JP 3.18 A CLIMATOLOGICAL FEATURES OF TYPHOON MAKING LANDFALL OVER THE KOREAN PENINSULA

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1. INTRODUCTION

The tropical cyclones (TCs), which form over the western North Pacific (WNP), account for 30 percent of the global total. Among these TCs, on average, three per year affect the Korean Peninsula (KP), and one lands over the KP with tremendous damage (Typhoon White Book 1996). According to National Emergency Management Agency (NEMA 2005), TCs explain approximately 65 percents of the amounts of damage caused by a natural disaster during the last 10 years. Also, it is noted that damage by TCs may be much more increased in case of considering a loss of life by TCs. Therefore, in order to reduce the damage brought by a TCs, the long-term variability of TC activity in each ocean basin has already been studied by many researchers. Chan and Shi (1996) showed that TCs activities in the western and central North Pacific basins have increased since the 1980s. In a study on the activity of TCs affecting the KP, Park et al. (2006) showed that the number of TC has rapidly increased since the 1990s. Actually, top 10 TCs with the highest economic damage in South Korea have struck in recent years and made landfall over the KP (KMA 2002). In addition, a heavy rainfall influenced only by the landfall TCs has increased since late 1970s (Kim et al. 2006). From this point of view, a study of the long-term variability of the activity of KP-landfall TCs will be meaningful and valuable.

In studies of the climatological and statistical characteristics of TCs that have affected the KP, Lee et al. (1992) classified the KP-affecting TCs into six-track type during the period 1960-1990 and then analyzed the large-scale circulation associated with each track type. Also, Park et al. (2006) investigated the KP-affecting TCs in terms of the relationship between rainfall connected to TCs and TCs' tracks or kinetic energy. Ho et al. (2004) reported that, through analysis of summertime TC activity in the WNP during the period 1951-2001, the passage frequency of TCs from the Philippine Sea to northeast China including South Korea and the western region of Japan was reduced after the 1980s. It is also known that TC motions are significantly controlled by regional atmospheric circulation rather than the variability of the SST in the subtropics or tropics (Kim et al. 2005).

However, it is not easy to find the previous study on KP-landfall TCs, but the study of Kim et al. (2006) is just found. They defined TC landfall as an event where the TC center enters a circle with a radius of 5° from central Korea (128°E and 36°N). After that, they analyzed the large-scale atmospheric circulation associated with heavy rainfall influenced only by the landfalling TCs.

There have been many previous studies on the climatological characteristics of TC in the WNP(Chan 1985, Dong 1988, Wu and Lau 1992, Lander 1994, Wang and Chan 2002, and Yumoto and Matsuura 2001). They focus on the variability of TC genesis in the WNP, which is mainly related to the El Niño-Southern Oscillation (ENSO).

In the case of TC studies associated with the KP, the KP-affecting TCs are mainly made one of the objectives in this study. But, as stated above, economic loses caused by TCs in South Korea are much more great by those making landfall over the KP. Additionally, TC activity related to the KP

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need to be studied separately from the climate patterns of subtropical or tropical regions in order to reduce the damage by TCs making landfall over the KP. The present study aims to show the interannual and interdecadal variabilities of the KP-landfall TC.

2. DATA

In order to select the KP-landfall TC, the present study employs the dataset of TC best- track for the WNP that has been 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; kt) of TCs. Here, the MSW along the TC intensity is divided into 5 grades such as tropical depression (TD; MSW < 34kt), tropical storm (TS; 34kt ≤ MSW ≤ 47kt), severe tropical storm (STS; 48kt ≤ MSW ≤ 63kt), typhoon (TY; MSW ≥ 64kt), and extratropical cyclone (ET).

We also use the 6-hourly wind (m s^{-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).

3. INTERANNUAL VARIATION IN THE KP-LANDFALL TCs

Fig. 1 shows the 5-year variation of the landfall frequency of the KP-landfall TCs. The landfall frequency of the early 1960s and early 2000s is quite high and that of the period of the 1970s to the 1980s is relatively low. However, the landfall frequency again increases from the late 1980s onward, which is consistent with Park et al. (2006), who analyzed the trend of TCs that affected the KP. The correlation coefficient between both is 0.55, which is significant at the 95% confidence level. The increase in the landfall frequency of KP-landfall TCs after the late 1980s is more remarkable in that of a TC with intensity greater than the TS. Simultaneously, the landfall frequency of the TD decreases. This result reflects that the landfall frequency of TCs with strong intensity has increased more and more in recent years.

