believe that the onset, end, and duration of these events according to the definition used in this study did not negatively affect the results.

As is well known, the rate of surface temperature rise in the East Asian region including the DPRK under the background of global warming is faster than in other regions of the world, especially in winter. Jong et al. [14] concluded that the main reason why the winter temperature of the DPRK abruptly changed in the late 1980s, from the perspective of atmospheric circulation variation, is related to the interannual variability of the Arctic Oscillation and the EAWM. This study supports the idea that another reason why the seasonal climate over the DPRK changed during P2 compared to P1 is the interdecadal abrupt change of ENSO events around the late 1970s.

Our sliding correlation analysis further supports this view by showing that the ENSO–winter temperature relationship over the DPRK weakened significantly after the late 1980s, consistent with the previously reported weakening of the ENSO–EAWM relationship [13].

During El Niño and La Niña events, the climate over the DPRK did not change uniformly across the entire region from P1 to P2. Furthermore, during El Niño, JJA precipitation showed a decreasing trend in the central south during P2 compared to P1, whereas the opposite trend was observed for La Niña. This is likely due to the fact that the number of typhoons affecting the DPRK is greater during La Niña than during El Niño, combined with the faster rate of temperature rise from P1 to P2 under global warming. For example, as shown in **Figure 1** of Jong et al. [34], eight typhoons affected the DPRK in 1985 (a La Niña year that started in September 1983 and ended in May 1986), whereas no typhoons affected the region in 1977, 1983, 1996, and 2017 (neutral years). On the other hand, a question remains as to why temperature and precipitation over the central north of the study area changed only slightly in both P1 and P2. In other words, the effect of ENSO is not significant over the central north of the DPRK. Further studies are needed to address this.

The observed decadal shift in the ENSO–winter temperature relationship over the DPRK is consistent with broader changes in EAM–ENSO coupling. Recent studies have further elucidated the mechanisms underlying these changes. For instance, Guo et al. [10] demonstrated that the relationship between the northern mode of the EAWM and ENSO shifted from insignificant to significant in the late 1990s, coinciding with a westward transition of the Walker circulation. This transition was linked to enhanced ENSO-induced tropical precipitation anomalies over the CP, which strengthened the teleconnection to mid-latitude East Asia. In contrast, the southern mode of the EAWM has maintained a stable and robust negative correlation with ENSO, a feature that CMIP6 models project will persist under future warming scenarios [10,11].

Furthermore, the PDO and AMO have been identified as key modulators of the ENSO–EAWM relationship on decadal timescales. Zhong et al. [6] found that the PDO exerts a stronger modulation on the ENSO–EAWM connection during early winter (November–December), particularly in its negative phase, by influencing the development of the Pacific–North American teleconnection and the westward extension of tropical height anomalies. In late winter (January–March), however, the AMO plays a more prominent role, with negative AMO phases enhancing the ENSO signal and strengthening the EAWM response [6]. Ge et al. [7] further showed that during the warm phase of the PDO, moderate La Niña events exert a more profound impact on East Asian winter temperatures compared to strong La Niña events, due to the enhanced Siberian High and strengthened northerly winds along the East Asian coast. These findings suggest that the weakened ENSO–DPRK winter temperature correlation after the late 1980s may be part of a larger-scale reorganization of Pacific–East Asia teleconnections, driven by the phase shifts of the PDO and AMO and their modulation of the Walker circulation and mid-latitude wave trains [6,10].

