ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 26, NO. 2, 2009, 202–210

Cluster Analysis of Tropical Cyclones Making Landfall on the Korean Peninsula

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(Received 1 November 2007; revised 14 May 2008)

ABSTRACT

Cluster analysis has been performed on the tracks of 51 Tropical Cyclones (TCs) that made landfall on the Korean Peninsula (KP) for the period of 1951–2004. The classification technique of the landfalling tracks used in this study was the fuzzy clustering method (FCM) and the resultant silhouette coefficient suggested four clusters as an optimal cluster number. Most TCs of Cluster 2 and Cluster 3 (C-23) tended to pass through mainland China before landfall, but those of Cluster 1 and Cluster 4 (C-14) tended to mostly land after moving northward from the East China Sea (ECS) without passing over mainland China. The TC landfalling frequency of C-14 has begun to clearly increase since the late 1980s, particularly the maximum landfalling frequency in the early 2000s set a record for the 54-year analysis period. The ridge axis of the western North Pacific high (WNPH) of C-23 bends more equatorward than that of C-14, so that the monsoon trough of C-23 is located more equatorward than that of C-14. As a consequence, most TCs of C-23 tend to recurve inland of China, but over the ECS for C-14.

Key words: Korean Peninsula, tropical cyclone, landfall, fuzzy cluster, Arctic Oscillation, Niño-3.4

Citation: Choi, K.-S., B.-J. Kim, C.-Y. Choi, and J.-C. Nam, 2009: Cluster analysis of tropical cyclones making landfall on the Korean Peninsula. *Adv. Atmos. Sci.*, **26**(2), 202–210, doi: 10.1007/s00376-009-0202-1.

1. Introduction

Statistically, the Korea Peninsula (KP) is affected by three Tropical Cyclones (TCs) per year; one out of three TCs land on the KP and then does great damage to property and human life (Korea Meteorological Administration, 1996). Since the 1980s, the property damage caused by TCs has tended to geometrically increase along with industrial development (Korea Meteorological Administration, 2002). Therefore, in order to reduce the damage by TC and to improve the TC intensity and track forecast, a study of the numerical modeling for TC forecasting has been developed. In particular, the study of the initialization, using a bogus TC, contributed considerably to the accuracy of the TCs track and intensity forecast (Jeong, 1991; Kim, 1993). However, these kinds of numerical models need to be studied after a classification of the TC track and an atmospheric circulation, related to a classified track pattern, are analyzed.

Track classification studies of TCs affecting the KP have already been performed by a number of researchers. As the representative study, Lee et al. (1992) classified the tracks of TCs affecting the KP for 30 years (1960–1990) and summarized the statistical and synoptic characteristics of the typical TC case of each classified TC track. The TC tracks in this study were classified into eight types on the basis of the movement of the TC and the existence and nonexistence of the recurving of the TC, but anomalous TC tracks were excluded in the classification. After that, Sohn et al. (1998) more objectively treated the classification method of Lee et al. (1992) by using the multivariate statistical technique. This classification, however, did not include all the TCs that affected the KP. Youn and Kim (1999) also classified TCs into seven groups, but only the cases that passed over the East China Sea (ECS) were classified in detail. These studies share the common feature of TCs affecting the KP defined by the KMA. Meanwhile, Park et al. (2006) first made a new definition to minimize the defects of the KMA's definition on TCs affecting the KP and

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then classified the TC tracks selected from this definition into seven groups. However, this new definition of TCs affecting the KP has the merit of including all the TCs that affected the KP, but the grouping method of the TC track is still not objective.

The study of the track classification focused on TCs over the western North Pacific (WNP) has been actively made. Harr and Elsberry (1991) classified TC tracks into a "straight track", a "recurve-south track", and a "recurve-north track" on the basis of the TC recurving direction and then analyzed the atmospheric circulation on each classified track. Hodanish and Gray (1993) also used TC recurving for TC track classification, but differently from Harr and Elsberry (1991); they used not a direction but the recurving shape. After that, they classified TC tracks into a "sharply recurving cyclone", a "gradually recurving cyclone", a "left-turning cyclone", and a "non-recurving cyclone". However, in the two studies noted above, it is difficult to classify the TC cases with an ambiguous direction and recurving shape. Meanwhile, Lander (1996) more comprehensively classified TC tracks into a "straight moving pattern", a "recurving pattern", a "non-oriented pattern", and a "pattern staying in the South China Sea" using the TC moving pattern, but this classification is still not objective.