Fig. 2 shows the decadal variation of the monthly landfall frequency of KP-landfall TCs.

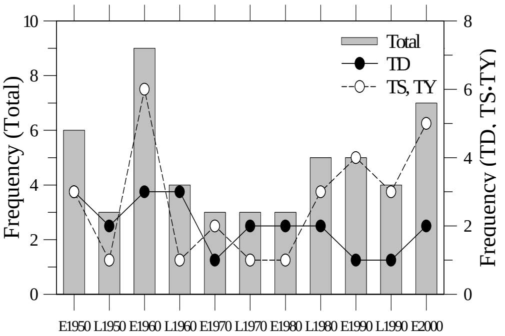


Fig. 1. 5-year variation of the landfall frequency of KP-landfall TCs. The bar and solid and dashed lines denote a 5-year total frequency, a TD and extratropically transiotioned cyclone frequency, and a TS and TY frequency, respectively. A capital E and L denotes "early" and "late," respectively.

Until the 1970s, most TCs made landfall in August, but, since the 1980s, the months of more frequent landfall has changed to June and July. Generally, we can see that the landfall frequency of KP-landfall TCs is the highest in July and August, but the ratio of that in June to the total landfall frequency is also not low.

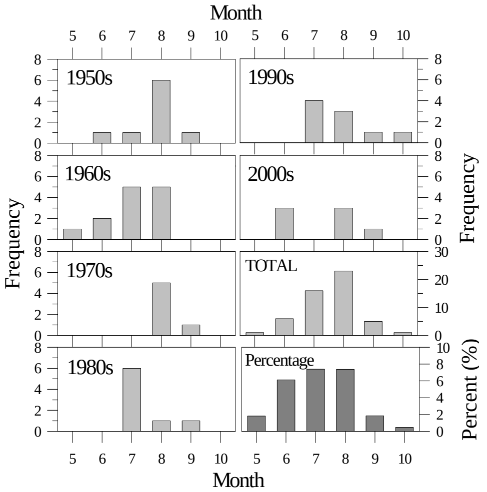


Fig. 2. Decadal variation of the monthly frequency of KP-landfall TCs. The units of the light and dark gray bars are frequency and percent, respectively.

The decadal variation of the landfalling track patterns of KP-landfall TCs shows more distinctive characteristics (Fig. 3). TCs in the past mainly passed through the middle or northern region of the KP, but, in recent years, they have made landfall on the south coast and then passed over the east coast of the KP. That is, this reflects that the main landfalling track of KP-landfall TCs tends to shift south-eastward. This south-eastward shift is more clear in the change of the mean regression track at each decade (thick lines in Fig. 3).

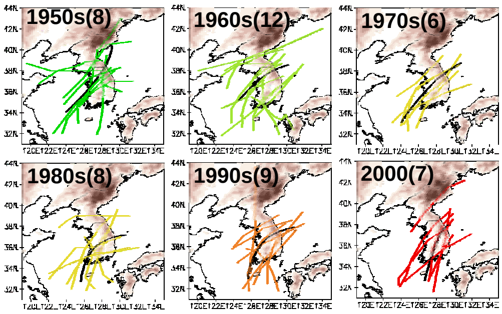


Fig. 3. Decadal variation of the landfalling track of KP-landfall TCs. In (b), thick lines denote regression mean tracks and the numbers in parentheses represent the landfall frequency of KP-landfall TCs during each decade.

This is because, in the past, many KP-landfall TCs tended to land at the KP after recurving on Mainland China. However, in recent years, the tracks of the TCs have changed to come not via Mainland China but from the East China Sea (Fig.4). Therefore, the increase in recent landfall frequency of KP-landfall TCs with strong intensity is due to the recent increase of TCs passing over the sea that can sufficiently supply the energy to the TC.