The spatial heterogeneity in summer precipitation changes between El Niño and La Niña events further suggests a role for El Niño diversity. EP and CP El Niño events exert distinct influences on East Asian summer climate. Cao et al. [8] demonstrated that during EP El Niño summers, the southward displacement of the South Asian High, westerly jet, and WPSH enhances moisture convergence over the region south of the Yangtze River, leading to more intense extreme precipitation. In contrast, CP El Niño events induce a northward shift of these circulation systems, resulting in enhanced precipitation over the Mei-Yu–Baiu–Changma rainband and suppressed precipitation further south. Menzo et al. [9] further showed that CP El Niño events broadly exacerbate humid heat extremes over East Asia, while EP events have more localized but regionally varying impacts. The increasing frequency of CP El Niño events in recent decades may therefore partly explain the observed shift in JJA precipitation patterns over the DPRK between P1 and P2. In addition, Fan et al. [35] revealed that the interdecadal change in the EASM precipitation–ENSO relationship since the late 1980s is primarily driven by the strengthened concurrent correlation between summer tropical North Atlantic (TNA) SST and ENSO. The TNA-induced precipitation anomaly pattern, which differs from that of ENSO, has increasingly overlapped with ENSO events, altering the overall precipitation response over East Asia. This mechanism may also contribute to the complex changes in DPRK summer precipitation observed in our study.

The apparent discrepancy between non-significant point-wise tests and significant regional-mean tests underscores a fundamental characteristic of ENSO teleconnections: their impacts are coherent at large spatial scales but may be masked by local variability at individual stations. This scale dependency has important implications for climate prediction and adaptation planning in the DPRK, suggesting that regional-scale outlooks are more reliable than station-specific forecasts for ENSO-related seasonal climate anomalies.

Thus, as the behaviors of large-scale atmospheric circulation and monsoon circulation have changed around the late 1980s, ENSO events have caused different patterns of change in seasonal mean air temperature and seasonal total precipitation over the DPRK.

5. Conclusion

The main conclusions obtained in the study are as follows:

(1) During the study period, El Niño and La Niña events, as defined by the Niño3.4 index, occurred 25 and 20 times, respectively, corresponding to frequencies of approximately once every 3 years and once every 3.7 years. The statistically significant period of the Niño3.4 index time series was 1–5.7 years, and this time series underwent an abrupt change around the late 1970s at a statistical confidence level exceeding 95%.

(2) After removing the long-term global warming trend, the seasonal mean temperature anomalies over the DPRK during El Niño events showed statistically significant increases in both DJF ($p < 0.01$) and JJA ($p < 0.05$) between P1 and P2 (**Table 2**). For La Niña events, temperature changes were not statistically significant ($p > 0.05$). Regarding precipitation, El Niño JJA precipitation showed a significant decrease ($p < 0.05$), while La Niña DJF precipitation showed a significant change ($p < 0.05$) (**Table 3**). These findings indicate that the relationship between ENSO events and climate over the DPRK has changed, with the statistical evidence for El Niño winter warming and summer drying trends. Complete seasonal data including MAM and SON are provided in **Tables S1–S4**. Sliding correlation analysis further reveals that the ENSO–winter temperature relationship was strong and significant during P1 but weakened after the late 1980s, confirming a decadal shift in the teleconnection.

(3) The JJA mean air temperature over the DPRK showed a clear increasing trend from P1 to P2, mostly in the central south of the study area, but the trend was not significant in the central north. For JJA total precipitation, a decreasing trend was observed in the central south during P2 compared to P1 for El Niño, whereas the opposite trend was found for La Niña. In the central north, the change between the two subperiods was mostly insignificant. These results differed from those in DJF, when ENSO events were decaying.

We believe that the results obtained in this study can be useful in long-term forecasting of seasonal mean temperature or seasonal total precipitation in East Asia including the DPRK.

Supplementary Materials

The supporting information can be downloaded at https://journals.bilpubgroup.com/files/JASR-12977-Supplementary-Materials.docx.

Author Contributions

K.-B.S.: Data curation, validation, writing—review & editing; H.-S.R.: Software; S.-I.J.: Conceptualization and methodology; Y.-S.H.: Study design and manuscript writing. All authors have read and agreed to the published version of the manuscript.

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The data that support the findings of this study are not publicly available because they are owned by a third party and are subject to access restrictions. However, the data may be obtained from the corresponding author upon reasonable request, pending permission from the third-party data owner.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the analysis, interpretation of data, or generation of scientific content in this manuscript. AI-based tools were used solely for minor language polishing and grammar checks during the final preparation stage.

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