However, there are some studies that objectively classify TC tracks using the statistical method. Camargo et al. (2005) developed the regression mixture model based on the polynomial fitting method for the TC moving shape and then objectively classified TC tracks into seven groups. In particular, there is an advantage in that this model well classifies the intensity and seasonal features of the TC, although this model simply uses the location of the TC genesis and TC track as input data. Also, Kim and Ho (2005) objectively grouped TC tracks using the fuzzy clustering method (FCM). Eleven types of TC track patterns are grouped by this method and have an advantage of the geographical similarity of the TC passage. Additionally, these studies have the benefit of an objective track classification but simultaneously have a critical point in that they cannot include all TCs occurring over the WNP.

Until now, studies of TC track classification generally have involved the subjectivity of researchers. In particular, this is much more distinctive in the cases of TCs affecting the KP and it is also not easy to find studies of TC track classification by an objective method. Additionally, considering that the top ten percent of property damage amounts are mostly the result of KP-landfall TCs (Korea Meteorological Administration, 2002), a study should focus not only on TCs affecting the KP but also on KP-landfall TCs. Therefore, this study using Kim and Ho (2005)'s FCM, first aims to more objectively classify the KP-landfall TC tracks and then analyze the statistics and an atmospheric circulation for each classified.

2. Data and methodology

2.1 *Data*

In order to select the KP-landfall TCs, the present study uses the dataset of the TC's 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 the central pressure (hPa) and maximum sustained winds (MSW; kt) of TCs.

We also used the 6-hourly zonal and meridional wind (m s^{-1}) and geopotential heights (gpm) reanalyzed by the National Centers for Environmental Prediction-the National Center for Atmospheric Research (NCEP-NCAR) to characterize the related atmospheric circulation patterns (Kalnay et al., 1996; Kistler et al., 2001). This data is available on a $2.5° \times 2.5°$ grid at standard pressure levels.

2.2 *Methodology*

From a RSMC best-track dataset, 51 KP-landfall TCs were selected. Here, a KP-landfall TC means that the center of the RSMC best-track dataset encounters the coastline of the KP on the surface weather chart. After that, the TC's track of entering the area east of 120°E and north of 32°N then passing over the KP, are classified by using the FCM. Statistical characteristics at, before, and after landfall along with climatological and synoptic characteristics for each cluster are analyzed. Here, "before landfall" and "after landfall" means that "last fix before making landfall over the KP according to the RSMC best-track" and "first fix after just passing over the KP in the RSMC best-track", respectively.

3. Fuzzy clustering method (FCM)

The FCM has already been explained in detail by Kim and Ho (2005) and Kaufman and Rousseeuw (1990). Therefore, in this study, we briefly explain the FCM as follows:

Applying vector empirical orthogonal function (EOF) analysis to the latitude-longitude center position of the KP-landfall TCs, the principal components (PCs) corresponding to each TC track are obtained. These PCs imply the eigen-characteristics of each track. Using the PCs, a dissimilarity index be-

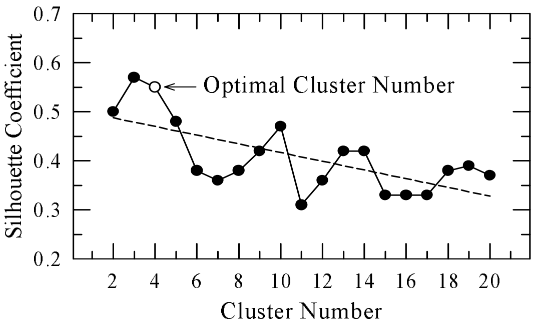

Fig. 1. Silhouette coefficient (solid line with dots) at each cluster number using the fuzzy clustering method (FCM) and its trend (dashed line). In this study, the optimal cluster number (open circle) was selected as four clusters. Shaded area indicates topography higher than 200 m above the sea level.

tween the tracks is constructed. Then, fuzzy clustering analysis is performed using the dissimilarity index as an input of the algorithm. The optimal cluster number is determined by examining the silhouette coefficient (Kaufman and Rousseeuw, 1990). Although the silhouette coefficient in this study was the largest in the third cluster, the fourth cluster was consistent with our current study course and was selected.

