Possible combined effect of El Niño–Southern Oscillation and Pacific Decadal Oscillation on Korea affecting tropical cyclone passage frequency

Jae-Won Choi1 | Hae-Dong Kim2

1College of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing, China
2Department of Global Environment, Keimyung University, Daegu, Korea

Abstract
This study found that the passage frequency of tropical cyclones (TCs) affecting Korea has had negative correlations with the Pacific Decadal Oscillation (PDO) and the El Niño–Southern Oscillation (ENSO) since the early 1980s. To examine the actual combined effects of PDO and ENSO on the passage frequency of TCs affecting Korea, the positive PDO and ENSO years for 9 years and the negative PDO and ENSO years for 9 years were selected during the periods of 1951–1981 (pre-1981) and 1982–2012 (post-1981), and then the average difference between these two phases was analyzed. An analysis of anomalous stream flows at 500 hPa showed the formation of anomalous cyclonic circulations in an east-to-west direction from East Asia to the North Pacific both in the pre-1981 and post-1981 periods in the positive PDO and ENSO years. However, the anomalous cyclones in East Asia were stronger in the pre-1981 period, whereas the anomalous cyclones in the North Pacific were stronger in the post-1981 period. Consequently, China, Korea and the west of Japan were affected by strong anomalous northerlies in the pre-1981 period, and the TC passage frequency was lower in these regions as a result. In the post-1981 period, these countries were affected by anomalous northwesterlies or anomalous westerlies.

KEYWORDS
El Niño Southern Oscillation, Korea, Pacific Decadal Oscillation, tropical cyclones

1 | INTRODUCTION

A tropical cyclone (TC) is a natural disaster that has a great impact on human activities and can cause the loss of life and severe property damage on land by the accompanying strong winds and heavy rainfalls. Due to global warming, which has been actively discussed recently, the future changes in TC activity are drawing keen interest (Michaels et al., 2006; Landsea et al., 2006). In particular, the western North Pacific is a major TC genesis basin, where approximately 30% of the global TCs occur. Many studies have been conducted on the changes in TC activity in association with the increasing sea surface temperature (SST) as a result of global warming in this region (Webster et al., 2005; Chan, 2006; Webster et al., 2006). Webster et al. (2005) found that the TC genesis frequency did not increase much due to the increasing SST in the western North Pacific, but strong TCs (58/m or higher maximum sustained wind speed) increased. Based on the results of these studies, we should examine how the activity of TCs will change with the progress of global warming in countries (such as Korea, China, Japan, etc.) near the western North Pacific.
Recently in South Korea, interest in the changes in TC activity affecting Korea is rising with the increasing damages by strong TCs such as Typhoon Rusa in 2002 and Typhoon Maemi in 2003 (Kim et al., 2006; Park et al., 2006; Choi et al., 2011). Because the main energy of a TC is the vapor supplied from the warm sea surface (Gray, 1979), the TC intensity will be stronger if the SST grows warmer around Korea. Park et al. (2006) reported that with the increase in the western North Pacific SST, the cases where the maximum sustained wind speed of the TC stays higher than 33 m/s are increasing, as is the possibility of strong TCs making landfall in Korea. Furthermore, Kim et al. (2006) showed that heavy rainfalls from TCs are increasing in Korea due to the change of atmospheric circulations around a TC, and the intensity of these heavy rainfalls has increased significantly compared with the past.

Studies on the correlation between TC activity that makes landfall in Korea and El Niño–Southern Oscillation (ENSO) are rare. Choi et al. (2011) found that although the frequency of TCs making landfall in Korea has a low correlation with ENSO, the track for landfall shifted to the north as the Niño 3.4 Index decreased. By contrast, Ho and Kim (2011) claimed that there was no significant correlation between TCs making landfall in Korea and ENSO. Moreover, it is difficult to find research on the correlation between TC activity affecting or making landfall in Korea and Pacific Decadal Oscillation (PDO). Therefore, this study aimed to examine the combined effects of PDO and ENSO on the passage frequency of TCs affecting Korea.

