

Relationship between Korean Peninsula Landfalling Tropical Cyclones and Interannual Climate Variabilities

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Abstract: The relationship between two interannual climate variabilities and the frequency of tropical cyclone (TC) that landed over the Korean Peninsula (KP) has investigated for the period of 1951-2004. In the analysis of the relationship between KP-landfall TC frequency and the ENSO phase, most TCs of C-14 (TCs that do not pass through mainland China before landing the KP) and C-23 (TCs that pass through mainland China before landing the KP) tended to more land in the warm phase than normal and cold phases. However, TC intensity at landfall was stronger in the cold and normal phases. In the analysis of the relationship between KP-landfall TC frequency and Arctic Oscillation (AO) phase, the TCs of C-14 tended to more land in the positive (POS) phase of AO and the negative (NEG) phase of AO for C-23. It was found that AO index was negatively correlated with the Niño-3.4 index. And then the TCs of C-14 landed more frequently over the KP in the AO POS - Niño-3.4 NEG phases and in the AO NEG - Niño-3.4 POS phases for the TCs of C-23.

Keywords: Korean Peninsula, tropical cyclone, Niño-3.4, Arctic oscillation

Introduction

Fluctuations in west Pacific tropical cyclone (TC) frequency have significant impacts on human life and property. Since TCs can bring tremendous amounts of precipitation over short-term period, TC precipitation can be a significant portion of total summer precipitation along the East Asian coast and Japan, as well as inland areas of East Asia. Therefore, an accurate understanding of the climatology and interannual variability of landfalling TCs will aid monthly and seasonal long-lead forecasts. Recent improvements in seasonal TC forecasts (Gray et al., 1993; Elsner and Schmertmann, 1993) have made it attractive for forecasters to use this information in their seasonal precipitation forecasts. Several studies have shown that the interannual variability of TC activity in the western North Pacific (WNP) basin is strongly related to such phenomena as: the El Niño-Southern Oscillation (ENSO) cycle, the stratospheric

quasi-biennial oscillation (QBO; Gray, 1984), and so on. The impacts of ENSO events on TC activity in the WNP have been considered by Chan (1985), Dong (1988), Lander (1994), Chan (2000), and many others. Especially, Wu et al. (2004) found that in the months of September, October, and November that is in the late season of El Niño years the number of TCs landfalling in the landmasses rimming the WNP is significantly reduced except for Japan and the Korean Peninsula (KP). On the other hand, in the late season of La Niña years, more frequent TC landfalls were expected to occur in China. However, the relationship between ENSO events and TC landfalling activity in the WNP seems to have received less attention in the literature as compared with the hurricane activity in the Atlantic basin. Also in an investigation of a possible relationship between the ENSO phenomenon and the interannual variations in the TC activity in the WNP, Chan (1985) found two peaks in the cross-spectrum between the time series of such variations in the TC activity and that of a Southern Oscillation index (which is defined as the sea level pressure difference between Easter Island and Darwin). One peak is at the well-known Southern Oscillation

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frequency with a period of about 3-3.5 years. The other peak has a period of about 26 months, which suggests that the TC variations at this frequency may be related to the QBO in the stratosphere. After this, Chan (1995) stressed that the relationship between the TC activity in the WNP and QBO is stronger for the more intense TCs, namely tropical storms and typhoons.

Besides, the relationships between landfalling TCs in Japan and Pacific Japan (PJ) pattern or landfalling TC in China and Tibet plateau snow cover by some researchers has studied (Yamada and Kawamura, 2007; Xie et al., 2005). These are studies on the relationship between landfalling TCs in specific nations of East Asia and climate change. However, we couldn't find studies regarding the relationship between landfalling TCs in Korea Peninsula and climate change. Statistically, the Korean Peninsula (KP) is affected by three Tropical Cyclones (TCs) per year, one out of three TCs lands over the KP and then does great damage to property and human life (KMA, 1996). Therefore it is important to more accurately understand the climatology and interannual variability on landfalling TCs in KP (hereafter KP-landfall TCs). The current study firstly aims to investigate the relationships between the frequency of KP-landfall TCs and ENSO and arctic oscillation (AO) phases. After this, we will show that the frequency of KP-landfall TCs are strongly correlated with winter and spring season snow cover on the Tibetan Plateau and the shift of WNP high and so on in the future study.

Data and Methodology

Data

In order to select KP-landfall TCs, the present study uses the dataset of the TC best-track for the WNP that was archived by the Regional Specialized Meteorological Centers (RSMC)-Tokyo Typhoon Center during the period 1951-2004. This dataset includes 6-hourly latitude-longitude positions and intensity such as central pressure (hPa) and maximum sustained wind (MSW; knot) of TCs.