The merit of the FCM is that it uses the concept of "fuzziness", which is opposite to the concept of a "hard decision". The largest differences between the two clustering methods are as follows: In the hierarchical clustering method (general clustering method), which uses the concept of a "hard decision", the cluster number is determined in advance and then cluster analysis is performed. Meanwhile, the FCM first performs cluster analysis, and then an analyst determines an optimal cluster number from the outputs of the performance.

4. Classification of the landfalling tracks

The silhouette coefficient yielded from the FCM shows that it is highest for three clusters (Fig. 1). This coefficient is the index that determines an optimal cluster number and a high index value means clustering is optimal. In Fig. 1, as the cluster number increases, the coefficient tends to decrease. After that, the TC tracks of three clusters for the period from before landfall to after landfall are analyzed (Fig. 2). The landfalling track patterns for each cluster are as follows:

Cluster A: moving northward from the south toward the KP,

Cluster B: landfall in the southern region of the west coast of the KP, and

Cluster C: landfall in the middle and northern regions of the west coast of the KP.

On the whole, the TC tracks appear to be fairly classified, however, more objects (TCs) are included in Cluster A than in Cluster B and Cluster C. Therefore, the landfalling tracks for the four clusters (Cluster 4 has the second highest coefficient in Fig. 1) are analyzed (Fig. 3). The largest difference between the three clusters and the four clusters is that Cluster A in Fig. 2 is divided into Cluster 1 and Cluster 4 in Fig. 3. Consequently, we can see that the objects of each cluster are more properly distributed in the four clusters than in the three clusters. All the TCs of Cluster 1 and Cluster 4 move northward from the south toward the KP and they can be divided into the landfall on the west coast category (Cluster 1) and/or the landfall on the south coast category (Cluster 4). However, Cluster 2 and Cluster 3 of Fig. 3 look very similar to Cluster B and Cluster C of Fig. 2, respectively and there is not a great difference in any numbers between them. Eventually the landfalling tracks of KP-landfall TCs are optimally classified into four clusters in this study.

5. Characteristics of each track pattern

5.1 *Full track*

Figure 4 shows the full tracks of the KP-landfall TCs for the four clusters. Most TCs of Cluster 2 and Cluster 3 move eastward from the west toward the KP and tend to pass through mainland China before landfall. Meanwhile, all the TCs of Cluster 1 and Cluster 4 move northward from the south toward the KP and tend to land over the KP without passing through China. This reflects the advantage of the FCM that is the geographical similarity of the TCs passage, as previously stated. Therefore, we know that the landfalling track patterns classified in this study are reasonable.

In the analysis of TC geneses, there are no distinctive characteristics, except that the TCs of Cluster 4, on average, form the farthest east. This may be because the FCM is only performed on the TC track so that the characteristics of the TC genesis are not included.

5.2 *TC intensity change before landfall and after landfall*

Table 1 shows the TC intensity change before landfall and after landfall for four clusters. The clusters of TCs that land with a relatively strong intensity are Cluster 1 and Cluster 4 (hereafter, C-14), on the other hand, the TCs of Cluster 2 and Cluster 3 (hereafter, C-23) land with nearly the same intensity (but weaker than the intensity of the TCs of C-14). This is because

