Hindawi Publishing Corporation
Advances in Meteorology
Volume 2016, Article ID 5051476, 15 pages
http://dx.doi.org/10.1155/2016/5051476

Research Article

Climatological Features of Korea-Landfalling Tropical Cyclones

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Received 6 July 2015; Accepted 24 August 2015

Academic Editor: Xiaofeng Li

The present study analyzed the interdecadal variation by applying the statistical change-point analysis to the frequency of the tropical cyclone (TC) that landed in the Korean Peninsula (KP) for the recent 54 years (1951 to 2004) and performed cluster classification of the Korea-landfall TC tracks using a Fuzzy Clustering Method (FCM). First, in the interdecadal variation analysis, frequency of TC that landed in the KP was largely categorized into three periods: high frequency period from 1951 to 1965, low frequency period from 1966 to 1985, and high frequency period from 1986 to 2004. The cluster analysis result of the Korea-landfall TC tracks produced the optimum number of clusters as four. In more detail, Cluster A refers to a pattern of landing in the southern coast in the KP starting from East China Sea followed by heading north while Cluster B refers to a pattern of landing in the west coast of the Korean Peninsula, also starting from East China Sea followed by heading north. Cluster C refers to a pattern of landing in the southern region of the west coast in the KP moving from mainland China while Cluster D refers to a pattern of landing in the mid-north region of the west coast in the Korean Peninsula, also moving from mainland China.

1. Introduction

Although many studies on tropical cyclone (TC) that affected the Korean Peninsula have been conducted [1, 2], few studies have been done on TC that landed in the Korean Peninsula. As a study on TC that landed in the Korean Peninsula, Choi and Kim [3] analyzed interannual and interdecadal variation of frequency of TC, track of TC, and intensity of TC, which landed in the Korean Peninsula for recent 54 years (1951 to 2004), and conducted analysis of large-scale atmospheric circulations with regard to causes of variation of the Korean Peninsula landed TC activity. Choi et al. [4] also performed cluster analysis on TCs that landed in the Korean Peninsula for recent 54 years using a Fuzzy Clustering Method and analyzed large-scale atmospheric circulations of the TC track characteristics for each cluster.

Furthermore, Park and Moon [5] analyzed TCs that affected the Korean Peninsula, starting from the tropical and subtropical western North Pacific, climatologically, and studied the characteristics of rainfall due to TC in relation to the track or kinetic energy. Lee et al. [6] analyzed the central pressure and the maximum sustained wind speed statistically about all the TCs that approached mid-latitude regions in East Asia and affected the Korean Peninsula for 30 years from 1960 to 1989 thereby classifying the typhoons according to their movement characteristic and presenting the large-atmospheric circulations characteristics of the representative case for each category. Kim et al. [7] analyzed the long-term change of TCs using data obtained from 1951 to 2001, proposing the location and intensity of the subtropical western North Pacific high (SWNPH) among the large-scale atmospheric circulations as the most influential factors that affected the course of TC, and studied how the variation of the large-scale atmospheric circulations influenced the TC track that affected the Korean Peninsula. As other studies on TC in relation to its damage, Yoo and Jung [8] presented the damage caused by typhoon "Saomai" and "Prapiroon," which affected the Korean Peninsula in 2000, and compared them with other typhoons that had similar tracks in the past. Furthermore, Park et al. [1] categorized the TC track that affected the Korean Peninsula into 7 types and showed that typhoons that affected Korea via China and via Japan accounted for 24.6% and 22.9%, respectively. That is, they claimed that about 50% of TCs that affected the Korean Peninsula approached Korea via the neighboring countries.

TC is one of the major weather phenomena that incurs human casualties and property damage as it passes through the Korean Peninsula and the surrounding regions mainly in June to September, and intensity of typhoon and hurricane has been intensified more and more [9, 10]. Weather phenomena that incurred the most damage in Korea for the last 10 years (1998 to 2007) are heavy rainfall and TC, which account for 97% of entire human casualties and 89% of property damage. In particular, property damage and human casualties caused by TCs that landed in Korea were 53% and 40% [11]. A study on current status analysis of meteorological disasters that occurred in Korea from 1987 to 2003 [12] showed that 2002 had the largest damage due to Typhoon Rusa (0215), about 6.1153 trillion Korean Won (KRW), followed by 2003 of 4.38321 trillion KRW due to Typhoon Maemi (0314). In addition, Kwon et al. [13] presented that the damage caused by typhoon "Rusa" accounted for 0.9% of GDP in Korea, which was considerably high compared to the recent economic growth rate. As described above, TCs that landed in Korea caused much damage and incurred economic loss greatly so that many studies on TCs have been conducted. Therefore, the present study also examines the characteristics of the Korea-landfall TC activity in order to reduce property damage and human casualties caused by the TCs that landed in the Korean Peninsula every year.

This paper is organized as follows. In Section 2, data and analysis method are introduced. In Section 3, interannual and interdecadal variation of the Korea-landfall TC activity are analyzed. In Section 4, cluster analysis is performed with the Korea-landfall TC track and analysis of the TC activity on each classified cluster is conducted. Finally, in Section 5, conclusion is presented.

2. Data and Methods

2.1. Data. The TC data in this study was obtained from the best-track of TC provided by Regional Specialized Meteorological Center- (RSMC-) Tokyo Typhoon Center. This data consists of TC name, latitude and longitude location of TC, TC central pressure, and TC maximum sustained wind speed (MSWS), which were observed in every 6 hours for 54 years from 1951 to 2004. TC is generally classified into four classes by the criteria of MSWS: Tropical Depression (TD: MSWS < 17 m s^{-1}), Tropical Storm (TS: 17 m s^{-1} ≤ MSSWS ≤ 24 m s^{-1}), Severe Tropical Storm (STS: 25 m s^{-1} ≤ MSSWS ≤ 32 m s^{-1}), and Typhoon (TY: MSSWS ≥ 33 m s^{-1}). Along with the four classes of TC above, this study included extratropical cyclone which was transformed from TC for analysis. This was because such extratropical cyclone also incurred great damage on property and human in the mid-latitude regions in East Asia.

Moreover, this study also used the variables of geopotential height (gpm) data from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis [14, 15]. This NCEP-NCAR reanalysis data consisted of spatial resolution such as latitude and longitude 2.5° × 2.5° and 17 vertical layers.

2.2. Methods. In order to detect the significant climate regime shift of the Korea-landfall TC frequency, this study performed statistical change-point analysis used by Ho et al. [16]. This statistical method is known to be effective in finding the significant climate regime shift objectively from time series data such as TC frequency. More information about this statistical method can be found in Elsner et al. [17] and Chu [18].

As one of the indexes applied to the statistical change-point analysis, Accumulated Cyclone Energy (ACE) was calculated [19]:

$$\text{Accumulated Cyclone Energy (ACE)} = \sum \frac{V^2}{10^4}. \quad (1)$$

The ACE is calculated by summing the squares of the MSWS (V) of greater than every TS at 6-hour intervals on all the KP landfalling TCs for each corresponding decade. The numbers are usually divided by 10,000 to make them more manageable. The unit of ACE is 10^4 kt^2 and for use as an index, the unit is assumed.

This study used the Student's t-test to determine significance [20]. In case that two independent time series follow a t distribution and their time averages are denoted as $\overline{x_1}$ and $\overline{x_2}$, respectively, the test statistic is given by

$$t = \frac{\overline{x_1} - \overline{x_2}}{\left(s_1^2/n_1 + s_2^2/n_2\right)^{1/2}}, \quad (2)$$

where S_1 and S_2 are standard deviations 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 α (×100)% significance level.

In this study, TC life time was defined as a stage from formation to decay observed in every 6 hours in the best-track data from RSMC-Tokyo Typhoon Center. TC recurving location was defined as a location where direction of TC was changed from northwest movement to northeast movement.

3. Interannual and Interdecadal Variations

3.1. Change-Point Analysis. Figure 1 shows total Korea-landfall TC frequency (TDET) and Korea-landfall TC frequency (TSTY) having intensity above TS, Accumulated Cyclone Energy (ACE) for TCs having intensity above TS, and Total Moving Distance (TMD) during the TC life. Overall, all the four indexes showed high values until the mid-1960s while showing low values from the late 1960s till the mid-1980s and high values again after the late 1980s. In addition to tropical cyclones, it is also of interest to investigate whether there is any change-point in the SST records or