We also used the 6-hourly zonal and meridional wind (ms^{-1}) and geopotential heights (gpm) reanalyzed by the National Center for Environmental Prediction-the National Center for Atmospheric Research (NCEP-NCAR) to characterize the related atmospheric circulation patterns (Kalnay et al., 1996). These data are available on a $2.5^\circ \times 2.5^\circ$ grid at standard pressure levels. Also, the monthly mean NOAA Extended Reconstructed Sea Surface Temperature (SST; $^\circ\text{C}$) with $2^\circ \times 2^\circ$ grid is used.

A classification of warm, cold, and normal events from the Niño-3.4 index during each July, August, and September (JAS; months of the maximum frequency of KP-landfall TCs) season, constructed by the Climate Prediction Center (CPC) for the period 1951-2004, is used to relate TC activity and the ENSO phase. This ENSO classification is based on the pattern and magnitude of SST anomalies in the tropical Pacific and can be found on the CPC's Web site. The warm, cold, and normal events from the SST anomalies over the ($5^\circ\text{-}15^\circ\text{N}$, $125^\circ\text{-}160^\circ\text{E}$) are determined by the following criteria:

- warm: $\text{SST}(\text{Niño-3.4}) \geq 0.5^\circ\text{C}$,
- cold: $\text{SST}(\text{Niño-3.4}) \leq -0.5^\circ\text{C}$, and
- normal: $-0.5 < \text{SST}(\text{Niño-3.4}) < 0.5^\circ\text{C}$.

Niño-3.4 is the average sea surface temperature anomaly in the region bounded by 5°N to 5°S , from 170°W to 120°W .

The Arctic Oscillation (AO) index also is used to relate with TC activity and is constructed by the CPC for the same period as a classification of ENSO events. The two indices again were standardized for the period 1951-2004.

Methodology

From a RSMC best-track dataset, 51 KP-landfall TCs were selected. Here, KP-landfall TC means that the TC center of the RSMC best-track dataset encounters the coastline of the KP on the surface weather chart. After this, TC tracks from entering at the area of $120^\circ\text{-}132^\circ\text{E}$, 32°N to after passing over the KP are classified by using the Fuzzy Clustering Method (FCM). Here, "before landfall" and "after

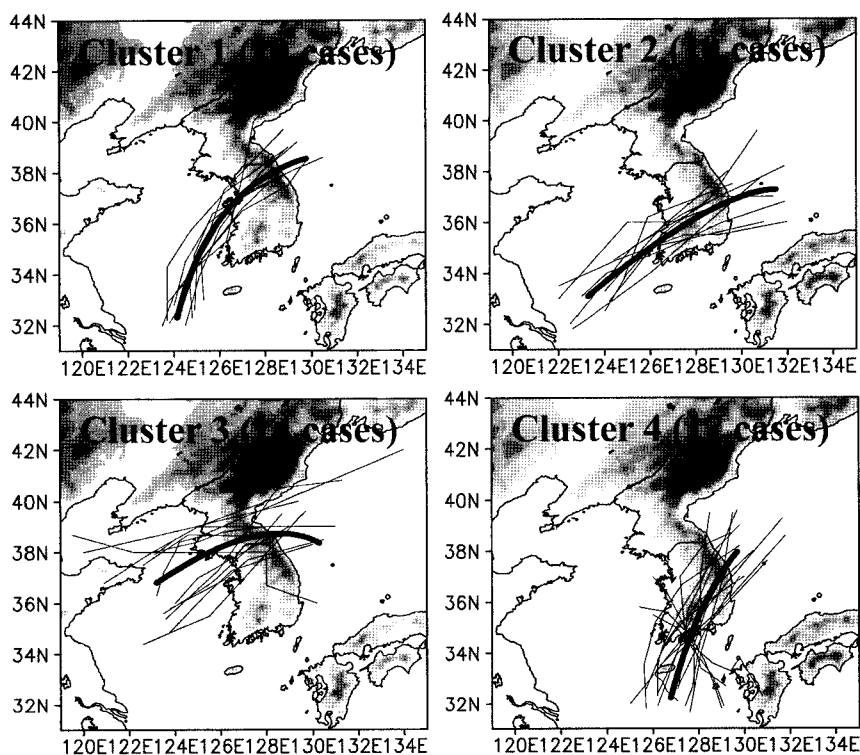


Fig. 1. Landfalling tracks of KP-landfall TC classified into four clusters by Choi and Kim (2007). The numbers in parentheses represent the number of TCs' belonging to each cluster (Units are degree).

landfall" means that "the time when the TC center of the RSMC best-track made the closest approach to the KP" and "the time after the TC center of the RSMC best-track just passed over the KP", respectively. More detailed description related to the procedure of the FCM and the definition of the KP-landfall TC was given by Choi and Kim (2007). They have showed that the landfalling tracks of KP-landfall TC are optimally classified into four clusters (Fig. 1). Also they have suggested that most TCs of Clusters 1 and 4 (C-14) do not pass through mainland China and then land at the south coast of KP have much stronger intensity than TCs of Cluster 2 and 3 (C-23) pass through mainland China and then land at the west coast of KP. Lastly, the relationship between the

landfalling frequency of the KP-landfall TC and climate changes such as ENSO and AO are examined.

