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K–MEANS CLUSTERING FOR CLASSIFICATION OF THE NORTHWESTERN PACIFIC TROPICAL CYCLONE TRACKS

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Abstract: Based on the Joint Typhoon Warning Center (JTWC) best-track dataset between 1965 and 2009 and the characteristic parameters including tropical cyclone (TC) position, intensity, path length and direction, a method for objective classification of the Northwestern Pacific tropical cyclone tracks is established by using *k*-means Clustering. The TC lifespan, energy, active season and landfall probability of seven clusters of tropical cyclone tracks are comparatively analyzed. The characteristics of these parameters are quite different among different tropical cyclone track clusters. From the trend of the past two decades, the frequency of the western recurving cluster (accounting for 21.3% of the total) increased, and the lifespan elongated slightly, which differs from the other clusters. The annual variation of the Power Dissipation Index (PDI) of most clusters mainly depended on the TC intensity and frequency. However, the annual variation of the PDI in the northwestern moving then recurving cluster and the pelagic west-northwest moving cluster mainly depended on the frequency.

Key words: tropical cyclone; classification of tracks; K-means clustering; character of cluster

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1 INTRODUCTION

Tropical cyclone (hereafter TC) track is an important component to judge the area and extent affected by TC. Classification of TC tracks is mostly conducted according to TC track's spatial characteristics, such as track shape, path length, and position. Although these characteristic parameters do not include lifespan, active season, energy or landfall, there actually are quite obvious features among the clusters. Therefore the classification of TC tracks is important in acquiring TC characteristics and assessing its impact.

Subjective identification methods were mainly adopted in previous classification of TC tracks (Chen and Ding[1]; Liang[2]; Chen[3]; Meng et al.[4]). In recent years, objective analysis methods were used to classify TC tracks (Camargo et al.[5]; Elsner[6]; Nakamura[7]). Camargo et al.[5] classified TC tracks over northwestern Pacific by quadratic polynomial regression function, with longitudinal and latitudinal positions versus time as independent variables. More and more meteorologists paid attention to the classification of TC tracks based on the *k*-means method, but differed in parameters selection. Elsner [6] classified the Northern Atlantic TC tracks by *k*-means Clustering. The parameters he selected only contained longitude and latitude coordinates of maximum and final hurricane intensities. His study did not include TC tracks' information at each point. Nakamura et al.[7] calculated the centroid and variance of each TC track by the *k*-means method, with wind speed at each moment as its weight associated with the location. The centroid and variance were adopted as characteristic parameters of entire track shape, length and location. The track characteristic at its strong period was the main factor to be considered.

Based on the clustering method of Nakamura[7], this paper adjusts some weighting factors and establishes objective classification of Northwestern Pacific TC tracks. The adjustments mainly include: (1) Square root of wind ($\sqrt{V_i}$) is adopted as the weight when calculating five indexes in order to decrease the weight difference of positions along the track. (2) Alter the coefficients of the standardized indexes. In Nakamura[7], two coefficients of centroid are 1/4 and three coefficients of variance are 1/6. In this paper, the coefficients are all 1/5 instead to highlight the role of variance, which delegates the entire track direction, length and shape. In addition, based on TC tracks' classification, we comparatively analyzed the characteristics of each track cluster, such as genesis location, intensity, energy, lifespan, active

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season, landfall probability and climatic tendency, in order to provide some information for TC tracks analysis and climatological forecast.

2 DATA AND METHODOLOGY

2.1 *Data introduction*

The TC data used in this paper were based on the Joint Typhoon Warning Center (JTWC) best-track dataset between 1965 and 2009, including TC position (latitude and longitude) and intensity (maximum wind speed) at 6-hour intervals. The unit of wind velocity is knot, which is converted to ms^{-1} by a coefficient of 1 kt=0.514 ms^{-1}. 1 111 TCs were selected as the samples, whose maximum wind velocity is greater than or equal to 17.2 ms^{-1} and its lifespan exceeds 1 day. The positions of TCs generation are the locations where the wind velocity $\geqslant$17.2 ms^{-1} first appears.

2.2 *Clustering methodology*

2.2.1 TC TRACKS DESCRIPTION PARAMETERS

The latitude and longitude of centroid are calculated using Eqs. (1) and (2), and the centroid lies in the area interior to the curve (figure omitted).

$$\bar{X}=\frac{1}{\sum_{i=1}^{n} w(i)}\sum_{i=1}^{n} w(i)x_i \qquad (1)$$

$$\bar{Y}=\frac{1}{\sum_{i=1}^{n} w(i)}\sum_{i=1}^{n} w(i)y_i \qquad (2)$$

where x_i and y_i are the latitude and longitude at the ith moment, n is the total times of single TC, $w(i)$ is a weight associated with the ith moment, and the square root of intensity($\sqrt{V_i}$) is adopted in this paper.