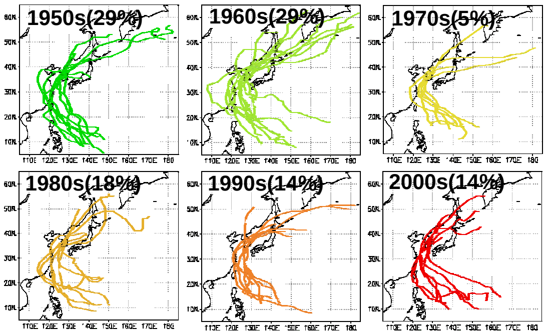


Fig. 4. Decadal variation of the full tracks of KP-landfall TCs. The numbers in the parentheses denote the ratio of TCs that passed through Mainland China to the total number of TCs during each decade

The landfalling track change of KP-landfall TCs is likely to be related to that of the recurving location. Fig. 5 shows the recurving frequency at each grid box and that of the 10-year mean of KP-landfall TCs. The region of the maximum recurving is in the vicinity of Nanjing in Mainland China and the axis of relatively high frequency also is toward the southwestern sea of the KP. In the variation of the 10-year mean recurving location, we can see the clockwise and simultaneously southward shift of the recurving location, which is the same direction as the landfalling track shift of KP-landfall TCs.

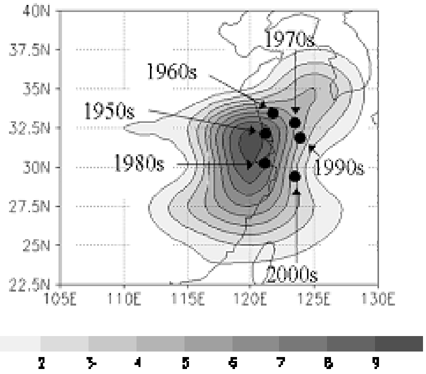


Fig. 5. Decadal variations of the recurving locations (dark circles) and the recurving frequency (contour) of KP-landfall TCs

4. INTERDECADAL VARIATION IN THE KP-LANDFALL TCs

In order to examine the characteristics of interdecadal variation on the frequency of TC landfalling the KP, the change-point analysis is applied. The indices associated with the KP-landfall TC used in the analysis are following :

- Frequency of TC (TDET) with intensity of tropical depression to extratropical transition of TC
- Frequency of TC (TSTY) with intensity of tropical storm to typhoon
- Accumulated cyclone energy (ACE) on TC with intensity of tropical storm to typhoon
- Total moving distance (TMD) of TC for its life time.

Fig. 6 shows the interdecadal variations of TDET and TSTY, ACE and TMD. The 5-year running mean, 54-year mean, period mean in each index are given to find a significant change-point. It can be found that there are obvious change-points in mid-1960s and mid-1980s. The exact years showing a significant change-point are somewhat different among indices. For example, in case of TDET, significant change-point years are 1967 and 1984 at 95% confidence level and ACE are 1964 and 1986. In particular, the change-point of mid-1980s is consistent with the result of Choi and Kim (2007) that the frequency of KP-landfall TC begins increasing after late-1980s. Higher TDET and TSTY and larger ACE than 54-year mean values are appeared until early 1960s and afterward late 1980s. TMD lies in phase with other indices. Undoubtedly, as the TDET and TSTY with intensity greater than TS increases, the other indices will increase. However, if the duration of TC with intensity greater than TS is short even though its frequency is high, the ACE will become small (Goldenberg et al. 2001). In addition, as the TC intensity is weak, the moving distance of the TC is short (Wu et al. 2004). Eventually, it might be mentioned that the intensity (ACE) of the KP-landfall TC is largely dependent on the duration of TC with intensity greater than TS though its frequency is high. Therefore, in this study, the frequency of the KP-landfall TC can be divided into three periods as follows:

- High frequency period (H5165) : 1951~1965 (15 years)
- Low frequency period (L6685) : 1966~1985 (20 years)
- High frequency period (H8604) : 1986~2004 (19 years)