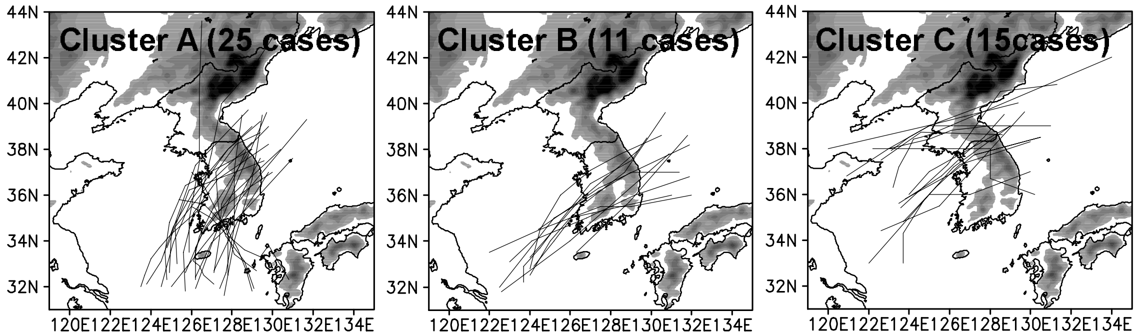

Fig. 2. Landfalling tracks of KP-landfall TCs classified into three clusters. The numbers in parentheses represent the number of TCs belonging to each cluster. Shaded area indicates topography higher than 200 m above the sea level.

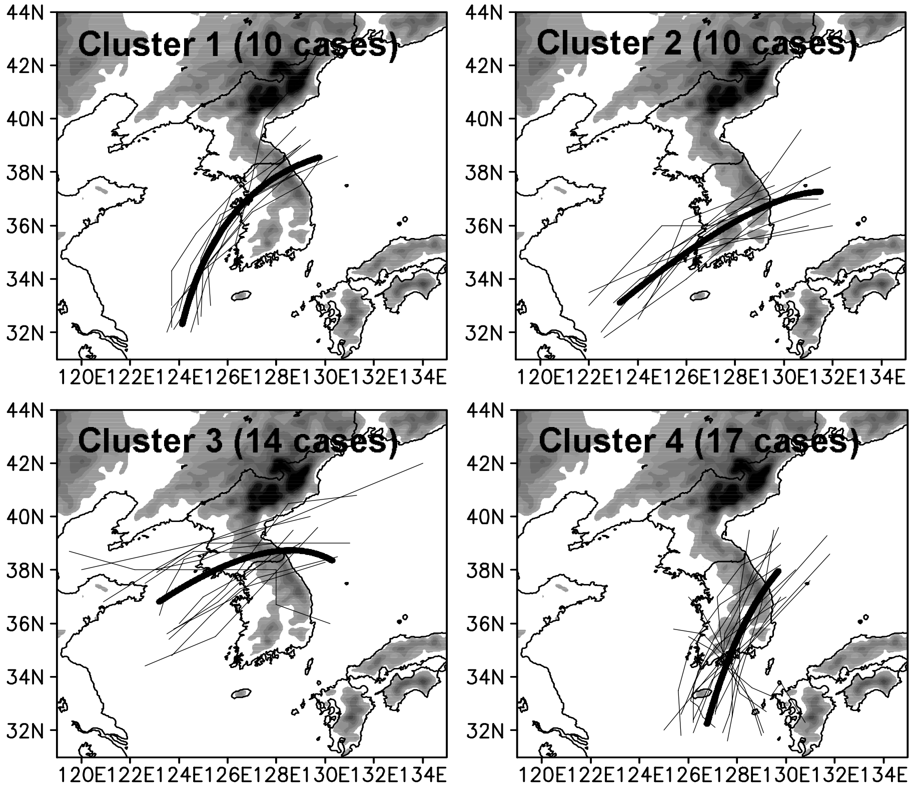

Fig. 3. As in Fig. 2 but for four clusters. Thick lines denote mean regression tracks. Shaded area indicates topography higher than 200 m above the sea level.

the TCs of C-14 land over the KP without passing through mainland China. In detail, most TCs of C-14 land with winds greater than tropical storm force (TS; MSW$\geqslant$17 m s^{-1}). While on the contrary, most TCs of C-23 land with winds less than tropical depression strength (TD; MSW<17 m s^{-1}). In addition after landfall, the TCs of C-14 still maintain a greater intensity than TSs. Most TCs of C-23 weaken to less than an extratropical cyclone (EC) strength.