Relationship between KP-landfall TC Frequency and ENSO

Landfalling frequency and intensity along ENSO phase

Table 1 shows the ENSO phase of each year that TCs landed over the KP. The classified ENSO phase years are nearly consistent with those of Larson et al. (2005). Also in the two groups (C-14 and C-23), the frequency of KP-landfall TCs belonging to each ENSO phase is shown in Figure. 2a. In the case of C-14, the landfalling frequency during the warm phase is

Table 1. ENSO phase on years when TCs land over the KP

Warm	Normal	Cold
1951, 1953, 1957, 1963, 1965, 1976, 1986, 1987, 1991, 1994, 1997, 2002, 2004	1952, 1960, 1962, 1966, 1979, 1980, 1990, 1992, 2001, 2003	1959, 1961, 1971, 1973, 1978, 1981, 1984, 1985, 1989, 1995, 1999, 2000

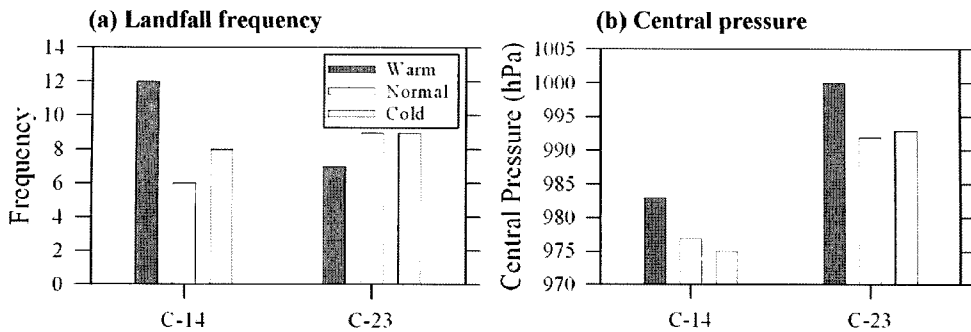


Fig. 2. (a) Landfalling frequency of KP-landfall TCs and (b) central pressure at landfall for C-14 and C-23 along each ENSO phase (warm, normal, and cold phases) (Units are degree).

the most. However, among the three phases of C-23, there is no large difference in landfalling frequency. The central pressure at landfall averaged for TCs belonging to each ENSO phase of C-14 is lower during the cold and normal phases than during the warm phase, although the landfalling frequencies of the cold and normal phases are less than that of the warm phase (Fig. 2b). The central pressures of the cold and normal phases for C-23 also are lower. Eventually, in the warm phase, the frequency of the KP-landfall TC is the most, but TC intensity at landfall is the weakest. This may be because the intensity of TCs at landfall is affected by SST around the TCs.

Atmospheric circulation along ENSO phase

In a number of previous studies, the views on the relationship between TCs in the WNP and ENSO are varied. As representative studies, Chan (1985), Dong (1988), and Wu and Lau (1992) suggested that the TC during El Niño tends to form more eastward and the frequency of occurrences is less than normal. However, Wang and Chan (2002) mentioned that, to date, the changes in the TC activities between the El Niño and La Niña years have not been documented yet. Yumoto and Matsuura (2001) showed that the TC activity changes also are caused by not only SST but also by the interaction between atmospheric circulation and SST. In the present study, the characteristics of SST and atmospheric circulation along the ENSO phase for the two groups are examined.

Figures 3 and 4 show that the 850-hPa mean

streamline and SST (left panels) and zonal wind shear anomalies (right panels) between 200-hPa and 850-hPa along the ENSO phase for C-14 and C-23, respectively. The ridge axes (solid lines) of the western North Pacific High (WNPH) in C-23 in the three SST phases bend more equatorward, but those in C-14 are located above 30°N. Therefore, the main flow around the KP in C-14 is southerly and southwesterly in C-23 without being related to the ENSO phase. The geneses of TCs for the two groups also are made around the monsoon troughs (dashed lines). And all the monsoon troughs of C-14 begin near Taiwan, but begin near Hainan Island in C-23. However, a large difference between the two groups is in an extent of the eastward expansion of the monsoon trough. In the case of C-23, there is no large difference in eastward expansion of the monsoon troughs among the three phases, which is that monsoon troughs in three phases expand to about 150°E. Meanwhile, the eastward expansion in the cold and normal phases in C-14 is similar in C-23, but that the eastward expansion in the warm phase expands as far east as 170°E. These characteristics reflect the frequency among the three phases for C-23 is similar, but the frequency of the warm event for C-14 is the most (Fig. 3a).