The three variances (zonal, meridional and diagonal) are calculated respectively by Eqs.(3), (4) and (5).

$$Var(x)=\frac{1}{\sum_{i=1}^{n} w(i)}\sum_{i=1}^{n} w(i)(x_i-\bar{X})^2 \qquad (3)$$

$$Var(y)=\frac{1}{\sum_{i=1}^{n} w(i)}\sum_{i=1}^{n} w(i)(y_i-\bar{Y})^2 \qquad (4)$$

$$Var(xy)=\frac{1}{\sum_{i=1}^{n} w(i)}\sum_{i=1}^{n} w(i)(x_i-\bar{X})(y_i-\bar{Y}) \qquad (5)$$

The five equations above, which summarize the TC track information of centre position, length, direction and curvature, can be used to identify track clusters.

2.2.2 CLUSTER ANALYSIS AND DETERMINATION OF CLUSTER NUMBER

TC clusters can be identified effectively by the k-means method. The vector includes five indexes: the latitude and longitude of the centroid, and the three variances (in the zonal, meridional and diagonal direction). The time series of each index is standardized for k-means clustering later.

Cluster analysis requires that the samples distinguish among the clusters and cohere within the same cluster. The distance between any two samples is described as the absolute distance of the five indexes above:

$$d_{ij}=\sum_{m=1}^{5}|x_{im}-x_{jm}| \qquad (6)$$

The clusters are identified randomly by the k-means cluster analysis package in Matlab 7.0. A "silhouette" value, used to measure sample adhesion degrees within the same cluster and distinction among clusters, was defined. The silhouette (S_i) of ith sample is defined as:

$$S_i=\frac{\min(b_i)-a_i}{\max[a_i,\ \min(b_i)]} \qquad (7)$$

where a_i is the average distance from the ith sample to the other samples within the cluster, b_i is the average distance from the ith sample to samples in another cluster and S_i ranges from −1 to 1. The higher the mean silhouette value is, the more distinguished it is among the clusters. The negative silhouette value indicates a possible misclassified point. The optimal cluster number is determined by the maximum mean and minimum number of negative silhouette values. Fig.1 shows the change of the mean silhouette values and number of negative silhouette values along with the classified number, based on TC data calculation. When cluster number is less than 7, the mean silhouette value increases and the number of negative values decreases with increasing cluster number. However, these two values change slightly when the cluster number is larger than 7. A larger number of classified clusters are not the more the better. Too many clusters are not beneficial for induction. By all accounts, the Northwestern Pacific TC tracks were classified into seven clusters, marked as cluster A-G.

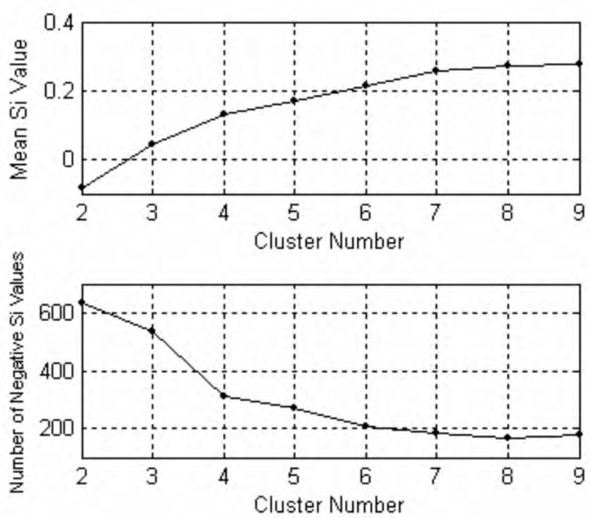

Figure 1. Mean silhouette values (top) and number of negative silhouette values (bottom).