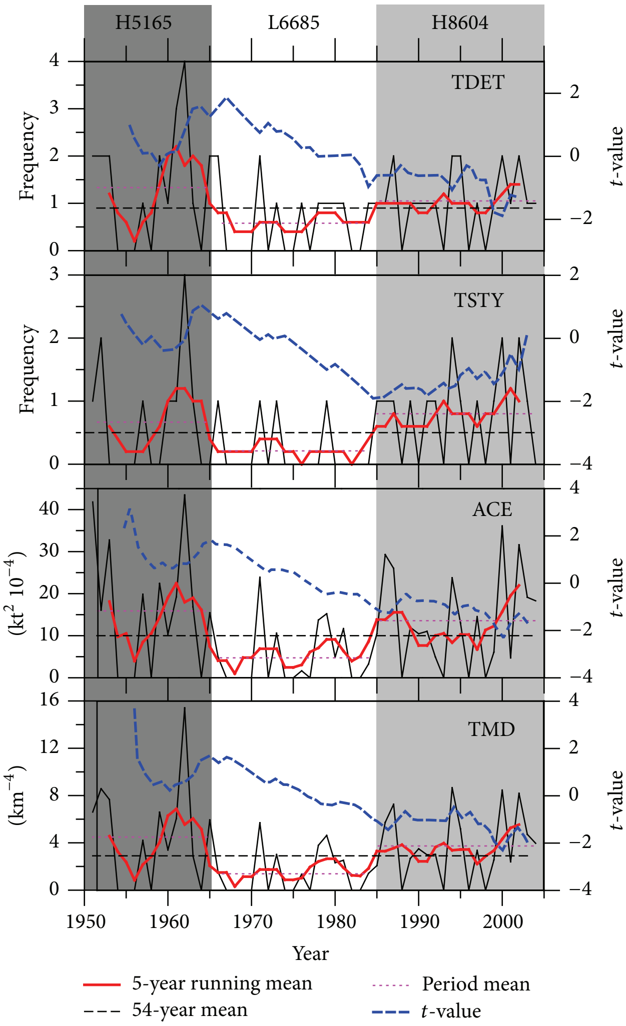


FIGURE 1: Decadal variation related to a Korea-landfall TC activity. Indices in order from an upper-most side are the total TC frequency (F-TDEC), the TC frequency with intensity greater than tropical storm (TS) (F-TSTY), Accumulated Cyclone Energy (ACE) of TC with intensity greater than TS, and total moving distance (TMD) for the TC lifetime, respectively. The periods of H5165, L6685, and H8604 indicate the first high frequency period for 1951–1965, the low frequency period for 1966–1985, and the second high frequency period for 1986–2004 defined by t-value (thick blue line) of the statistical change-point analysis. The thick red, black dashed, and red dotted lines denote 5-year running mean, 54-year mean, and each period mean, respectively.

typhoon passage frequency series. Because these variables do not follow a Poisson distribution, we use a different method to detect climate regime shifts in the temperature or passage frequency series: using a log-linear regression model in which a step function is expressed as an independent variable. If the estimated slope is at least twice as large as its standard error, one may reject the null hypothesis (i.e., the slope being zero) at the 5% significance level. Therefore, this study conducted statistical change-point analysis in order to determine whether climate regime shift existed in the four indexes for the recent 54 years. The analysis results showed that the climate regime shift existed in 1965 and 1985 as shown in the figure. It meant that, in the four variables, high values existed from 1951 to 1965, low values from 1966 to 1985, and high values again from 1986 to 2004. Therefore, in this study, interdecadal variation of the Korea-landfall TC frequency was categorized into high frequency of 1951–1965 (hereafter referred to as H5165), low frequency period of 1966–1985 (hereafter referred to as L6685), and high frequency period of 1986–2004 (hereafter referred to as H8604).

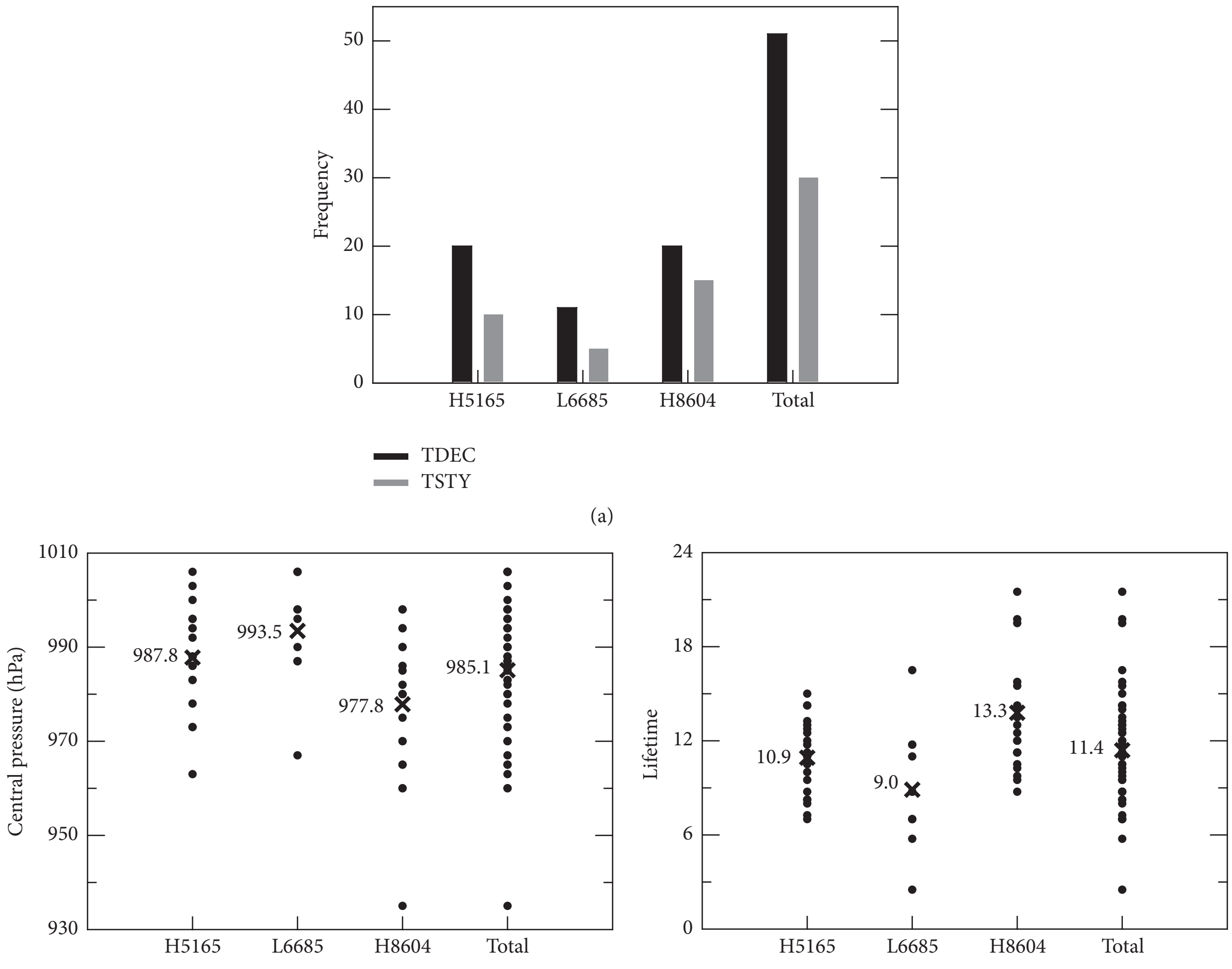
3.2. TC Intensity.

TC frequency and TC intensity for the three periods defined above were examined (see Figure 2). First, the number of the total Korea-landfall TC frequencies during the recent 54 years was 51, and 30 TCs, which accounted for 60% of them, had landed in Korea with intensity above TS (see Figure 2(a)). The total Korea-landfall TC frequencies for the three periods of H5165, L6685, and H8604 were 20 TCs, 11 TCs, and 20 TCs, showing that total Korea-landfall TC frequency in the high frequency period was almost twice the number in the low frequency period. However, TC frequency that landed in Korea with more than TS intensity in the two high frequency periods showed that H5165 had 10 TCs while H8604 had 15 TCs, indicating that more intensified TCs landed in Korea recently. In the L6685 period, only 4 TCs that landed in Korea had more than TS intensity. Regarding TC intensity, when TC landed in Korea, the climatological mean of the TC central pressure was analyzed as 985.1 hPa (see Figure 2(b)). The averages of TC central pressure in the three periods of H5165, L6685, and H8604 were 987.8 hPa, 993.5 hPa, and 977.8 hPa, indicating that recent landed TCs had more intensity. Regarding TC lifetime, the H8604 period had the longest life time as 13.3 days (see Figure 2(c)).

This high frequency of TC with strong intensity which recently landed in the Korean Peninsula can be found in 5-year variation of the case where TCs with TD intensity landed in Korea and the case where TCs with above TS intensity landed in Korea (see Figure 3). Frequency of TC with TD intensity that landed in Korea decreased gradually during the recent 54 years whereas frequency of TC with strong intensity above TS that landed in Korea increased rapidly since the late 1980s.

3.3. TC Track.

The Korea-landfalling TC track for the three periods was analyzed (see Figure 4). During the H5165 period, TCs landed mainly in the mid-north region in the west coast, while, during the L6685 period, TCs landed mainly in the southern region of the west coast. During the H8604 period, TCs landed in the southern region of the west coast and the south coast mainly. That is, TC's landfalling showed a pattern that landfalling location moved from the west sea to the south sea more and more in recent activities. Therefore, this study analyzed the regression mean track for the three periods to determine the average movement during the three periods (thick solid line). As shown in the figure, during H5165 period, TC landed in the central region of the west coast, during the L6685 period, the southern region of the west coast, and during the H8604 period, the



(a)

(b)

(c)

Figure 2: The (a) frequency, (b) central pressure at landfall, and (c) lifetime of the Korea-landfall TC in each period. × marks in central pressure and lifetime denote averages in each period.