The difference of the intensity change before landfall and after landfall is also larger in C-14 than C-23. That is, the stronger the TC intensity at landfall, the larger the decay rate of the TC. The decay rate of the central pressure and the MSW before landfall and after landfall is the largest in Cluster 4 (central pressure: +14.1 hPa, MSW: −15.1 kt) and the next in order, are Cluster 1, Cluster 2, and Cluster 3. This coincides with the results of Kaplan and DeMaria (1995, 2001) and Roy Bhowmik and Kalsi (2005), who noted that the TC decay rate is proportional to the TC landfall

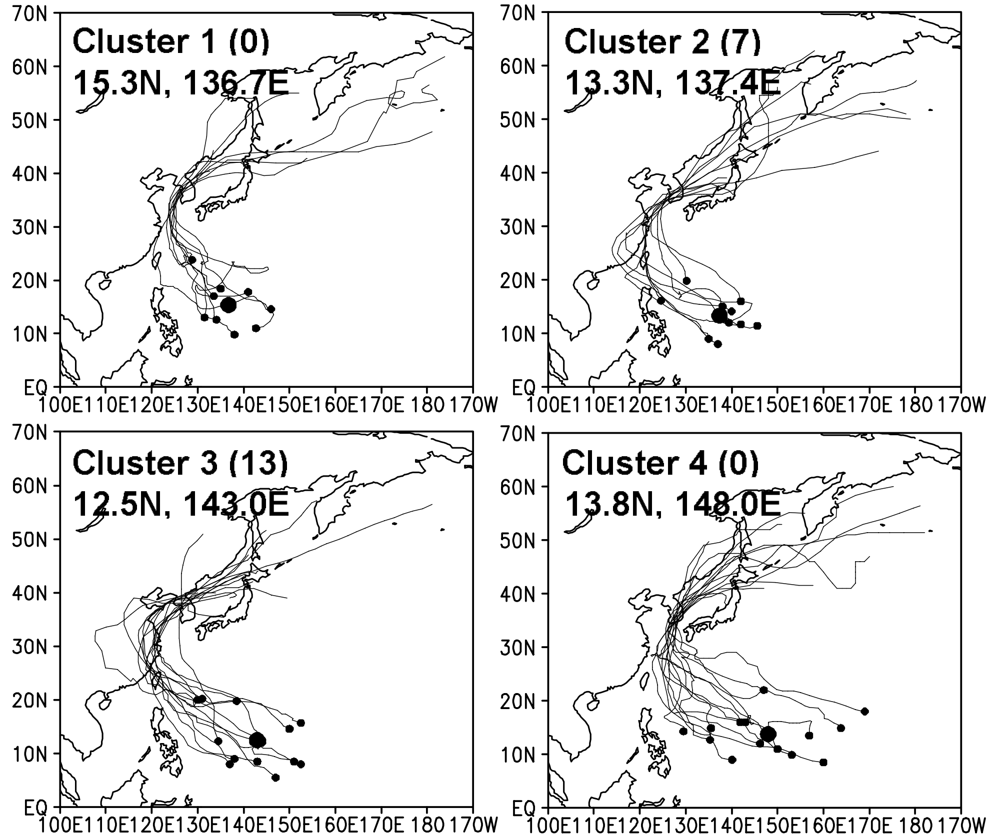

Fig. 4. As in Fig. 3 but for the full track. Small solid and big solid dots denote each TC genesis location and each cluster mean genesis location (latitude and longitude) of KP-landfall TCs, respectively. The numbers in the parentheses represent TC frequencies without passing through mainland China.

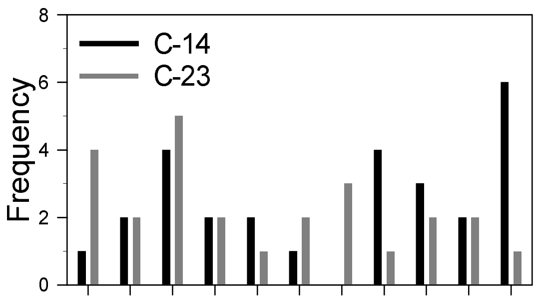

Fig. 5. 5-year variation of the landfalling frequency of C-14 and C-23 of KP-landfall TCs. The E and L characters mean "early" and "late", respectively. For examples, E50s (L50s) denotes early (late) 1950s.

intensity and the decay rate is highest immediately after landfall. Also, Powell et al. (1991) reported that the MSW abruptly decreases for 24 hours after a storm crosses the coastline, and after that, the MSW remains constant. In the case of the KP-landfall TC, the MSW also rapidly decreased for 24 hours after landfall. However, after that, the MSW tended to not remain constant but slowly decrease. This discrepancy with Powell et al. (1991) is because TCs after landfall in the Atlantic and the Indian Oceans continuously move over land, whereas TCs after passing over the KP, again move over the East Sea.