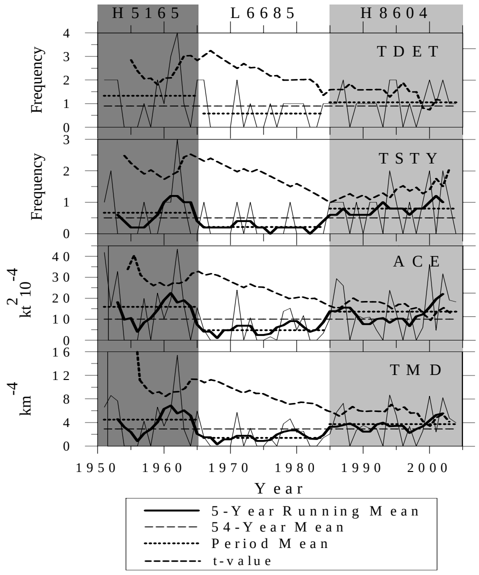


Fig. 6. Decadal variation of Korean peninsula (KP) - landfall TC. The indices in order from an upper-most side is the frequency of total KP-landfall TC (TDET), the frequency of KP-landfall TC with intensity greater than tropical storm (TSTY), accumulated cyclone energy (ACE), and total movement distance (TMD) for the TC life time, respectively. The periods of H5165, L6685, and H8604 indicate the first high frequency period 1951-1965, the low frequency period 1966-1985, and the second high frequency period 1986-2004 calculated from t-value (bold dashed line) of the change point analysis. The thick solid, dashed, and dotted lines denote 5-year running mean, 54-year mean, and each period mean, respectively.

And the significant change-points of mid 1950s and early 2000s obtained from the analysis are not considered here to make a comparative study of the intensity and track of TC and the associated atmospheric circulations in each period with 15~20 years.

Shown Fig. 7 are the frequency, central pressure at landfall, and life time of the KP-landfall TC in each period. Landfalling frequency is three times higher in H5165 and H8604 than in L6685. TDET has the same number in both H5165 and H8604, while TSTY is much higher in H8604. That, is, most of TCs (approximately 70 percentage) landed in H8604 has the intensity greater than TS. It is found that in recent years the KP-landfall TC becomes stronger in the intensity as well as higher in the frequency, which is in good agreement with the study of Choi and Kim (2007). They also showed that the main landfalling track of KP-landfall TCs tends to shift southeastward from the climatological analysis of the track of KP-landfall TCs. This finding could be confirmed in the analysis of the central pressure at landfall of TC. The central pressure at landfall is the lowest in H8604 with 978 hPa, meaning that the KP-landfall TC is the strongest among each period. The difference of central pressure at landfall between H5165 (averaged central pressure : 988 hPa) and L6685 (averaged central pressure : 993 hPa) is only 5 hPa, showing the small variation of intensity of KP-landfall TC during 35 years of 1951 to 1985. Recently, Wu et al. (2004) suggested that the stronger TC is, the longer TC life time is. However, the life times of TDET showing from tropical depression to transition of TC are very similar irrelevant of high or low frequency periods. On the contrary, the life time of TSTY with intensity greater than TS is the longest in H8604. Concretely speaking,

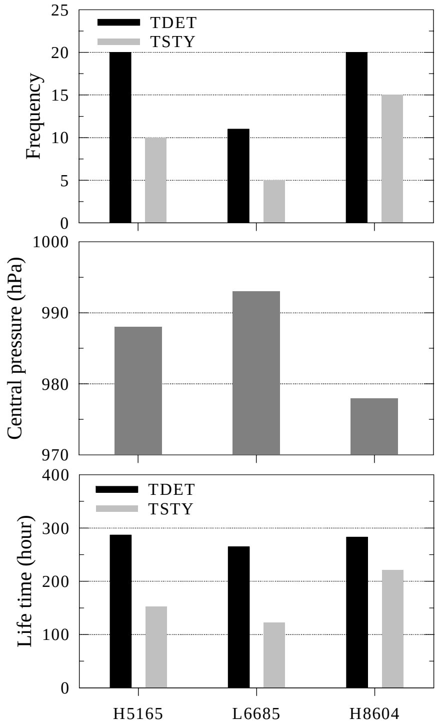


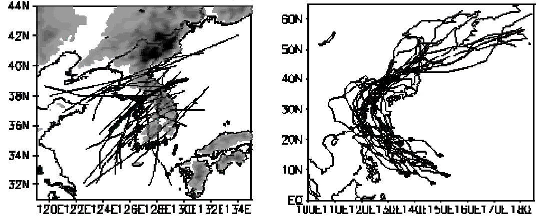
Fig. 7. The frequency (upper), central pressure at landfall (middle), and life time (lower) of the KP-landfall TC. In the upper-most and lower-most panels, dark and light barbs denote the times until disappearing in the best-track and during the intensity greater than TS.

the life time in H8604 is three days longer than that in H5165 and four days than in L6685. Thus, much attention should be paid on the higher frequency and stronger intensity of KP-landfall TC, particularly in case of TC with intensity greater than TS, during the recent 19 years