SST anomaly fields show the reason why TC intensity in the warm phase in both groups is weak. In the case of C-14, SST anomalies of cold and normal phases are generally warm over the WNP, but cold for the warm phase. Especially, SST anomalies around the

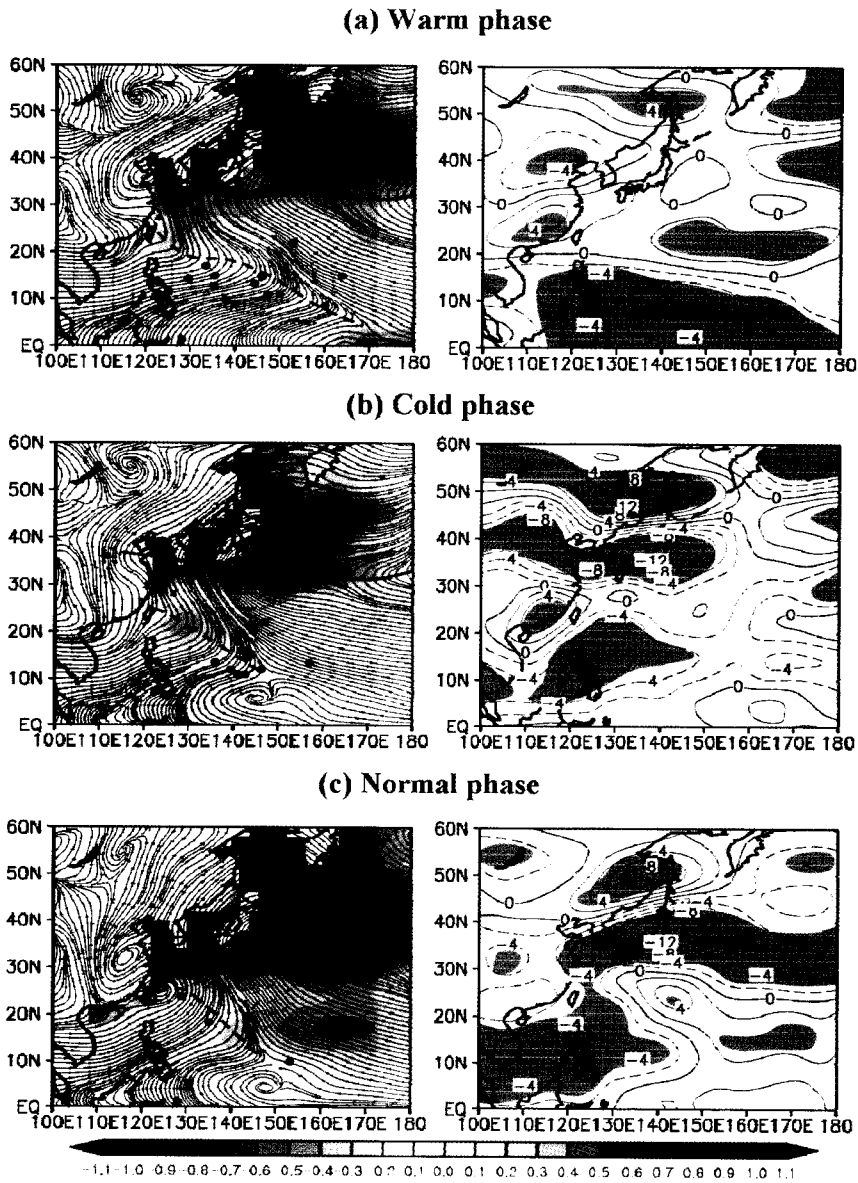


Fig. 3. 850-hPa streamline and SST anomalies along each ENSO phase (right panel) and zonal wind shear anomalies (ms^{-1}) between 200-hPa and 850-hPa (left panel) for C-14. In the left panels, solid and dashed lines denote the ridge axes of the WNPB and the monsoon troughs, respectively. Solid black dots and triangles denote the geneses and recurring locations, respectively. In the right panels, the areas exceeding the 95% confidence level are shaded (Units are degree).