5.3 *Long-term variability of TC landfalling frequency*

As seen in the previous section, the landfalling tracks of KP-landfall TCs were classified into four clusters. However, along with the TCs passing through mainland China before landfall, four clusters can be re-grouped into two groups such as C-14 and C-23. In addition, the numbers of TCs belonging to C-14 and C-23 are impartially distributed as 26 and 25, respectively. Hereafter, the characteristics of the two groups (C-14 and C-23) are examined.

Figure 5 shows the five-year variation of TC landfalling frequency for the two groups. Although not many TCs landed on the KP in each five-year period, we can see a distinctive variation of TC landfalling frequency. In the early 1960s, C-14 and C-23 reached a second maximum and the highest peaks, respectively.

Table 1. Statistical characteristics on the change of TC intensity before and after landfall over the KP.

Cluster	TY No.	Before landfall (A)			After landfall (B)			B−A	
		CP	MSW	Grade	CP	MSW	Grade	CP	MSW
Cluster 1	5209	975	62	9	982	56	9	7	−6
	6015	980	58	9	980	58	9	0	0
	6209	985	52	9	988	49	9	3	−3
	7120	985	52	9	998	36	9	13	−16
	7310	985	52	9	990	46	9	5	−6
	8613	965	71	TY	976	61	EC	11	−10
	0012	965	71	TY	990	46	TS	25	−25
	0205	980	58	TS	988	49	EC	8	−9
	0407	986	51	EC	992	44	EC	6	−7
	Average	980.1	57.0		986.8	49.9		8.7	−9.1
Cluster 2	5114	998	36	EC	1000	33	EC	2	−3
	5909	998	36	EC	1000	33	EC	2	−3
	6104	994	42	EC	988	49	EC	−6	7
	6205	996	39	9	1004	25	9	8	−14
	7615	1004	25	TD	1004	25	EC	0	0
	7910	965	71	TY	975	62	TS	10	−9
	8007	996	39	EC	996	39	EC	0	0
	8120	1004	25	EC	1004	25	EC	0	0
	8403	1004	25	EC	1008	15	EC	4	4
	9219	994	42	TS	994	42	EC	0	0
	Average	995.3	38.0		997.3	34.8		2.0	−3.0
Cluster 3	5211	988	49	9	992	44	9	4	−5
	5304	990	46	9	998	36	EC	8	−10
	5309	1008	15	EC	1008	15	EC	0	0
	5905	990	46	9	994	42	EC	4	−4
	6107	988	49	EC	988	49	EC	0	0
	6210	988	49	9	984	53	9	−4	4
	6217	1002	29	EC	996	39	EC	−6	10
	6513	996	39	EC	996	39	EC	0	0
	6518	1005	22	TD	1003	27	EC	−2	5
	7128	996	39	EC	1002	29	EC	6	−10
	8708	998	36	EC	998	36	EC	0	0
	9015	998	36	EC	998	36	EC	0	0
	9507	990	46	EC	996	39	EC	6	−7
	Average	995.2	38.5		996.4	37.2		1.2	−1.3
Cluster 4	5707	965	71	9	975	62	9	10	−9
	6110	990	46	9	1000	33	EC	10	−13
	6304	975	62	9	990	46	EC	15	−16
	6615	994	42	TD	996	39	TD	2	−3
	6617	988	49	9	1002	29	TD	14	−20
	7811	985	52	TS	1005	22	EC	20	−30
	8508	990	46	TS	994	42	TS	4	−4
	8705	970	67	TY	980	58	STS	10	−9
	8911	990	46	TS	1000	33	TD	10	−13
	9112	980	58	STS	992	44	TS	12	−14
	9411	994	42	TS	996	39	TS	2	−3
	9429	980	58	STS	988	49	EC	8	−9
	9503	960	75	TY	994	42	TS	34	−33
	9711	985	52	STS	990	46	TS	5	−6
	0014	970	67	STS	982	56	EC	12	−11
	0215	960	75	TY	996	39	TD	36	−36
	0314	935	95	TY	970	67	STS	35	−28
	Average	974.8	61.2		990.1	45		14.1	−15.1
Total average		986.4	48.7		992.7	41.7		6.3	−7.0