2 DATA AND METHODS

To analyze TCs in this study, data from the Regional Specialized Meteorological Center-Tokyo Typhoon Center was used. In addition, the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP–NCAR) Reanalysis dataset (Kistler et al., 2001) was used to analyze the large-scale atmospheric circulation and the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed monthly Sea Surface Temperature (SST) (Reynolds et al., 2002). The used variables in NCEP-NCAR Reanalysis dataset are zonal and meridional wind (m/s). This data is composed of spatial resolution with the latitude and longitude at 2.5° × 2.5° and 17 vertical layers. The SST data has a horizontal resolution of 2.0° × 2.0° latitude-longitude and are available for the period of 1854 to the present day.

Furthermore, this study focused on TCs that affected Korea from July to September. All the analyses used the average data from this period because TCs that affect Korea are concentrated in the period from July to September (Choi et al., 2011).

To determine the significance of the results of this study, a student’s t test was used (Wilks, 1995). In case that two independent time-series follow a t distribution and their time averages are denoted as \( \bar{x}_1 \) and \( \bar{x}_2 \) respectively, the t-statistic is given by

\[
t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}^{1/2}
\]

…where \( s_1 \) and \( s_2 \) are SDs and \( n_1 \) and \( n_2 \) are numbers of the two time-series, respectively. From the above formula, if the absolute value of \( t \) is greater than threshold values with a level of significance, the null hypothesis would be rejected at the \( \alpha \times 100\% \) significance level.

The Korea Meteorological Administration defines TCs that affect Korea as all TCs between 28 and 132°N. However, this study defined TCs that affect Korea as all TCs between 25 and 135°N because the TC frequency was reanalyzed by a 5 × 5° grid to calculate the TC passage frequency (red line in Figure 1).

In this study, the PDO index (Mantua et al., 1997) was obtained from the website of the University of Washington (http://jisao.washington.edu/pdo), and the ENSO index was obtained from the website of the NOAA Climate Prediction Center (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). Niño3.4 index based on SST anomalies is commonly used to define the El Niño and La Niña events. Actually, mega-ENSO index, which is well related to PDO and is best represented by ENSO, has much higher correlation with Niño3.4 index than other Niño indices (Zhan et al., 2018). A previous study found that the interannual variation of TC tracks and landfall along the South China coast is strongly influenced by ENSO events (Liu and Chan, 2003). The study found fewer (more) TCs making landfall along the southern China coast during strong El Nino (La Nina) events, especially during the late TC season (October–November), which is attributable to an eastward (westward) shift of the TC genesis location. During early summer (May–June) after La Niña (El Niño) years, there are more (fewer) TCs making landfall along the southern China coast, due to the existence of a persistent low-level cyclone (anticyclone) over the Philippines. The PDO can influence the track pattern of western North Pacific TCs by regulating the large-scale atmospheric circulation (Zhou et al., 2007; Liu and Chan, 2008; Li et al., 2017). The interdecadal variability of TC landfall in the Philippines has been found to be related to the PDO and ENSO (Kubota and Chan, 2009).

Also, this study used the method of 14-year sliding correlation. In some studies, the method of 14-year sliding window is used to remove short wave from long-term time series (Fan and Fan, 2016). That is, 14-year sliding window is used to show the decadal change in the long-term time series.
3 Correlation Between the Frequency of TCs Affecting Korea and PDO and ENSO

In this study, the correlations of the frequency of TCs affecting Korea with PDO and ENSO were analyzed (Figure 2).

Previous study has shown that two climate regime shifts of PDO take place in 1977/1978 and 1997/1998. PDO can modulate ENSO intensity to influence large-scale environmental factors, and then influence the relationship of ENSO-TC activity (e.g., Wang and Liu, 2016). However, the analysis of the

14-year sliding correlation between the passage frequency of TCs affecting Korea and the PDO index revealed a correlation higher than −0.32 (dashed line), which is a correlation coefficient that corresponds to the 90% confidence level, until the early 1980s (Figure 1a). After the early 1980s, the negative correlation between these two variables weakened rapidly. This means that until the early 1980s, the passage frequency of TCs

FIGURE 1 The differences within 5 × 5° grid box in TC passage frequency between positive PDO, ENSO years and negative PDO, ENSO years in (a) pre-1981 and (b) post-1981 periods for summer. Small squares inside the circles indicate that the differences are significant at the 95% confidence level. Red line indicates Korea affecting TC area (25 and 135°E)