KP during cold and normal phases are obviously warm. Therefore TC intensity at landfall for warm phase of C-14 is weaker than that for normal and cold phases of C-14. This result indicates that SST around TC at landfall plays an important role in the intensity change of TC at landfall. In the case of C-23, on the whole, the area and intensity of warm SST anomalies

over the WNP, respectively, are less and weaker than those for C-14. However, through the location of the TC genesis of C-23, warm phase TCs are likely to pass over cold SST for the period from genesis to KP landfall. Meanwhile, TCs of cold and normal phases pass over warm SST to 20°N or to 30°N. This difference of SST environment between warm phase

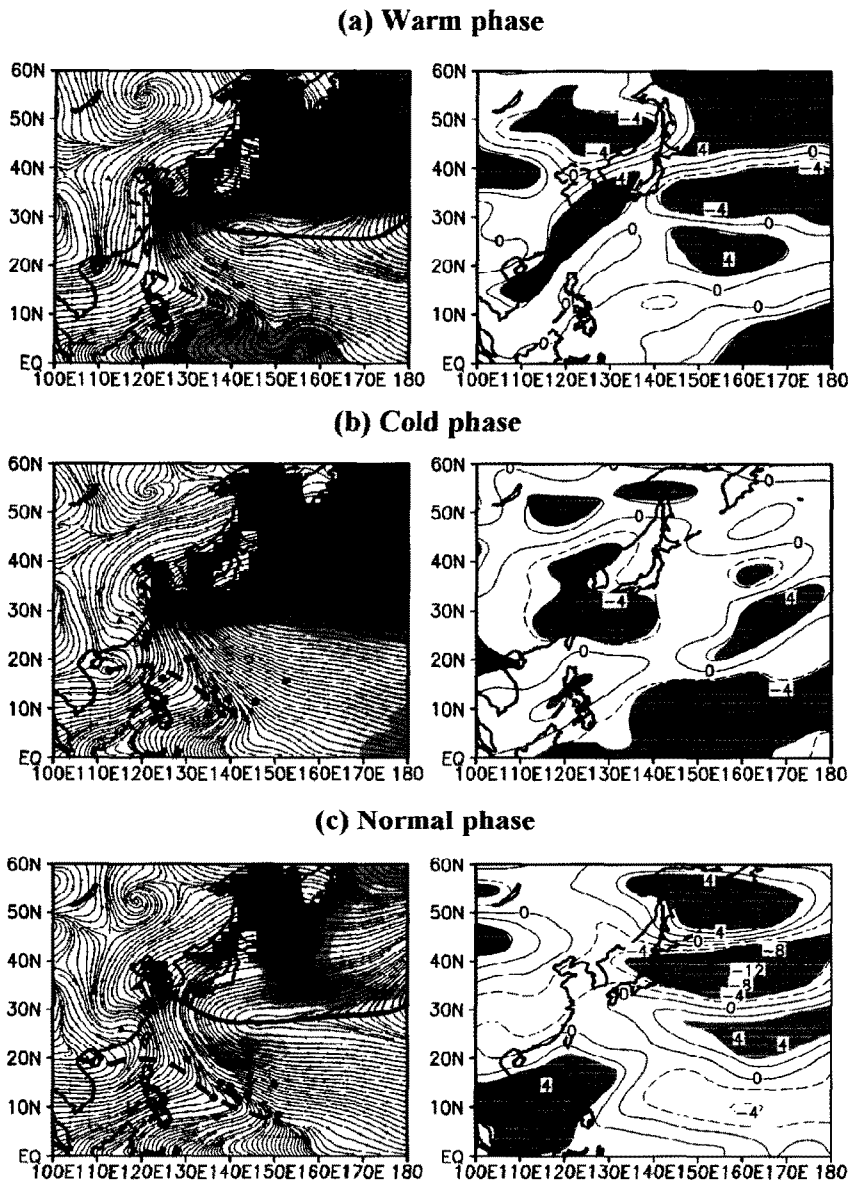


Fig. 4. As in Fig. 3 but for C-23 (Units are degree).

and cold and normal phases of C-23 seems to be the cause of the difference in TC intensity at landfall in Fig. 2b.

Zonal wind shear anomalies between 200-hPa and 850-hPa also show the reason for a difference of TC genesis frequency and intensity between ENSO phases (right panels in Figs. 3 and 4). In the case of C-14, most areas of below 20°N in warm and cold phases have weak shear, but the weak shear area of below

20°N in the normal phase is relatively small. Therefore, TC genesis for C-14 is the fewest in the normal phase as indicated in Figure. 2a. And the areas between 30°N and 40°N in the cold and normal phases have a weaker shear than that in the warm phase. Especially, between cold and normal phases, an area around KP has a weaker shear in cold phase. Therefore TC intensity at landfall for C-14 is the strongest in the cold phase as indicated in Fig. 2b.