Note: "Marge (5111)" of Cluster 1 and "OLGA (9907)" of Cluster 3 disappeared in China. TD: tropical depression; TY: typhoon; TS: tropical storm; EC: extratropical cyclone; STS: severe tropical storm; 9: Grade⩾TS.

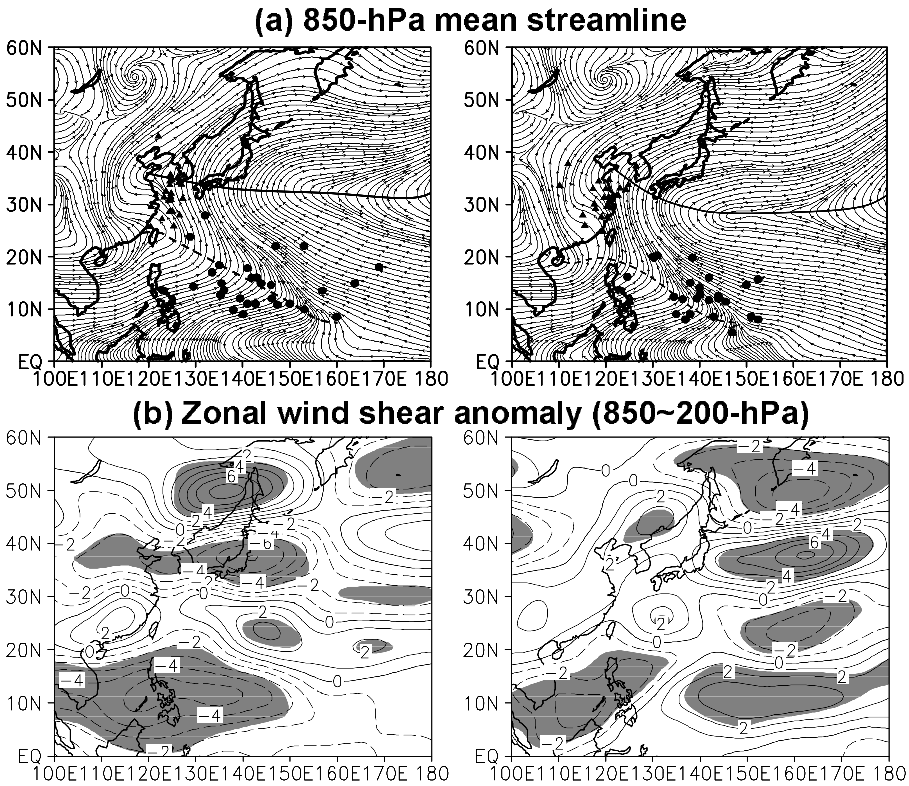

Fig. 6. (a) 850-hPa mean streamlines and (b) zonal wind shear anomalies (m s^{-1}) between 200-hPa and 850-hPa for C-14 (left panel) and C-23 (right panel). In 850-hPa mean streamline, solid and dashed lined denote the ridge axes of the western North Pacific high (WNPH) and the monsoon trough, respectively. Solid black dots and triangles denote the geneses and recurving locations, respectively. In the zonal wind anomalies, the areas exceeding the 95% confidence level are shaded.

For a period from the 1970s to the early 1980s, C-23 again increased, but C-14 constantly decreased. In particular, the TCs of C-14 did not land once during the early 1980s. Generally, C-23, until the early 1980s, had a higher landfalling frequency than C-14. However, this landfalling frequency between the two groups has abruptly reversed itself since the late 1980s. That is, the landfalling frequency of C-14 from the late 1980s, not only began to rapidly increase but also to overtake that of C-23. In particular, the landfalling frequency of C-14 in the early 2000s sets the best record for 54 years. This result is consistent with a report that the top 10% of the property damage amounts by TCs in the KP have mostly occurred since the late 1980s (Korea Meteorological Administration, 2002). Therefore, we know that the landfalling frequency of strong TCs that do not pass through mainland China has tended to increase in recent years.