3 RESULTS OF CLUSTER ANALYSIS

3.1 *Centroid and variance*

The actual output of the *k*-means clustering is groups of centroid locations and variance ellipses (Fig. 2), and only the samples between 1990 and 2009 are shown. Table 1 presents the mean centroid location and variance ellipse for each cluster. The mean location of cluster A is near Guam, with zonal variance slightly larger than meridional variance. The centroid of cluster B sits northwestward to that of cluster A, with its zonal variance larger than the meridional one. The mean location of cluster C is southeastward to Okinawa Island, with zonal variance slightly smaller than meridional variance. Cluster D's centroid is farthest east and north and its variance ellipse is close to be a circular. The centroid of cluster E lies in the basin southeastward to Japan. Its variance ellipse is the largest in all clusters. Its zonal variance is larger than meridional one and the long axis is aligned southwest to northeast. The mean location of cluster F is beside the Philippines. Its variance ellipse has a long macro axis and a shortest minor axis. The centroid of cluster G lies in the South China Sea. The variance ellipse is the smallest in all clusters. Its shape and elongated direction are similar to that of cluster B, but its size is much smaller than cluster B's.

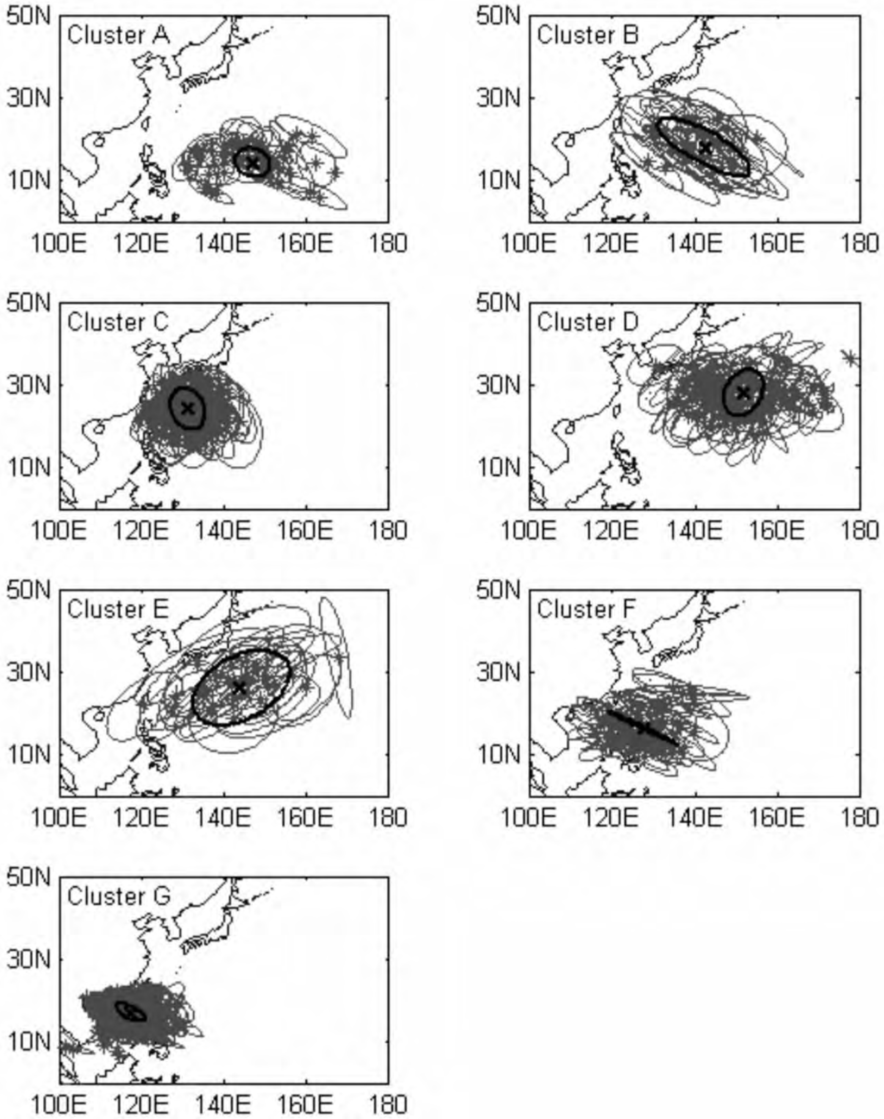

Figure 2. Centroid locations (asterisks) and variance ellipses (thin line) for each cluster. The mean centroid is marked with a dark "x", and the mean variance ellipse with a dark line.

3.2 *Genesis location and track shape*

Although the track location and shape are taken into account for the calculation of centroid and variance, the genesis location and actual track were not used directly in the previous analysis. The mean track of each cluster can be seen in Fig.3, in which the genesis location and track of single TC (only between 1990 and 2009) are also shown. Cluster A is named as a low-latitude recurving cluster (LLR_C), with its active region being southward and eastward, always in the basin o-

Table 1. Mean centroid and variance values for each cluster.