Meanwhile, in the case of C-23, most areas of below 20°N and between 30°N and 40°N have a weaker shear in the cold and normal phases and then TC genesis and the intensity in both phases is more and stronger than those in the warm phase. The results above coincide with the views of Kim and Ho (2005) and Yumoto and Matsuura (2001) that the TC activity in midlatitude East Asian countries such as Korea and Japan is more significantly controlled by a regional atmospheric circulation and by the interaction between atmospheric circulation and SST.

Relationship between KP-landfall TC and AO

Landfalling frequency along AO phase

AO is marked by opposing fluctuations in surface pressure over the polar cap region (60°N to 90°N) and midlatitudes (30°N to 60°N), together with opposing fluctuations in the strength of tropospheric westerlies at subpolar (near 60°N) and subtropical (near 30°N)

latitudes (Thompson and Wallace, 2000). They showed that AO has far-reaching effects on winter weather over the Asia, United States and Europe. They also noted that AO accounts for a significant portion of the total variance of the atmospheric circulation during portions of the warm season. To date, however, there has been relatively little study of the effects of AO on summer weather (e.g., Thompson et al. 2000).

Table 2 shows the landfalling frequencies of positive (hereafter, POS or +) and negative (hereafter, NEG or -) AO phases for C-14 and C-23. On the whole, the landfalling frequency in the POS AO phase for C-14 is more than that in the NEG AO phase and vice versa in C-23. In detail, that in the POS AO phase for C-14 is more after the late 1980s. That is, there are 13 frequencies for 1985-2004 out of 18 landfalling frequencies in the POS AO phase. On the contrary, in the case of C-23, that in the NEG AO phase is more before the late 1980s. Eventually, the KP-landfall TC in past years is more frequent in the NEG AO phase and in the POS AO phase in recent years.

Table 2. KP-landfall TC frequency along AO phase

C-14		C-23	
1957	1	1951	1
1960	1	1952	1
1961	1	1953	2
1962	1	1959	2
1963	1	1961	2
1966	2	1962	3
1971	1	1965	2
1973	1	1971	1
1978	2	1976	1
1985	1	1979	1
1986	1	1980	1
1987	1	1981	1
1989	1	1984	1
1991	1	1987	1
1994	2	1990	1
1995	1	1992	1
1997	1	1995	1
2000	2	1999	1
2002	2	2001	1
2003	1		
2004	1		
+	18	+	8
-	8	-	17

*Shaded years denote negative AO phases.

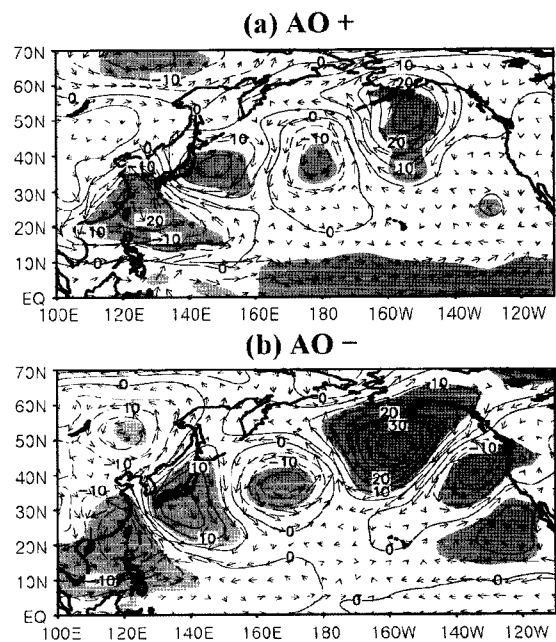


Fig. 5. 850-hPa wind and geopotential height anomalies (a) AO positive (POS) and (b) negative (NEG) phases. The areas exceeding the 95% confidence level are shaded (Units are digree).

Atmospheric circulation along AO phase

Shown in Fig. 5 are the 850-hPa geopotential height and wind anomalies in the POS AO and NEG AO phases. The monsoon trough of the POS AO phase expands much farther eastward than that of the NEG AO phase (see -10 gpm contours in Figs. 5a and 5b). Also southerly in the POS AO phase is strong the east of the KP, but on the other hand, is the west of the KP in the NEG AO phase. This result reflects the characteristics of the TC landfalling tracks of C-14 and C-23 in Fig. 1.

An anomalous wave train along the coast of the continent from SCS to the West Coast of U.S. is formed. The cells of the anomalous wave train in the NEG AO phase are clearer than those in the POS AO phase. And the East Asian continent and eastern part of U.S. are a positive geopotential height in the POS AO phase and negative in the NEG AO phase.