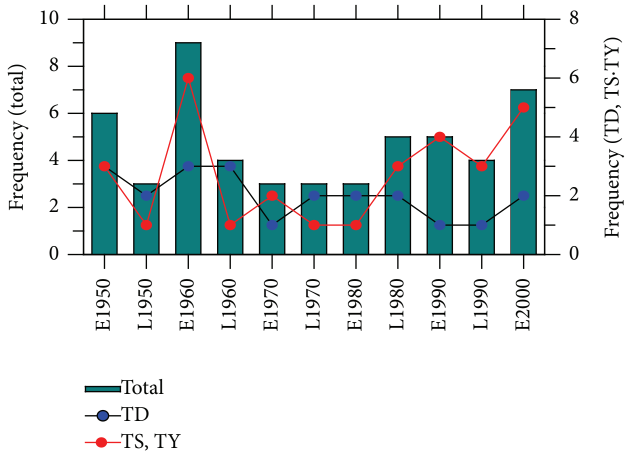
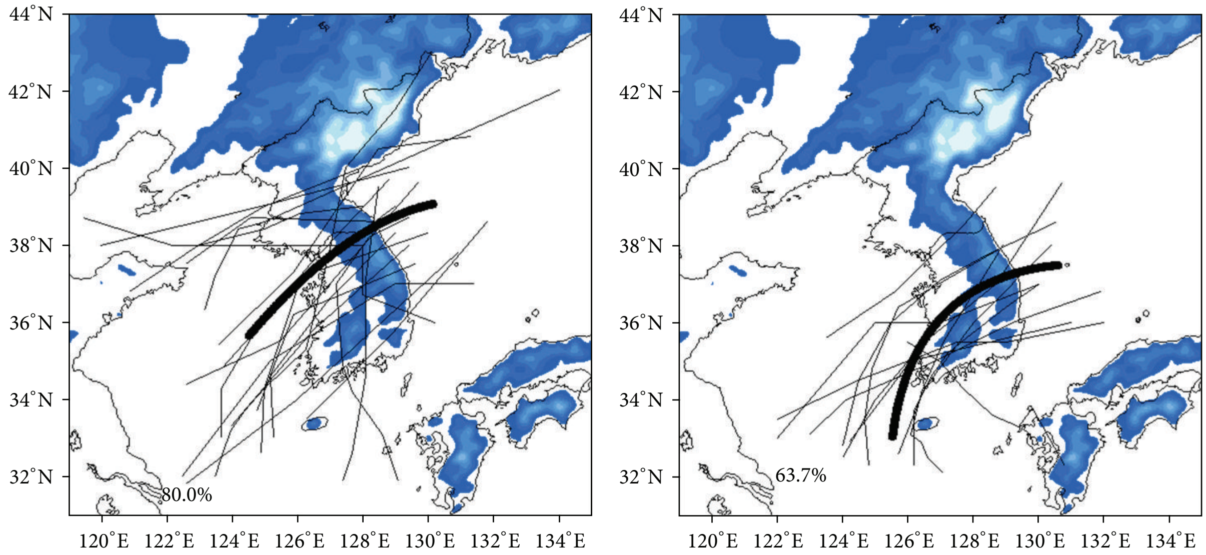
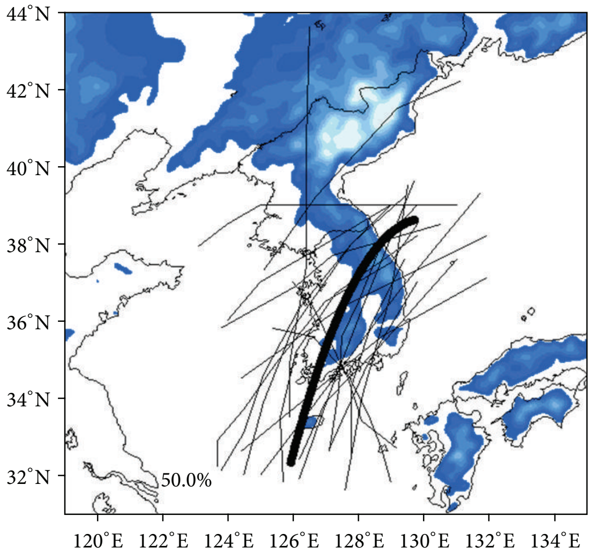


Figure 3: 5-year variation of the landfall frequency of Korea-landfall TCs. The bar and blue and red lines denote a 5-year total frequency, a TD and extratropically transitioned cyclone frequency, and a TS and TY frequency, respectively. Capital E and L denote "early" and "late," respectively.



(a) H5165 (b) L6685



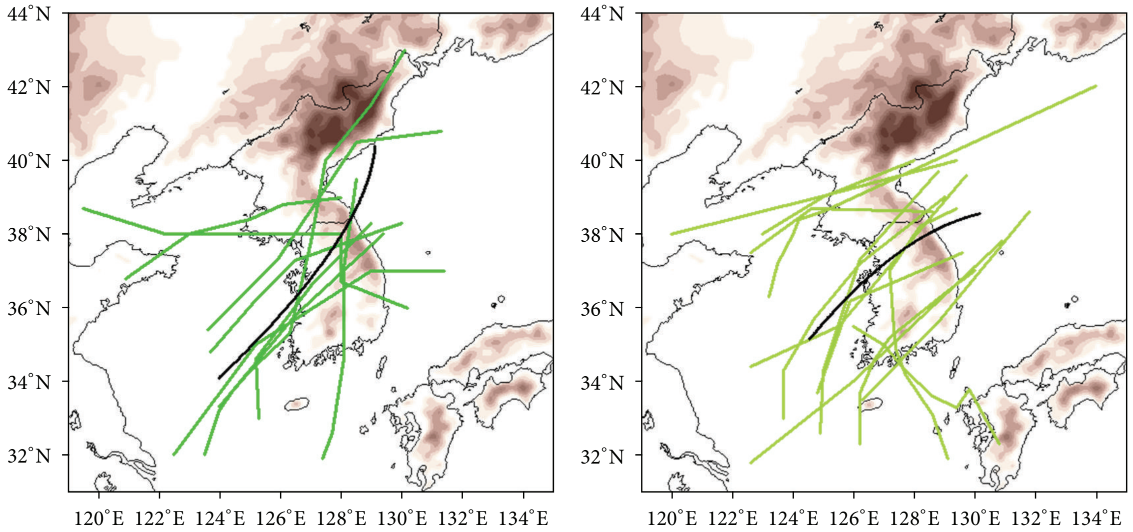
(c) H8604

Figure 4: Landfalling (left) of a Korea-landfall TC for the periods of (a) H5165, (b) L6685, and (c) H8604. The thick lines denote the mean regression tracks and the number in the lower-left corner denotes the ratio of the landfalling TC frequency at the west coast of Korea to the total TC frequency in each period. Shaded areas indicate topography higher than 200 m.

western region of the south coast mainly. Therefore, the Korea-landfall TC track has been changed to move easterly more for 54 years.

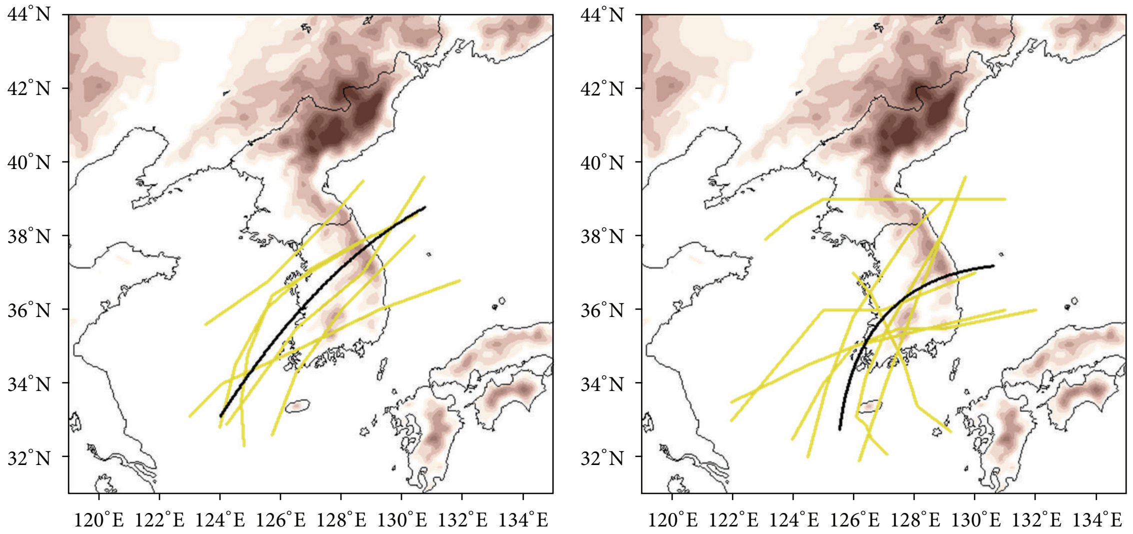
This trend of change in the Korea-landfall TC track was also found in 10-year variation (see Figure 5). The mean regression track analyzed in every 10 years showed that the Korea-landfall location was moved easterly more and more in recent years.