Cluster	Centroid *x*/°E	Centroid *y*/°N	Variance *x*	Variance *y*	Variance *xy*
A	146.9	14.2	15.86	12.61	−2.74
B	142.5	18.0	129.79	35.50	−42.27
C	131.2	24.1	15.50	24.29	−3.66
D	151.8	28.0	19.43	30.33	7.79
E	143.9	26.1	106.71	85.33	63.22
F	127.6	16.4	77.36	8.55	−16.99
G	117.3	17.0	12.57	3.71	−3.20

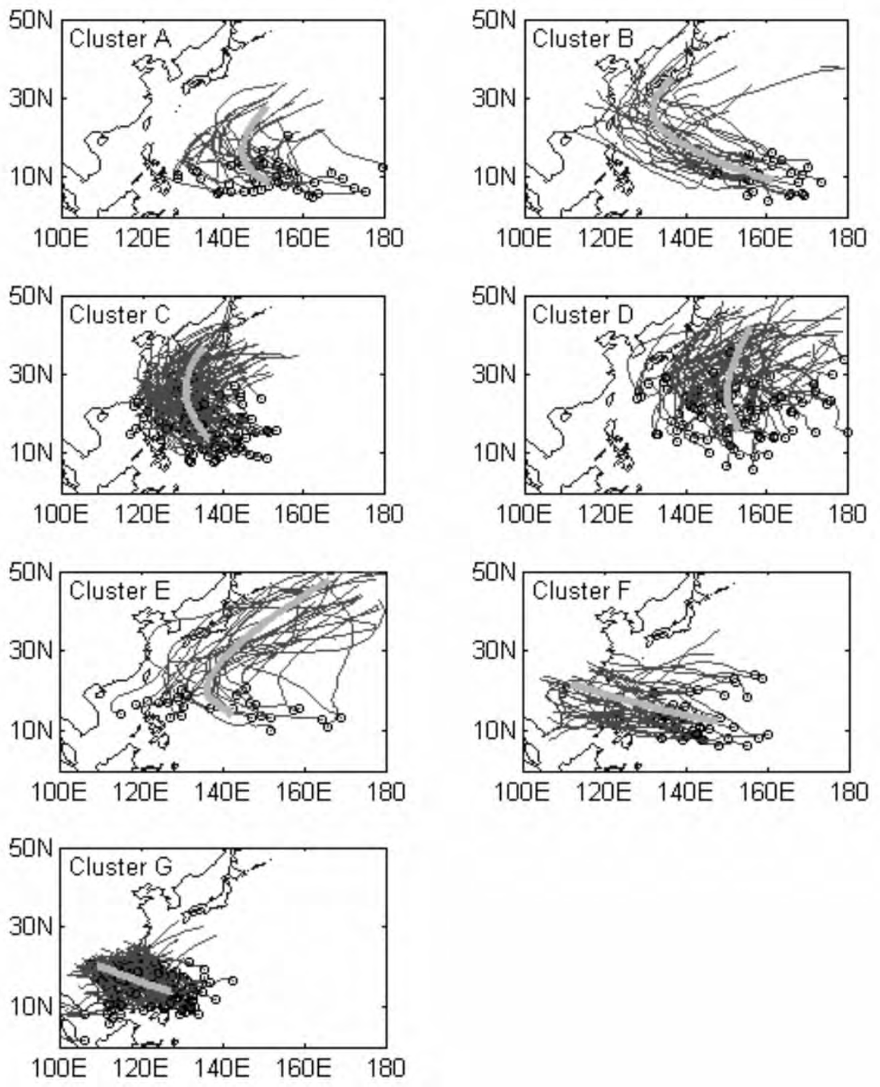

Figure 3. The genesis location (circle) and the track (thin line) for single TCs between 1990 and 2009. The mean track of each cluster is marked with a grey, thick line.

cean. It generates in the ocean east to the Philippines, and moves northwestward first, then turns to northeastward to get close to 15°N. Cluster B generates beside mid-ocean, with a spoon-like track. It moves northwestward steadily, turns northeastward reaching the area near 28°N southward to Japan, and then dissipates soon. Although being a recurving cluster, it has a primarily northwestward direction, therefore named "a northwestern-moving-then-recurving cluster" (NWR_C). Being a west-recurving cluster (WR_C), Cluster C generates at the ocean east to the Philippines and landfalls on Japan mostly. Cluster D is called an east-recurving cluster (ER_C), which generates eastward and diffuses, with a little change in direction angle. Cluster E resemble a spoon too, but its primary direction differs from that of Cluster B. It moves northwestward in short-term, and then turns northeastward when it gets close to 22°N. It stays on for a long time after recurving and reaches northernmost latitudes. We call it a recurving-then-northeast-moving cluster (RNE_C). Clusters F and G all are straight-moving clusters. By comparison, Cluster F generates more eastward and has longer track. Cluster G includes most of the South China Sea TCs. The two clusters move to the north by west, and make landfall on the Philippines, Vietnam or China, which are named, separately, a pelagic, west-northwest-moving cluster (PWNW_C) and an offshore, west-northwest-moving cluster (ONW_C).