In addition, the Pacific-Japan (PJ) pattern, which consists of an anomalous low around the Philippines and Taiwan and an anomalous high around Japan, is formed over the WNP. Nitta (1987) found that a PJ pattern of the anomalous WNP circulation exists in response to the tropical Pacific summer SST anomalies. Later, Chen et al. (1998) showed that the PJ pattern is embedded in a short wave train emanating from the tropics to the northwest Pacific. The north-south seesaw of the tropical and subtropical cells of this wave train results in the interannual variation of the typhoon activity of the WNP. In the present study, an anomalous low in the POS AO phase such that the TC lands with stronger intensity develops more. This result coincides with the research by Chen et al. (2006) that showed that the more an anomalous low near the Philippines and Taiwan in a PJ pattern develops, the stronger the TC activity in the WNP. However, although the cause of an occurrence of a PJ pattern and its influence on the East Asian climate have been studied by many researchers, a clear answer has not yet been found (Enomoto et al., 2003).

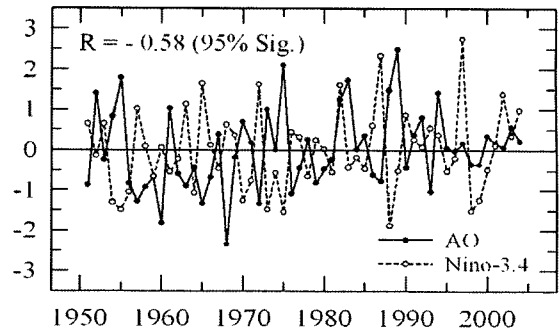


Fig. 6. Time-series of AO (Solid) and Niño-3.4 (dashed) indices averaged for July, August, and September (JAS). These indices are those standardized for the period of 1951-2004 (Units are degree).

Combined effects of ENSO and AO

According to Chen et al. (2006), both La Niña and the positive phase of AO are associated with atmospheric conditions known to favor increased Atlantic hurricane activity and the likelihood of U.S. hurricane landfall. Conversely, both El Niño and the negative phase of AO are associated with atmospheric conditions that tend to suppress TC activity in the same region. However, it is not easy to find studies on the combined effects of ENSO and AO on TC activity in the WNP.

Therefore, in the present study, a correlation coefficient between ENSO and AO firstly is analyzed in Fig. 6. There is a negative relationship (Corr = -0.58) between the two indices with the 95% confidence level as in the case of TC activity in the Atlantic. However, their negative relationship since the late 1990s tends to be weak relatively. The negative correlation coefficient when removing values after the year 1995 from the two indices becomes much higher at -0.69.

Table 3 shows the frequency of KP-landfall TC along the combined AO and ENSO phase. As stated in section 4.1, most TCs of C-14 and C-23 tended to land in the AO POS and NEG phases, respectively. Considering this tendency together with the Niño-3.4

Table 3. KP-landfall TC frequency along the combined AO and Niño-3.4 phases

(a) C-14		AO		(b) C-23		AO	
		+	-			+	-
Niño-3.4	+	5	6	Niño-3.4	+	2	11
	-	13	2		-	6	6

index, the TCs of the AO POS (NEG) phase in C-14 (C-23) tend to more land in the Niño-3.4 NEG (POS) phase (Hereafter, the AO POS and Niño-3.4 NEG phases: PN, and AO NEG and Niño-3.4 POS phases: NP) and vice versa. It is known that there is a clear negative relationship between the two indices. That is, the landfalling frequencies of AO NEG and Niño-3.4 NEG (NN) phases in C-14 and AO POS and Niño-3.4 POS (PP) phases in C-23 are the fewest.

Therefore zonal wind shear anomalies are analyzed to compare between the most frequency (PN in C-14 and NP in C-23) and the fewest frequency (NN in C-14 and PP in C-23) for two groups (Fig. 7). Both PN in C-14 and NP in C-23 have a weak shear below 20°N, which forms an opposite pattern to NN in C-14 and PP in C-23, respectively. And NP and PP of C-23 are weak and strong shears around the KP, respectively, so that the mean central pressure of NP