This study also examined the TC full-track variation for the three periods (see Figure 6). The important point of this analysis was to find out the change in TCs frequency that passed through mainland China before they landed in Korea. During the H5165 period, 12 TCs out of 20 TCs (60.0%) had passed through the inland of mainland China before they landed in Korea, while, during the L6685 period, 4 TCs out of 11 TCs (36.4%) and, during the H8604 period, only 6 TCs out of 20 TCs (30.0%) had passed the heart of mainland China, indicating that more and more TCs had not passed through the heart of mainland China but via the east coast of China before they landed in the Korean Peninsula in recent years. Therefore, the reason for the strong intensity of TC that landed in Korea recently was due to obtaining sufficient energy from the sea as they moved over the sea rather than via mainland China prior to Korea-landfall.



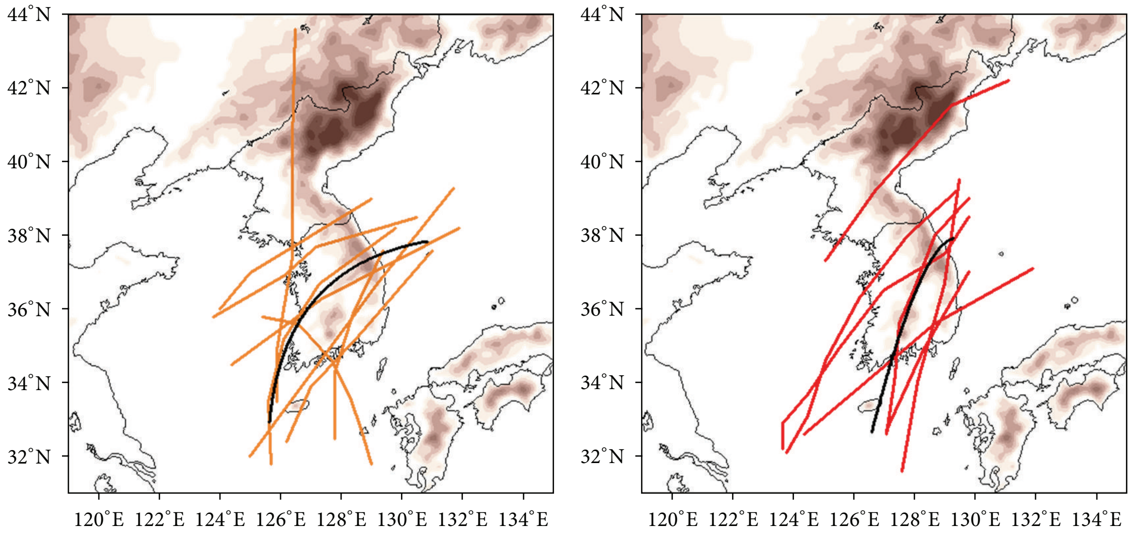
(a) 1950s

(b) 1960s



(c) 1970s

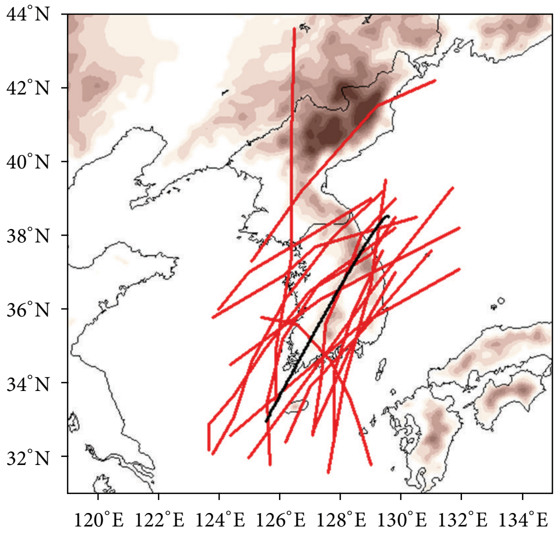
(d) 1980s



(e) 1990s

(f) 2000s

Figure 5: Continued.



(g) 1990s~2000s

Figure 5: Decadal variation of the landfalling track of Korea-landfall TCs. Thick black lines denote regression mean tracks. Shaded areas indicate topography higher than 200 m.

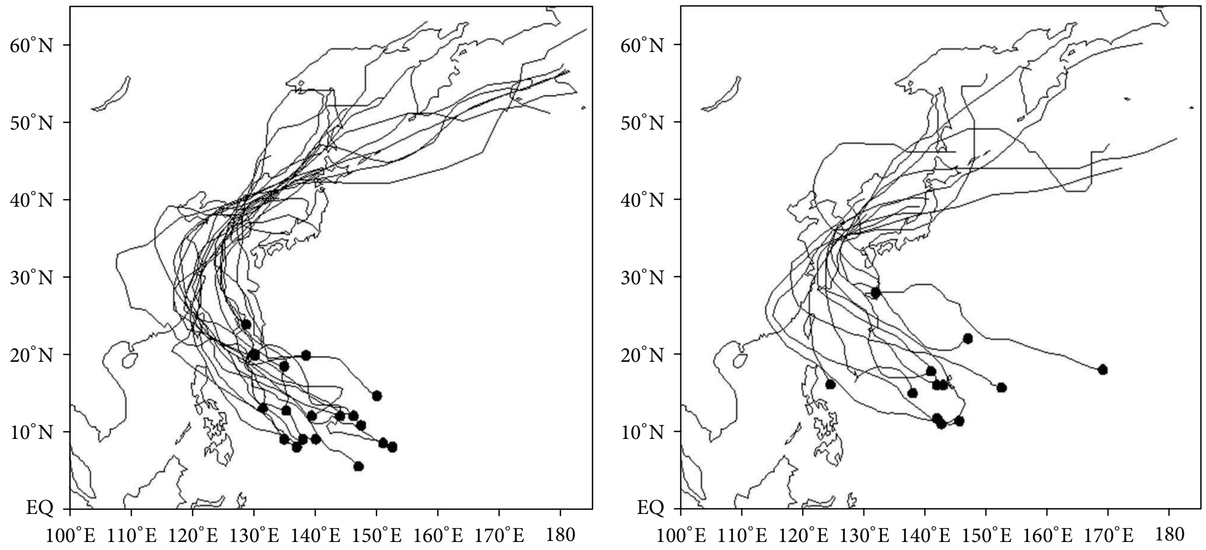
Such variation trend of the Korea-landfall TC full-track can be seen in the 10-year variation (see Figure 7). Prior to the 1980s, high frequency of TCs via mainland China before landing in Korea was found but, since the 1990s, this was decreased rapidly.

3.4. Large-Scale Atmospheric Condition. In order to determine the cause of the Korea-landfall TC intensity and TC track variations during the three periods, averaged 500 hPa geopotential height over the three periods was examined (see Figure 8). The ridge of the SWNPH (brown solid line) was developed westerly up to mainland China during the H5165 and L6685 periods whereas it was retreated easterly up to the southwest sea in Japan. Accordingly, the Korea-landfall TC track displayed a characteristic of moving easterly in recent years and frequency of TCs via mainland China before Korea-landfall decreased more and more in recent years. Such variation trend of the Korea-landfall TC full-track influenced the intensity of TCs upon Korea-landfall. Moreover, development of the SWNPH in the east-west direction also influenced the TC recurving location so that recurving occurred largely in mainland China during the H5165 and L6685 periods whereas recurving occurred mainly in East China Sea during the H8604 period (dots in Figure 8).

4. Classification of TC Tracks

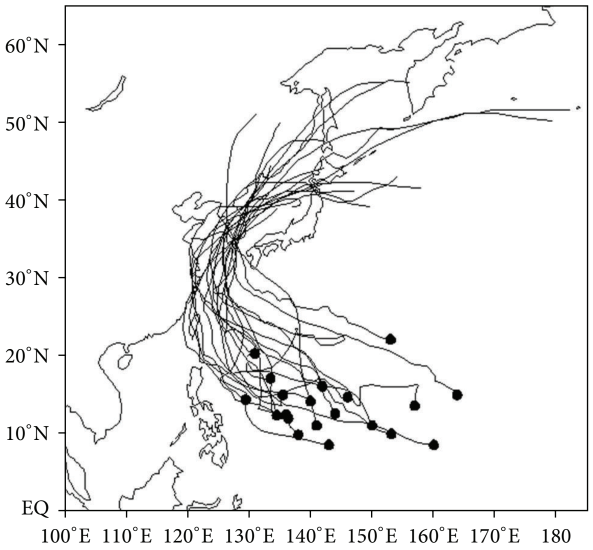
4.1. Fuzzy Clustering. This study introduced a Fuzzy Clustering Method (FCM) to conduct cluster analysis for Korea-landfall TC tracks. This analysis method is different compared to the Classical Clustering Method (CCM). For example, assuming that TC genesis location is classified into four clusters as shown in Figure 9 and object 1 (TC 1) is located between A and C groups, cluster analysis may generate errors due to object 1 which is ambiguous for cluster classification in CCM. On the contrary, the FCM can show the probability of object 1 on group that object 1 may belong so that it helps an analyzer to decide whether object 1 is removed from analysis or included to other groups. More information regarding the FCM can be found in studies of Kim et al. [21] and Kim et al. [22]. 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 Korea-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 between 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 [23]. 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.