FIGURE 2 The 15-year sliding correlations between Korea affecting TC passage frequency and (a) Pacific Decadal Oscillation (PDO) index and (b) Niño-3.4 index (for example, the correlation coefficient of 1961 is calculated for the period from 1961 to 1975), and time series between Korea affecting TC passage frequency and (c) PDO index and (d) Niño-3.4 index for summer (July–September). In (a) and (b), the dashed line shows the 90% significant level.
affecting Korea decreased (increased) when the PDO became strong (weak). On the other hand, the analysis of 14-year sliding correlation between the passage frequency of TCs affecting Korea and the Niño 3.4 Index revealed a correlation higher than −0.32 (dashed line), which is the correlation coefficient corresponding to the 90% confidence level, until the late 1970s (Figure 2b). In some studies, the method of 14-year sliding window is used to remove short wave from long-term time series (Fan and Fan, 2016). That is, 14-year sliding window is used to show the decadal change in the long-term time series. Therefore, the method of 14-year sliding window is the best way to show decadal change in the intensity of interannual variation from long-term timeseries. In addition, Yang et al. (2017) used the method of 14-year sliding window to show potential impact of the PDO and SST in the tropical Indian Ocean–Western Pacific on the variability of typhoon landfall on the China coast and then year 1982 was selected as the change point of decadal variation.

The negative correlation of the passage frequency of TCs affecting Korea with the PDO index has weakened since the early 1980s, and the negative correlation with the Niño 3.4 Index has weakened since the late 1970s. Therefore, in order to consider the effects of these two variables on passage frequency of TCs affecting Korea, the total analysis period of 62 years was divided in half into 31 years each covering the period of 1951–1981 and the period of 1982–2012, and the correlation analysis was conducted separately for each period (Figure 2c,d). First, the time series for the passage frequency of TCs affecting Korea shows a slightly decreasing trend, but this is not statistically significant (thick solid line). Furthermore, the trend of the PDO index and the Niño 3.4 Index time series changes very little (dashed lines). For the total analysis period of 62 years, the passage frequency of TCs affecting Korea shows low negative correlations of −0.28 and −0.21 with the PDO index and the Niño 3.4 Index, respectively, and both correlation coefficients are significant at the 90% confidence level. However, the correlations change if the total analysis period of 62 years is divided into two periods. In other words, during the period of 1951–1981 (hereinafter referred to as “pre-1981”), the correlations of the passage frequency of TCs affecting Korea with the PDO index and the Niño 3.4 Index showed negative correlation coefficients that are higher than −0.60, which are significant at the 95% confidence level. However, during the period of 1982–2012 (hereinafter referred to as “post-1981”), both of these correlations showed negative correlation coefficients that are lower than −0.15, but they are not statistically significant. This result means that the negative correlations of the passage frequency of TCs affecting Korea with PDO and ENSO have weakened in recent years.

To examine the actual combined effects of PDO and ENSO on the passage frequency of TCs affecting Korea, the positive PDO and ENSO years for 9 years and the negative PDO and ENSO years for 9 years were selected for periods of pre-1981 and post-1981, respectively (Table 1), and the average differences between these two phases were analyzed. This climate regime shift in the early 1980s is also observed from the variation of spring and summer rainfall in China (e.g., Cheng et al., 2008; Ding et al., 2008, 2009). Many researchers presented that most of the climate changes related to the air and sea in the North Pacific are climate regime shift in the early 1980s (e.g., Ho et al., 2004; Wu et al., 2005; Ye and Hsieh, 2006). Thus, this study focuses on a climate regime shift in the early 1980s. In the pre-1981 period, the average TC passage frequency was 3.7 during the positive PDO and ENSO years, but it was 6.6 during the negative PDO and ENSO years, with a difference of approximately 3. This difference is significant at the 95% confidence level.