5.4 *Atmospheric circulation*

Shown in Fig. 6a are the 850-hPa streamlines averaged for the lifetimes of KP-landfall TCs and the genesis locations for C-14 (left panel) and C-23 (right panel). The ridge axis of the western North Pacific high (WNPH; solid lines) of C-14 is nearly parallel to the latitude line of 35°N, but that of C-23 bends equatorward. These ridge axis characteristics can have an effect on the direction of air flow toward the KP and the recurving location of TCs. That is, in C-14, the main flow in the KP is southerly and consequently most TCs recurve over the ECS (solid black triangle). On the other hand, a southwesterly wind prevails, in C-23, and therefore most TCs recurve inland of China.

In the two groups, there is a common feature that a large number of TCs form around the monsoon trough (solid black dots). However, the difference between the two groups is in the location and extension of the monsoon trough. That is, the monsoon trough of C-14 has a longitudinal range from near Taiwan to about 160°E (some TCs occur around 170°E), but the monsoon trough of C-23 has a shorter longitudinal range from near Hainan Island to 150°E. Therefore, we know that the more southward located the monsoon trough is, such as in C-23, an equatorward bending of the ridge axis of the WNPH should be expected.

Figure 6b shows the zonal wind shear anomalies between 200-hPa and 850-hPa for C-14 (left panel) and C-23 (right panel). In the case of C-14, weak shear (negative value) prevails in areas south of 15°N and between 30°N and 40°N. On the contrary, the same areas in C-23 have strong shear (positive value). As stated above, it can be one of the reasons why the TC intensity of C-14 at landfall is stronger than that of C-23.

6. Summary and conclusions

Cluster analysis on landfalling tracks has been performed for 51 tropical cyclones (TCs) that landed on the Korean Peninsula (KP) for the period of 1951–2004.

The technique used to classify landfalling tracks is the fuzzy clustering method (FCM), and the silhouette coefficient yielded from this method suggested three clusters as an optimal cluster number. From the landfalling track analysis of each of the three clusters, the number of objects (TCs) of one cluster was more than two times than that of each object. Meanwhile, in the case of the four clusters, an object number of each cluster was adequately distributed. Therefore, in this study, the landfalling tracks of KP-landfall TC were optimally classified into four clusters and the characteristics of each pattern are as follows:

Cluster 1: moving northward from the south toward the KP and then landing on the west coast of the KP,

Cluster 2: moving from the west toward the KP and then landing in the middle and northern regions of the west coast of the KP,

Cluster 3: moving from the west toward the KP and then landing in the southern region of the west coast of the KP, and

Cluster 4: moving northward from the south toward the KP and then landing on the south coast of the KP.

Then, statistics and the atmospheric circulation of each cluster were examined. In the full track of TCs for four clusters, Cluster 2 and Cluster 3 (C-23) tended to pass over China before making landfall. Cluster 1 and Cluster 4 (C-14), however, tended to move northward from the East China Sea (ECS) without passing over China. This was related to synoptic characteristics such that the axis of the western North Pacific high (WNPH) of C-23. The axis was bent more southward than that of C-14, and simultaneously the monsoon trough of C-23 was located more southward. This reflected the advantage of the geographical similarity of the TC passage and was because the TC landfalling intensity of C-14 was much stronger than that of C-23. In particular, the stronger the TC intensity at landfall, the more rapid the decay rate of the TC after landfall, which coincided with the results of previous studies.

From the analysis of the long-term variability of KP-landfall TCs, the TC landfalling frequency of C-14 has increased since the late 1980s, and in the early 2000s, the frequency reached its maximum peak for the 54-year analysis period. This indicated that the TCs that have made landfall on the KP in recent years have tended to be stronger in intensity.

Acknowledgements. This research was carried out as a part of "A Study on Strategy Development of Meteorological Technology" supported by the National Institute of Meteorological Research (NIMR) in the Korea Meteorological Administration.

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