4.2. Patterns of TC Tracks. By performing the FCM, silhouette coefficient is produced, which can determine the optimal number of clusters (see Figure 10). The higher the silhouette coefficient is, the more optimal the number of clusters is. As shown in the figure, the result indicated three clusters as the optimal cluster number but this study selected four clusters as the optimal cluster number due to the following reasons. Figure 11 shows the Korea-landfall TC tracks when dividing the cluster into three. Overall, the cluster seemed well classified according to the landfall location. In case of Cluster 1, TCs showed a pattern of moving northerly from East China Sea to landing in the south and west sea in the



(a) H5165 (60.0%)

(b) L6685 (36.4%)

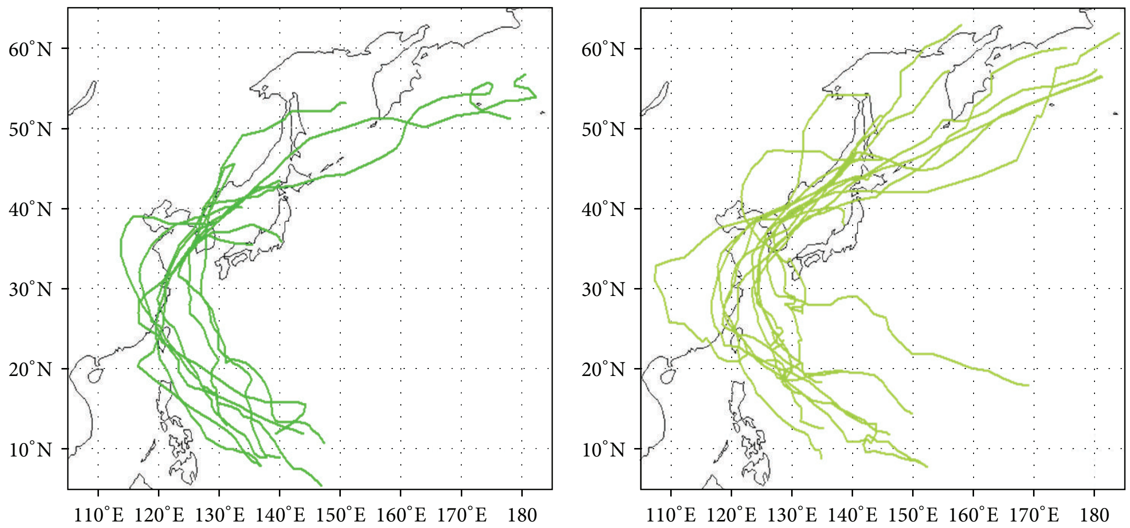


(c) H8604 (30.0%)

Figure 6: Full-tracks of a Korea-landfall TC for the periods of (a) H5165, (b) L6685, and (c) H8604. Dots are the genesis location of the Korea-landfall TC and the number in the upper-left corner denotes the ratio of a TC passage frequency over mainland China to the total TC frequency in each period.

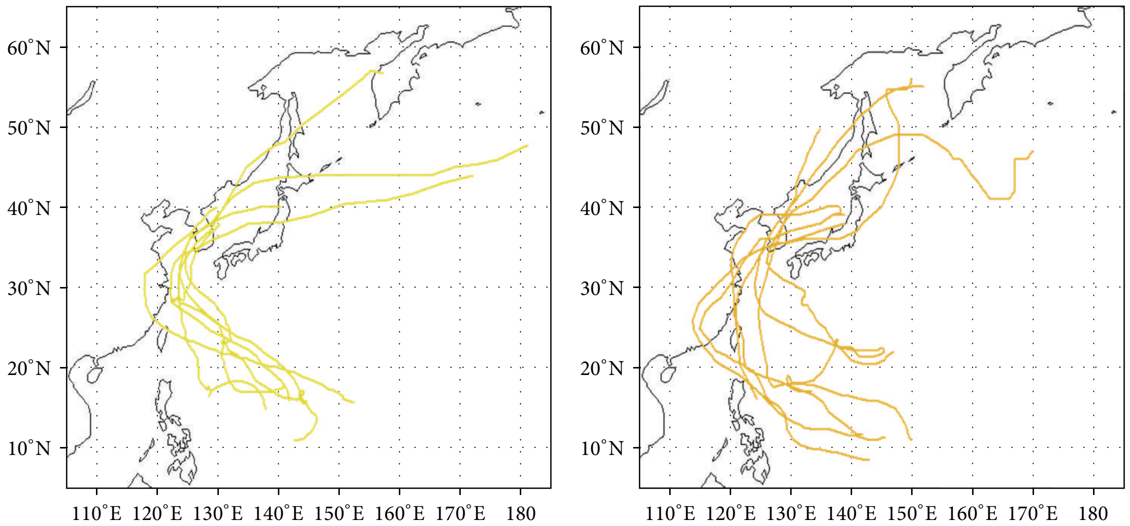
Korean Peninsula. In case of Cluster 2, TCs showed a pattern of moving from mainland China to landing in the southern region of the west coast in the Korean Peninsula. In case of Cluster 3, TCs also showed a strong tendency to moving from mainland China to landing in the mid-north region of the west coast in the Korean Peninsula. However, the result of cluster analysis revealed that Cluster 1 included too many objects (TCs) compared to Cluster 2 and Cluster 3 clearly.

Therefore, this study classified the Korea-landfall TC tracks using four clusters (see Figure 12). As a result, Cluster 1 in Figure 11 was named as Cluster A and Cluster B while Cluster 2 and Cluster 3 changed their name to Cluster C and Cluster D, respectively. That is, Cluster 1 was divided into two clusters (Cluster A and Cluster B). Accordingly, the number of objects (TCs) in each cluster was now distributed somewhat evenly. Thus, although the silhouette coefficient proposed three clusters as the optimal cluster number, this study selected four clusters as the optimal number of clusters due to the above reason. The study of the characteristics of TC track in each cluster showed that Cluster A showed a pattern of moving northerly from East China Sea to landing in the south coast of the Korean Peninsula (see Figure 12(a)) while Cluster B also showed a pattern of moving northerly from East China Sea to landing in the west coast in the Korean Peninsula (see Figure 12(b)). Cluster C showed a pattern of moving from mainland China to landing in the southern region of the west coast in the Korean Peninsula (see Figure 12(c)), while Cluster D also showed a pattern