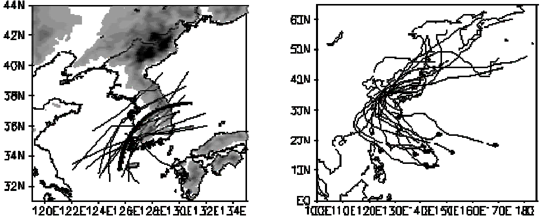
Fig. 8 shows the landfalling and full tracks of KP-landfall TCs in each period. 16 TC cases (80%) of 20 TC cases for H5165 make landfall in the west coast of the KP and then pass through the middle and north coast of the KP. In particular, the cases do not pass through Sobaeksanmaek in common. We know that landfalling tracks in L6685 go more southward than that in L5165 through the mean regression track. For L6685, 7 TC cases (63%) of 11 TC cases make landfall in the west coast of the KP and then 8 TC cases of 11 TC cases passed through Sobaeksanmaek. The mean regression track in H8604 shifts more southeastward than before so that TCs mainly make landfall in the south coast of the KP. 10 TC cases (50%) of 20 TC cases make landfall in the west coast of the KP and then they all pass through Sobaeksanmaek. However, 10 TC cases make landfall in the south coast do not pass through there.

Choi and Kim (2007) showed that in the past, many KP-landfall TCs tend to land at the KP after passing through the mainland China but, in recent years, change to come not via Mainland China but from the East China Sea. Also, they suggested that the intensity of KP-landfall TC by the change of this track tends to increase in recent years We can confirm the change of KP-landfall TC full track in Fig. 8. In H5165, 12 TC cases (60%) of 20 TC cases pass through the mainland China before landing at the KP, but in 6685, TC cases pass through the mainland China rapidly reduce until 36% (4 TC cases of 11 TC cases). These kinds of TC cases in H8604 is 30%, which is nearly the same percent as that of H6685. However, while the TC cases pass through the mainland China for H8604 only go pass by the east coast region, those for L6685 tend to penetrate into further inland of mainland China. With the result of that, intensity and life time of KP-landfall TC become stronger and longer in

(a) H5165



(b) L6685



(c) H8604

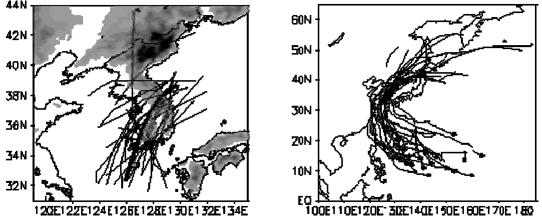


Fig. 8. Landfalling (left) and full tracks (right) of KP-landfall TC for the periods of (a) H5165, (b) L6685, and (c) H8604. In the left panel, thick lines denote the mean regression tracks.

recent years, respectively. There seems no distinctive feature except that the genesis of KP-landfall TC is located in farthest east in H8604.

6. SUMMARY

In this study, we investigated the climatological characteristics of tropical cyclones (TCs) that made landfall over the Korean Peninsula (KP) during the period 1951-2004, which can be summarized as follows:

1) Landfall frequency has increased since the late 1980s. Especially, that of TCs with an greater intensity than tropical storm (TS) has rapidly increased.
2) The pattern of landfall changed from the middle or northern region of the west coast of the KP to the south coast of the KP. That is, the tracks of the landfalling TCs tend to shift southeastward in recent years.
3) The change-point analysis showed the TC frequency as three periods such as high frequency period of 1951~1965 (H5165; 20 cases), low frequency period of 1966~1985 (L6685; 11 cases), and high frequency period of 1986~2004 (H8604; 20 cases).
4) TC intensity at landfall was much stronger in H8604 so that the duration of intensity greater than tropical storm (TS) was three days longer in H8604 than in H5165.
5) Full track of the KP-landfall TC passed through the mainland China in last years, but did not pass in recent years. This became the reason of the increases of TC intensity in recent years.
6) The Pacific-Japan (PJ) pattern in H8604 developed stronger than that in the other periods, in particular the anomalous low (monsoon trough) around the Philippines and Taiwan was much stronger. Also, the negative vertical wind shear (VWS) anomaly was distinctive in the western North Pacific. These synoptic conditions became the appropriate environment that TC in H8604 can develop more than those in the other periods.

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