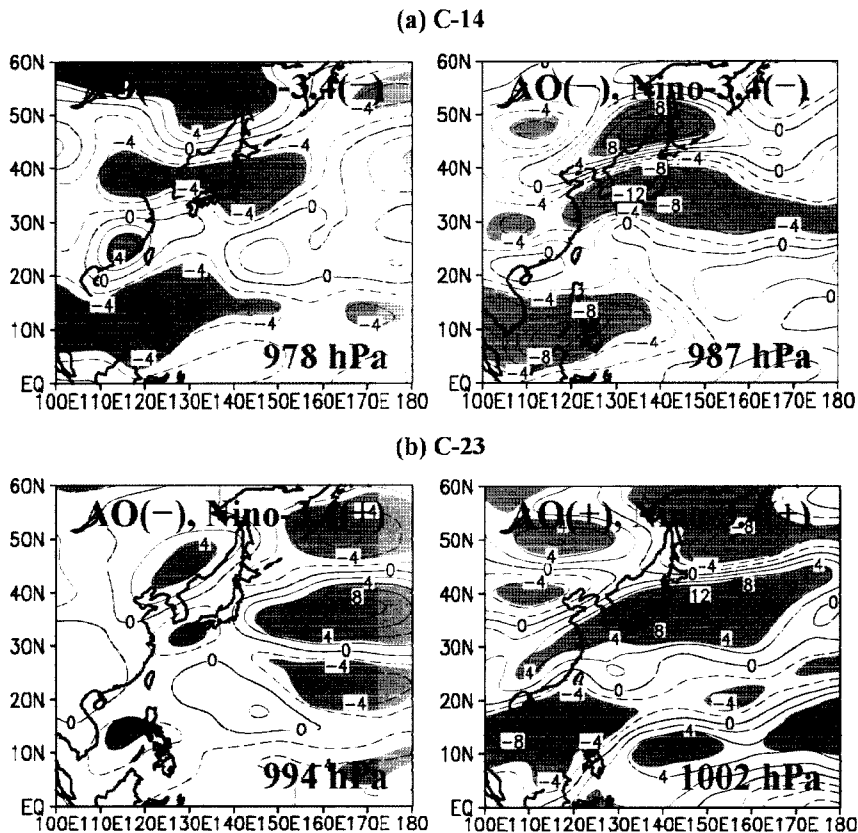


Fig. 7. Zonal wind shear anomalies between 200 hPa and 850 hPa in the (a) AO positive and Niño-3.4 negative phases (PN; left panel) and AO negative and Niño-3.4 negative phases (NN; right panel) for C-14 and (b) in the AO-negative and Niño-3.4-positive phases (NP; left panel) and AO-positive and Niño-3.4-positive phases (PP; right panel) for C-23. Numbers in the lower right side of each figure are the mean central pressure of TCs at landing over the KP in each case. The areas exceeding the 95% confidence level are shaded (Units are degree).

at landfall is lower by about 10 hPa than that of PP. Meanwhile, both PN and NN of C-14 have a weak shear around the KP, but a mean central pressure of PN is lower as by about 10 hPa. This may be because a very strong shear in NN is located in the middle and northern regions of the KP so that TCs become weak.

Summary and Conclusions

Cluster analysis on landfalling tracks of 51 tropical cyclones (TCs) landed over the Korean Peninsula (KP) for the period of 1951-2004 has been performed by Choi and Kim (2007). They have used the fuzzy clustering method (FCM) and classified four clusters as an optimal cluster number. These four clusters can be regrouped into two groups such as two clusters (C-14; TCs do not pass through mainland China before landing the KP) and two clusters (C-23; TCs pass through mainland China before landing the KP).

KP-landfall TCs had a higher landfalling frequency in the warm phase of ENSO, but have stronger landfalling intensity in the cold and normal phases. This meant that the SST around TCs at landfall plays an important role in landfalling TC intensity.

From a relationship analysis between the frequency of KP-landfall TCs and Arctic Oscillation (AO), the TC frequencies of C-14 and C-23 were high in the positive (POS) and negative (NEG) phases of AO, respectively. Especially, the TC frequency of C-14 has obviously increased since the late 1980s in the AO positive phase, because the AO index currently is in a positive phase. In particular, anomalous wave trains along the coast of the continent from the South China Sea (SCS) to the East Coast of U.S. in both the AO POS and NEG phases appeared. This train is much clearer in the AO NEG phase. Additionally, Pacific-Japan (PJ) patterns in two phases were formed, and especially, the anomalous low of the PJ pattern near the Philippines and Taiwan was more developed in the AO POS phase. This was one of reasons that the landfalling TC intensity of C-14 became stronger.

In an analysis of the relationship between the Niño-

3.4 and AO, two indices was correlated negatively ($r = -0.58$). That is, most TCs of the AO POS (NEG) phase in C-14 (C-23) tended to land in the Niño-3.4 NEG (POS) phase and vice versa. Also the fewest landfalling frequencies showed in the AO NEG (POS) and Niño-3.4 NEG (POS) phases in C-14 (C-23).

Acknowledgments

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