### Table 1

| Pre-1981 | Post-1981 |
|---------|-----------|
| + PDO + ENSO | − PDO − ENSO | + PDO + ENSO | − PDO − ENSO |
| **Year** | **TC frequency** | **Year** | **TC frequency** | **Year** | **TC frequency** | **Year** | **TC frequency** |
| 1953  | 3  | 1955  | 7  | 1982  | 4  | 1984  | 6  |
| 1957  | 3  | 1956  | 7  | 1986  | 4  | 1998  | 2  |
| 1958  | 2  | 1959  | 8  | 1987  | 4  | 1999  | 9  |
| 1965  | 4  | 1964  | 9  | 1990  | 6  | 2000  | 7  |
| 1968  | 6  | 1970  | 7  | 1991  | 6  | 2001  | 1  |
| 1976  | 6  | 1971  | 5  | 1992  | 5  | 2005  | 6  |
| 1977  | 3  | 1973  | 6  | 1993  | 5  | 2008  | 4  |
| 1979  | 4  | 1975  | 5  | 1997  | 5  | 2010  | 4  |
| 1980  | 3  | 1978  | 5  | 2004  | 8  | 2011  | 3  |
| **Average** | **3.7** | **Average** | **6.6** | **Average** | **5.2** | **Average** | **4.7** |
confidence level. On the other hand, in the post-1981 period, the average TC passage frequency was 5.2 during the positive PDO and ENSO years and 4.7 during the negative PDO and ENSO years. The difference (0.5) between these two phases is not large, and it is statistically insignificant.

In the analysis of the differences in the TC passage frequency between the two phases, TCs during the positive PDO and ENSO years in the pre-1981 period tend to move west from the far eastern Philippine Sea toward the southern coast of China or move north toward the eastern Sea of Japan (Figure 1a). On the other hand, during the negative PDO and ENSO years, TCs tend to move north from the East China Sea to the west of Korea and Japan. Therefore, the TC passage frequency in the TC area affecting Korea is much higher during the negative PDO and ENSO years. Accordingly, as analyzed above, the passage frequency of TCs affecting Korea has negative correlations with PDO and ENSO in the pre-1981 period. In the post-1981 period, the TC passage frequency is higher during the positive PDO and ENSO years in most of the western North Pacific, excluding the east coast of China and Korea (Figure 1b). Within the TC area affecting Korea, negative anomalies are evident in Korea and on the east coast of China, whereas positive anomalies appear in the Japanese islands. Thus, there are no big differences between the two phases. Consequently, as analyzed above, the negative correlations of the passage frequency of TCs affecting Korea with PDO and ENSO grew weaker.

Thus, in the following section, the reason that the negative correlations between these three variables recently became weak will be examined through an analysis of the large-scale environments.

4 | LARGE-SCALE ENVIRONMENTS

Figure 3 shows the stream flows for the average differences between the positive PDO and ENSO years and the negative PDO and ENSO years in the pre-1981 period (left panel) and the post-1981 period (middle panel) and the differences between the post-1981 and the pre-1981 (right panel) periods in the lower-level (850 hPa, upper panel), middle-level (500 hPa, middle panel), and upper-level (200 hPa, lower panel) of the troposphere. First, in the 850 hPa stream flows in the pre-1981 period, anomalous cyclones exist with their centers on the east coast of Japan and the Bering Sea south of the Aleutian Islands. In addition, the anomalous anticyclonic circulations are intensified between these two anomalous cyclones. Due to this spatial distribution of the anomalous pressure system, Korea and the west of Japan are affected by strong anomalous northerlies. These anomalous northerlies can play the role of anomalous steering flows blocking the northbound TCs to these regions, and this causes negative correlations of the passage frequency of TCs affecting Korea with PDO and ENSO in the pre-1981 period. Meanwhile, the spatial distribution of the anomalous pressure system in the post-1981 period is similar to that in the pre-1981 period. However, the anomalous cyclone in the North Pacific is much stronger than the one in the pre-1981 period, and the anomalous cyclone in Manchur is much weaker than the one in the pre-1981 period. This is because the anomalous anticyclone in the southern Sea of Japan became intensified in the post-1981 period. Due to such spatial distribution of the anomalous pressure system, China, Korea and the southwest of Japan are under the influence of anomalous northwesterlies or anomalous westerlies. These anomalous flows can play the role of anomalous steering flows that make the movement of TCs to these regions easier than the anomalous northerlies in the pre-1981 period. The intensified anomalous anticyclone in the southern Sea of Japan in the post-1981 period can be verified by the difference between the post-1981 and the pre-1981 periods. The anomalous stream flows at 500 hPa show a similar pattern to that of the anomalous stream flows at 850 hPa. The anomalous cyclones in East Asia are stronger in the pre-1981 period, and the anomalous cyclones in the North Pacific are stronger in the post-1981 period. In other words, in pre- (post-)1981 periods, the anomalous cyclones in East Asia (North Pacific) are stronger than the anomalous cyclones in the North Pacific (East Asia). As a result, China, Korea and the west of Japan are affected by strong anomalous northerlies in the pre-1981 period, whereas in the post-1981 period, these regions are affected by anomalous northwesterlies or anomalous westerlies. The difference between the post-1981 and pre-1981 periods is that the anomalous anticyclones are located in the southern Sea of Japan. The anomalous stream flows at 200 hPa show a similar pattern to the anomalous stream flows at 500 hPa. As a result, China, Korea and the southwest of Japan are affected by anomalous northwesterlies or anomalous westerlies in the pre-1981 period, whereas in the post-1981 period, these regions are affected by southwesterlies or anomalous westerlies. The difference between the post-1981 and pre-1981 periods is that the anomalous anticyclones are located near Japan as well.