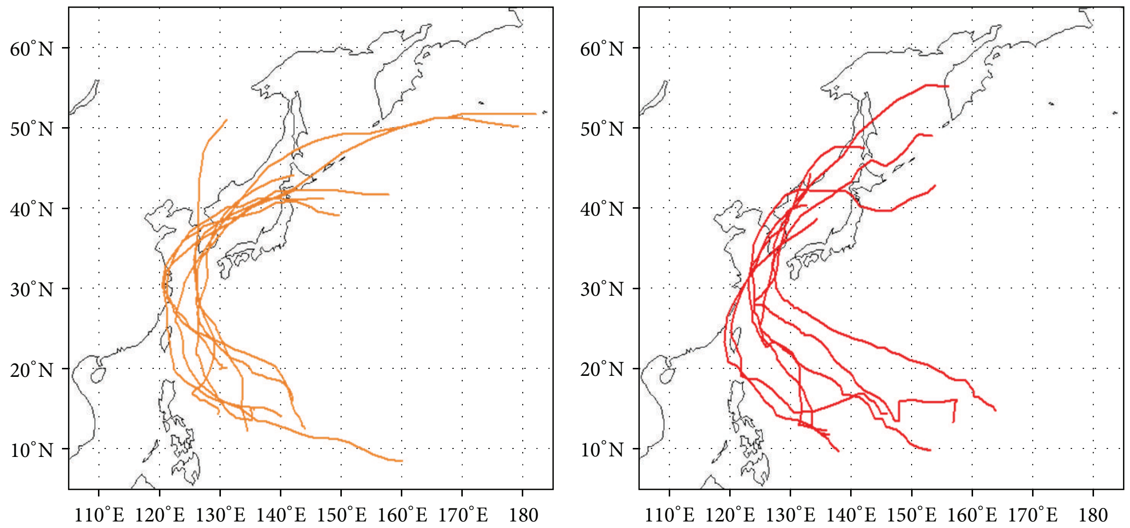
(a) 1950s

(b) 1960s



(c) 1970s

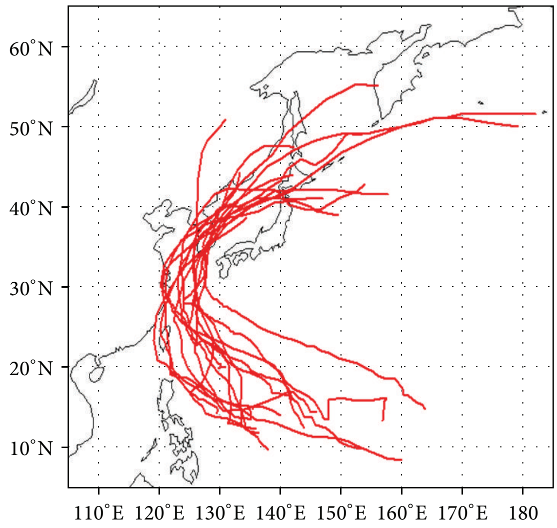
(d) 1980s



(e) 1990s

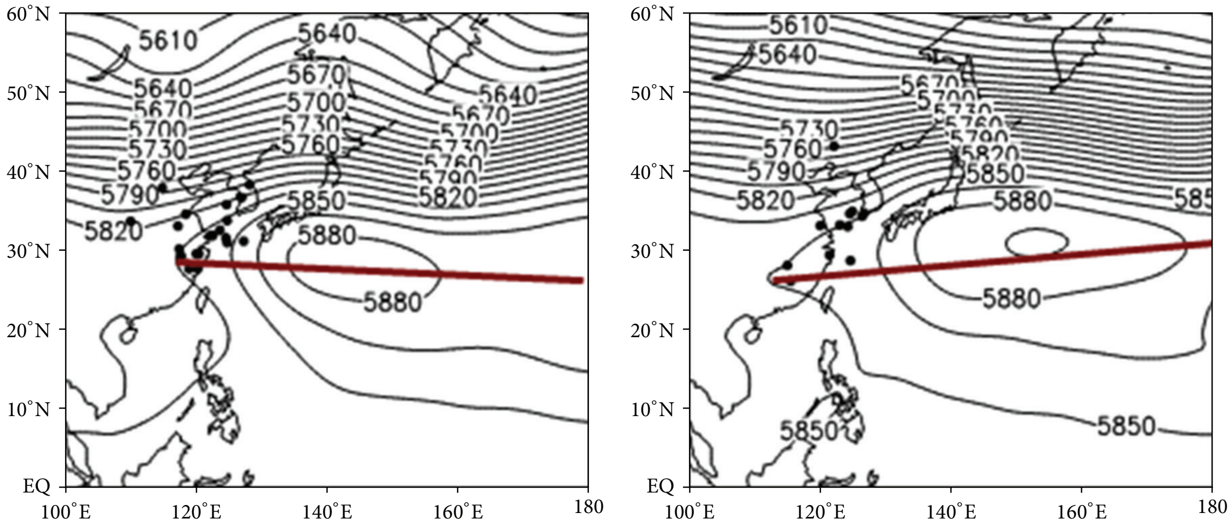
(f) 2000s

Figure 7: Continued.



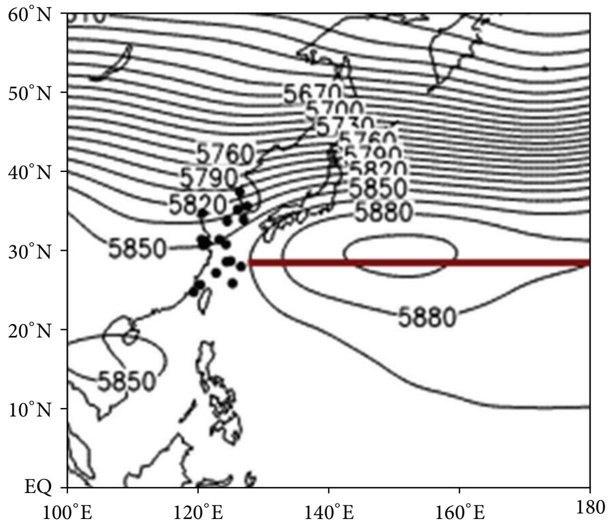
(g) 1990s~2000s

Figure 7: Same as Figure 5, but for TC full-track.



(a) H5165

(b) L6685



(c) H8604

Figure 8: Composites of geopotential heights at 500 hPa for the periods of (a) H5165, (b) L6685, and (c) H8604. Dots denote recurving locations of TCs. Brown sold lines denote ridges of WNPH.

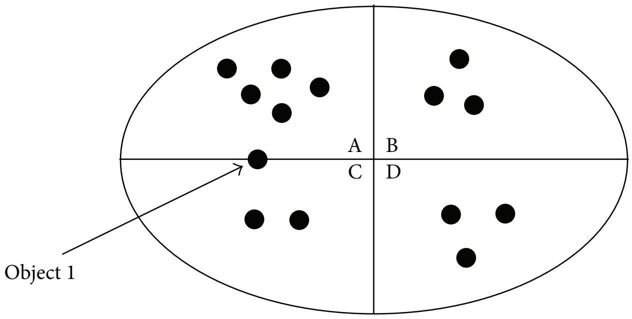


Figure 9: Example for the explanation of Fuzzy Clustering Method. Dots denote TC genesis locations in Areas A, B, C, and D.

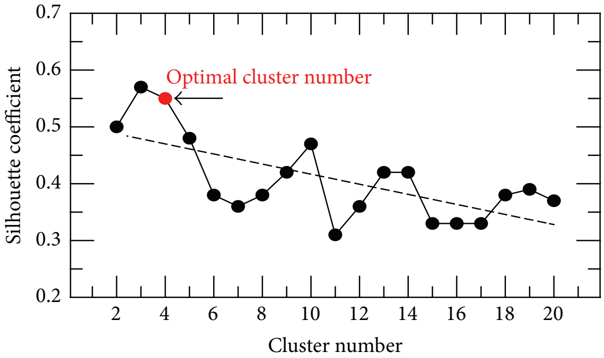


Figure 10: Silhouette coefficient (solid line with dots) at each cluster number using the Fuzzy Clustering Method (FCM) and its trend (dashed line). In this study, the optimal cluster number (red circle) was selected as four clusters.

of moving from mainland China to landing in the mid-north region of the west coast in the Korean Peninsula (see Figure 12(d)). The four clusters above could be classified largely into two groups: one is a pattern via mainland China before landing in Korea and the other is a pattern of moving northerly from East China Sea.

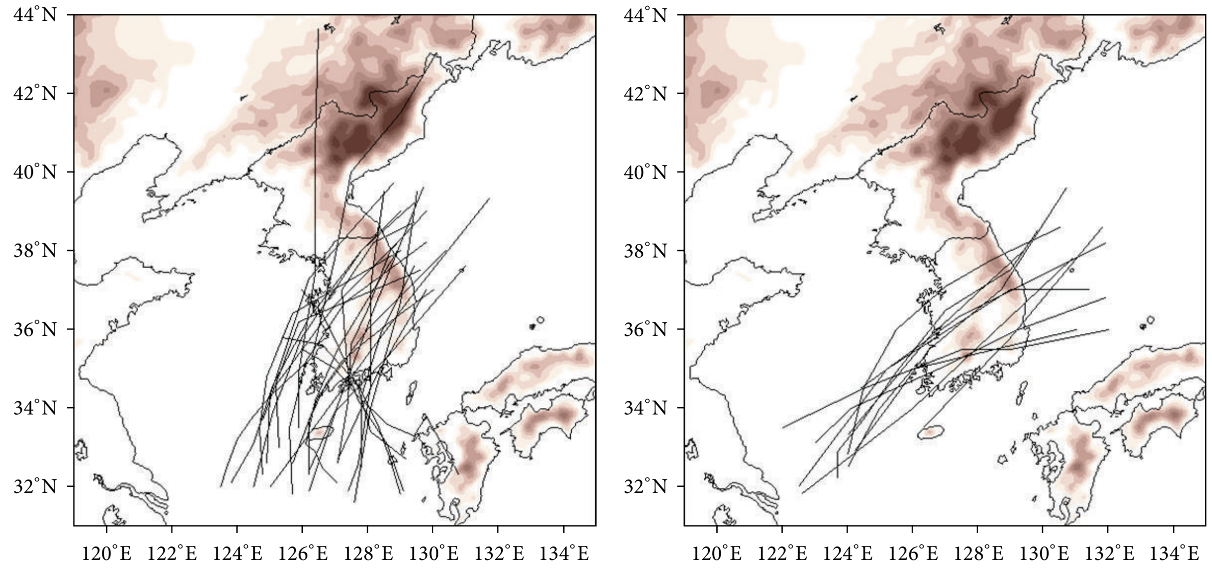
This study analyzed the Korea-landfall TC full-track based on the four clusters (see Figure 13). Any of TCs in Cluster A and Cluster B, which moved northerly from East China Sea, did not pass through mainland China whereas many TCs in Cluster C and Cluster D, which showed a pattern of moving from mainland China, showed a tendency of passing through mainland China prior to Korea-landfall.

As analyzed earlier, passing through mainland China prior to Korea-landfall could influence intensity of Korea-landfall TCs. Therefore, this study analyzed 5-year variation of Korea-landfall TC frequency as it divided TCs into Cluster A and Custer B (hereafter referred to as C-AB), which did not pass through mainland China before landing in Korea and Cluster C and Cluster D (hereafter referred to as C-CD), which passed through mainland China (see Figure 14). C-CD, which passed through mainland China, showed decreasing frequency more and more in recent years (blue bar graph) whereas C-AB, which did not pass through mainland China, showed a trend of increasing frequency more and more in recent years (red bar graph). This result is well matched with the previous analysis that more and more Korea-landfall TCs do not pass through mainland China in recent years. Therefore, intensity of TCs in C-AB, which did not pass through mainland China, may have higher possibility of strong intensity than C-CD.

5. Summary

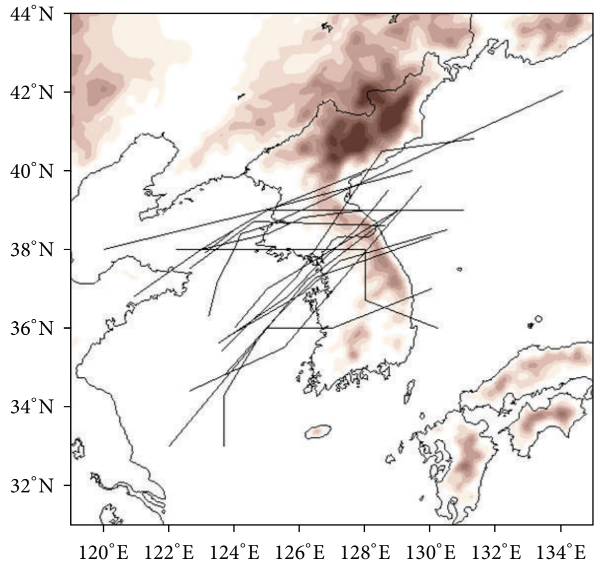
The present study analyzed the interdecadal variation by applying the statistical change-point analysis to the frequency of TC that landed in the Korean Peninsula for the recent 54 years (1951 to 2004) and performed cluster classification of the Korea-landfall TC tracks using a Fuzzy Clustering Method (FCM).

First, in the interdecadal variation analysis, frequency of TC that landed in the Korean peninsula was largely categorized into three periods: high frequency period (H5165) from 1951 to 1965, low frequency period (L6685) from 1966 to 1985, and high frequency period (H8604) from 1986 to 2004. The pattern of the Korea-landfall TC track in the three periods showed that TC in the H5165 period landed in the mid-north region of the west coast in the Korean



(a) Cluster 1

(b) Cluster 2

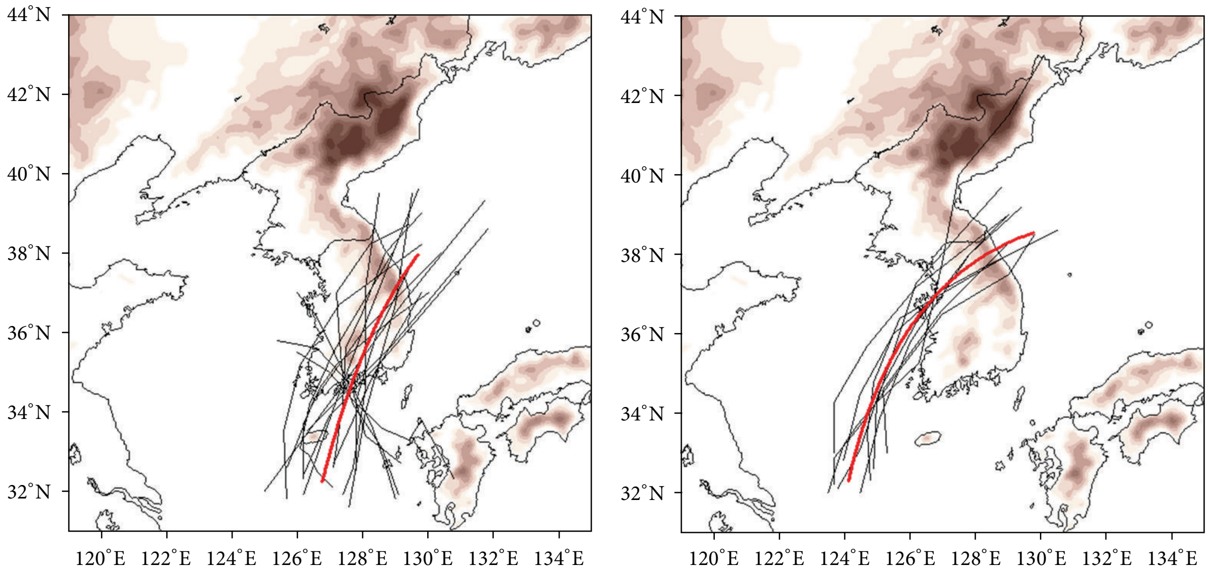


(c) Cluster 3

Figure 11: Landfalling tracks of Korea-landfall TCs classified into three clusters. Shaded area indicates topography higher than 200 m above the sea level.

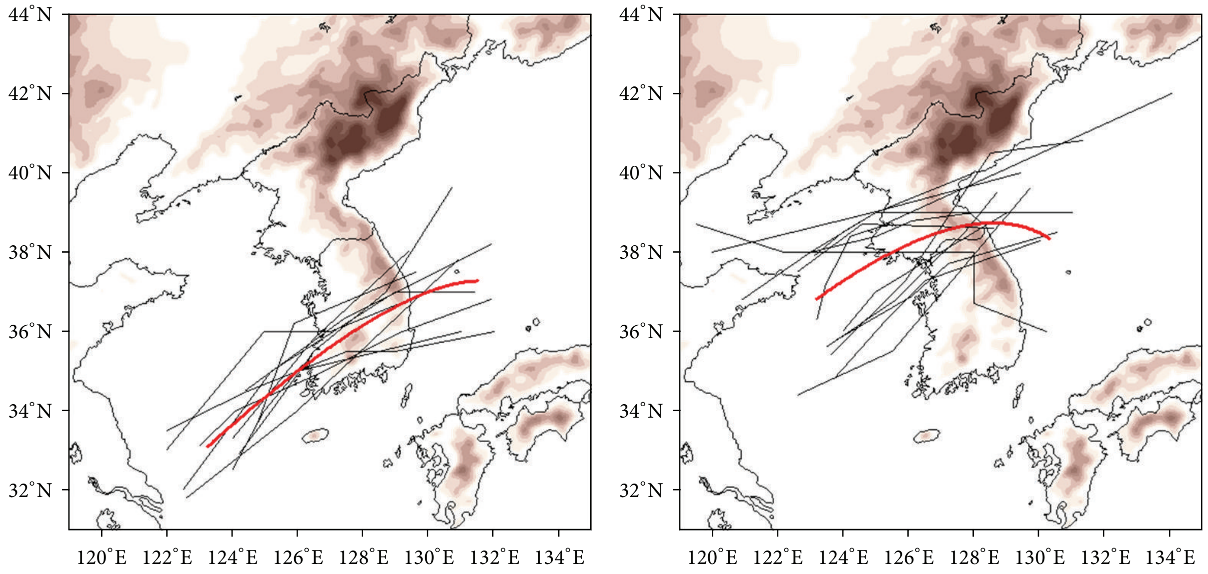
Peninsula, TC in the L6685 period landed in the southern region of the west coast, and TC in the H8604 period landed in the southern region of the west coast and the south coast. This meant that the Korea-landfall location of TCs tended to move easterly gradually. This tendency of moving easterly of Korea-landfall location was also analyzed in 10-year variation of the Korea-landfall TC track. The result of the Korea-landfall TC full-track analysis during the three periods showed that frequency of TC, which passed through mainland China before landing in the Korean Peninsula, has decreased. Therefore, intensity of TCs during the H8604 period, which has the lowest frequency of passing through mainland China, was the strongest.

Silhouette coefficient, which was produced by the cluster analysis result on the Korea-landfall TC tracks, suggested three clusters as the optimal cluster number. However, the number of objects (TCs) in Cluster 1, which moved northerly from East China Sea and landed in the southern region of the west coast and south coast in the Korean Peninsula, was significantly larger than the number of objects in Cluster 2, which moved from mainland China and landed in the southern region of the west coast in the Korean Peninsula,