As described above, the characteristics of anomalous atmospheric circulations in the pre-1981 and post-1981 periods are well reflected in the average difference between the positive PDO and ENSO years and the negative PDO and ENSO years for SST (Figure 4). The spatial distributions of the SST in these two periods appear similar in general. However, in the case of the pre-1981 period, warm SST anomalies are formed in 10–30°N to the west of 180°E (Figure 4a). As analyzed above, these anomalies were formed by the anomalous anticyclonic circulation in the subtropical central Pacific. On the other hand, in the case of the
post-1981 period, the spatial distribution shows a perfect south-high, north-low type in the North Pacific by the anomalous huge cyclonic circulation in the North Pacific. This is the SST space pattern in a typical positive PDO phase (Figure 4b).

5 | SUMMARY AND CONCLUSION

The total analysis period of 62 years was divided into the period of 1951–1981 (pre-1981) and the period of 1982–2012 (post-1981), and the correlations of the passage frequency of TCs affecting Korea with PDO and ENSO were analyzed for each period. In the pre-1981 period, the correlations of the passage frequency of TCs affecting Korea with the PDO index and the Niño 3.4 Index showed negative correlation coefficients that are higher than −0.60, whereas in the post-1981 period, both correlations showed negative correlation coefficients that are lower than −0.15.

To examine the actual combined effects of PDO and ENSO on the passage frequency of TCs affecting Korea, the positive PDO and ENSO years for 9 years and the negative PDO and ENSO years for 9 years were selected in the pre-1981 and post-1981 periods, respectively, and the average differences between these two phases were analyzed.

In the analysis for the TC passage frequency, TCs during the positive PDO and ENSO years in the pre-1981 period tended to move west from the far eastern Philippine Sea toward the southern coast of China or move north toward...
the eastern Sea of Japan. On the other hand, TCs during the negative PDO and ENSO years tended to move north from the East China Sea toward the west of Korea and Japan. In the post-1981 period, negative anomalies were observed in Korea and on the east coast of China, whereas positive anomalies were observed in Japan, with no big difference between the two phases.

In the analysis of anomalous stream flows at 500 hPa, an anomalous cyclonic circulation was formed in the east-to-west direction from East Asia to the North Pacific during positive PDO and ENSO years. However, the anomalous cyclones in East Asia were stronger in the pre-1981 period, and the anomalous cyclones in the North Pacific were stronger in the post-1981 period. Consequently, China, Korea and the west of Japan were affected by strong anomalous northerlies in the pre-1981 period, whereas in the post-1981 period, these regions were affected by anomalous northwest-erlies or anomalous westerlies. The difference between the post-1981 and pre-1981 periods is that the anomalous anticyclones in the southern Sea of Japan were intensified (Figure 5). Therefore, in the pre-1981 period, when China, Korea and the west of Japan were under the influence of anomalous northerlies, the TC frequencies in these regions were lower.

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ORCID

Jae-Won Choi  https://orcid.org/0000-0002-6512-9310

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