(a) Cluster A

(b) Cluster B

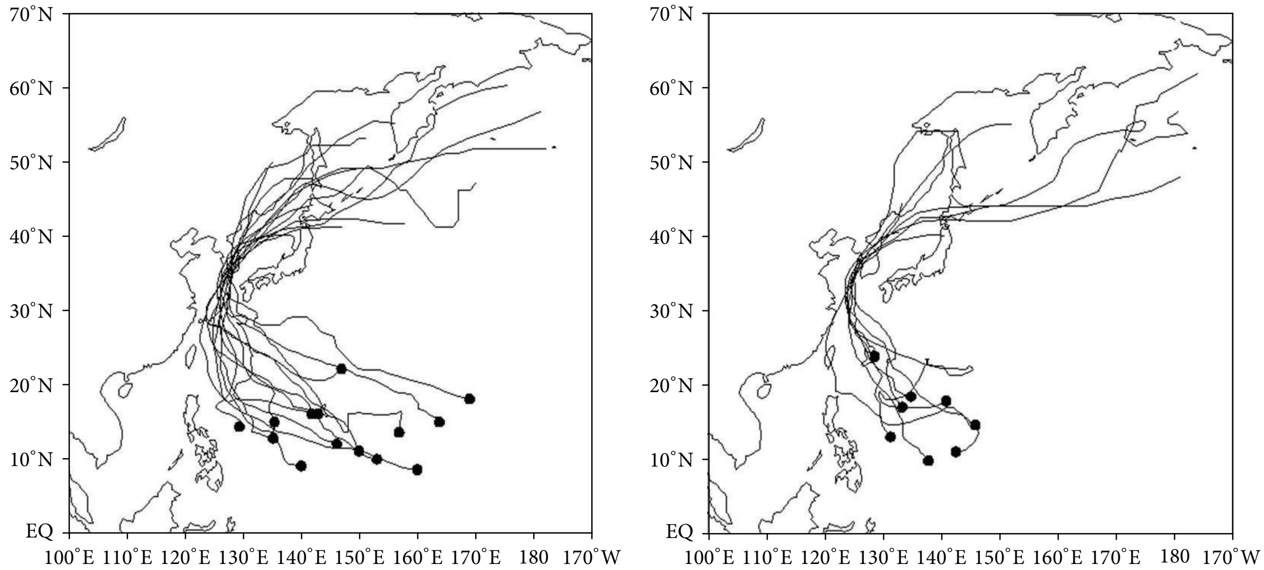


(c) Cluster C

(d) Cluster D

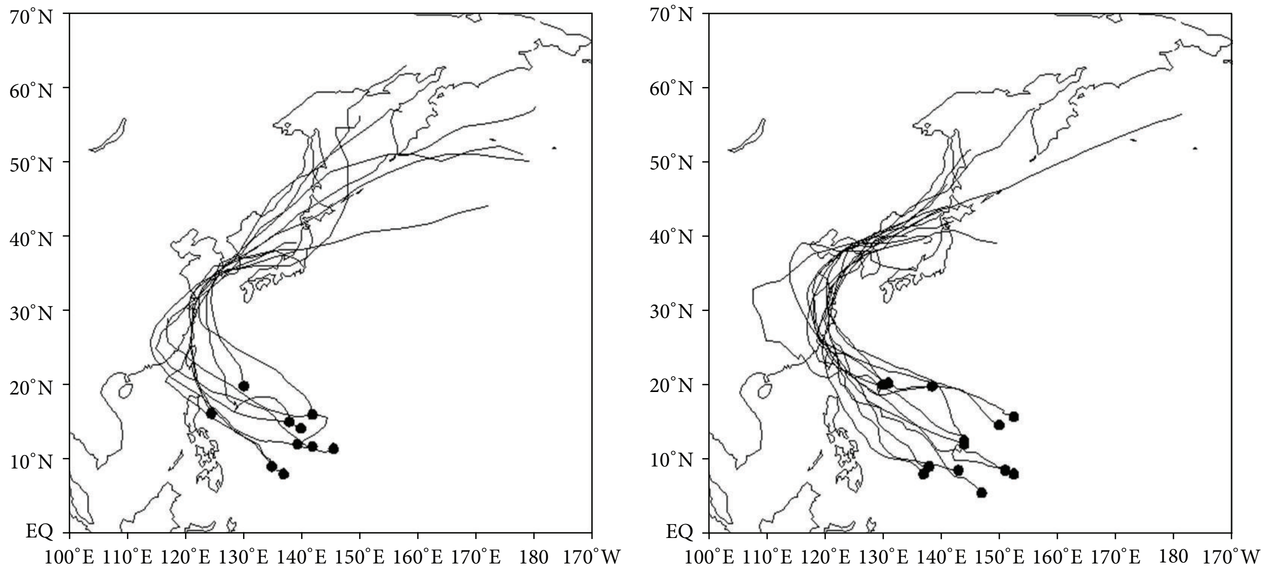
Figure 12: Same as Figure 11, but for four clusters. Thick red lines denote mean regression tracks. Shaded area indicates topography higher than 200 m above the sea level.

or the number of objects in Cluster 3, which also moved from mainland China and landed in the mid-north region of the west coast in the Korean Peninsula. Accordingly, 4 clusters were selected as the optimum number of clusters. Cluster 1 in the three clusters was divided into Cluster A, which moved northerly from East China Sea and landed in the south coast in the Korean Peninsula, and Cluster B, which also moved northerly from East China Sea and landed in the west coast in the Korean Peninsula, while Cluster 2 and Cluster 3 were named as Cluster C and Cluster D, respectively. Therefore, the divided four clusters were classified largely into two groups: one is a pattern showing moving northerly from East China Sea prior to landing in Korea and the other is a pattern of moving from mainland China before landing in Korea. In Clusters A and B (C-AB), which start TCs from East China Sea followed by heading north, there were no TC that passed through mainland China before it landed in the Korean Peninsula whereas many TCs that passed through mainland China were found in Clusters C and D (C-CD). The 5-year variation of TC frequency between the two groups showed that TC frequency of C-AB group, which do not pass through mainland China, has increased more and more until recently, which is related to the strengthening of intensity of TC that landed recently in the Korean Peninsula.



(a) Cluster A (0)

(b) Cluster B (0)



(c) Cluster B (7)

(d) Cluster B (13)

FIGURE 13: Same as Figure 12 but for the full-track. Small solid dots denote each TC genesis location of Korea-landfall TCs, respectively. The numbers in the parentheses represent TC frequencies without passing through mainland China.

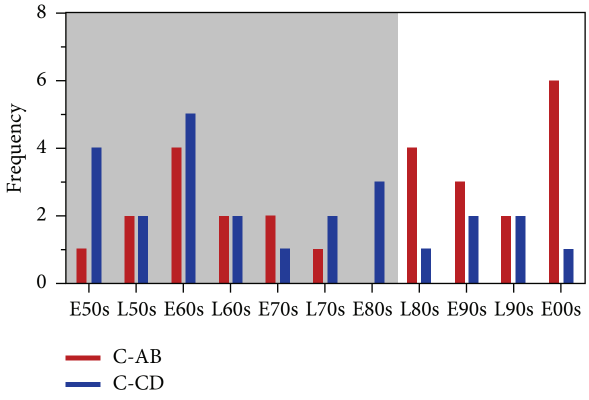


FIGURE 14: 5-year variation of the landfalling frequency of C-AB and C-CD of Korea-landfall TCs. The E and L characters mean "early" and "late," respectively. For example, E50s (L50s) denotes early (late) 1950s.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work (15-2-40-41) was supported by Researcher Program through grant funded by the DEGEC. The authors thank Dr. Joo-Hong Kim of Seoul National University for providing the program of fuzzy clustering analysis.

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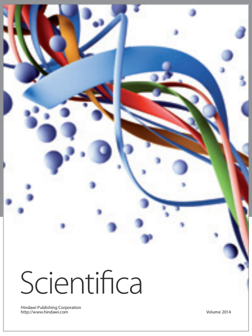
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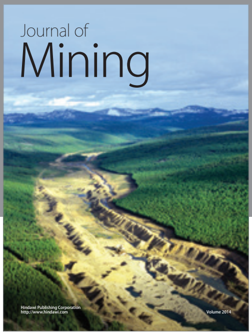
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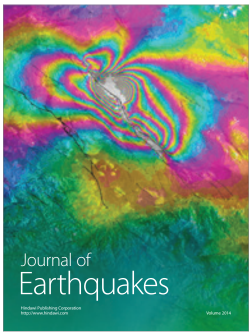
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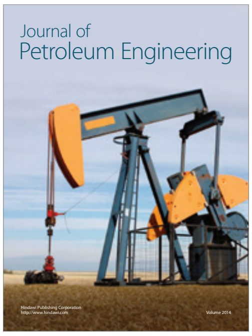
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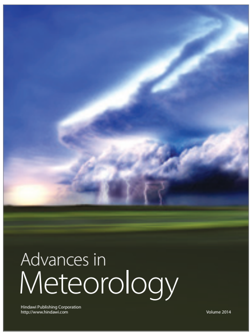
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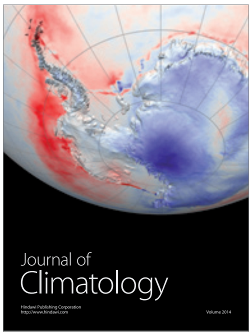
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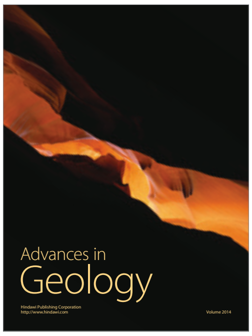
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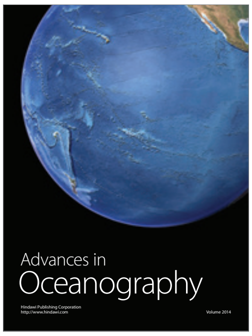
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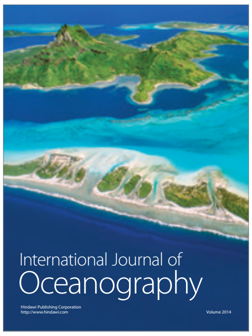
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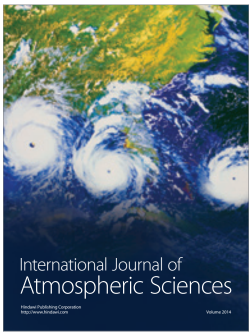
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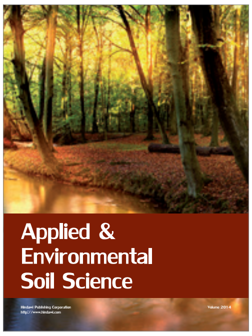
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