3.3 *Intensity of lifespan*

Figure 4 shows the distribution of maximum wind speed in each cluster and the whole group of TCs. In all clusters, the NWR_C is the strongest, followed in turn by the PWNW_C and the RNE_C cluster, and the WR_C is slightly stronger, but the LLR_C and the ER_C are weaker, than the total mean, and the ONW_C cluster is the weakest of all. The medians are greater than the means in the NWR_C and the PWNW_C, indicating that the majority of TCs are stronger than the cluster mean in these two clusters. For other clusters and as a whole, the medians are less than the means, indicating that the majority of TCs are weaker than the cluster mean.

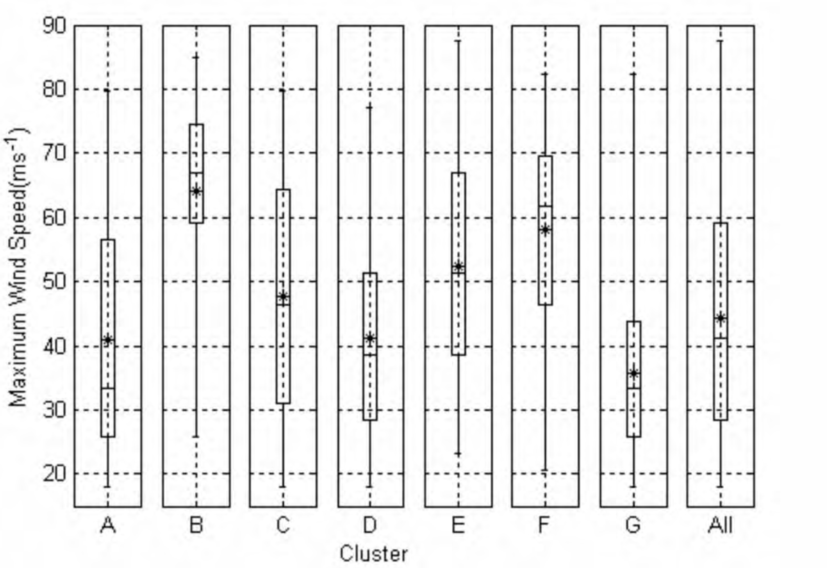

Figure 4. The 25th and 75th percentiles (upper and lower bounds of the box), the mean (asterisk), the median (bar in box), and the bounds (dashed line outside the box) of the distribution of TC maximum wind speed (m s^{-1}) in each cluster and as a whole.

Analysis of the distribution of lifespan in each cluster (figure omitted) indicates that lifespan ranges from one day to nearly twenty days. The sequence of lifespan is consistent with the intensity, except that the RNE_C exchanges order of intensity with the PWNW_C. The longer the lifespan, the longer the time the tropical cyclone has to take to intensify as long as the conditions remain favorable (i.e., warm waters and low shear). For the total of TCs, the correlation coefficient of maximum wind speed and lifespan reach up to 0.70. Except the medians of the NWR_C and the WR_C are close to the means, the medians of other clusters and the total are shorter than the means, it indicates that most TCs persist for less time than the means.

The power dissipation index (PDI) is defined by Emanuel[8]:

$$\mathrm{PDI}=\int_1^n V^3 \mathrm{d}t \tag{8}$$

where n is the number of time, steps with dt in seconds, and the unit of wind velocity V is ms^{-1}, PDI unit is $\mathrm{m}^3\mathrm{s}^{-2}$. PDI, a combination of maximum wind speed and life span, is used as a measure of integrated intensity. Not surprisingly, the NWR_C is the greatest (figure omitted). The PWNW_C takes the second place. The RNE_C is a little smaller than it. The ONW_C is the least of all. It is different from the distribution of maximum wind speed and life span, except for the NWR_C, whose medians of other clusters and the whole are smaller than the mean obviously, indicating that most TCs are less intense than the mean of their cluster.

3.4 *Active season*

Based on the track shape and geographic location, the *k*-means method classifies the clusters of TC tracks and there are obvious differences between different clusters as described in the previous subsections. A key reason for these differences is possibly the diverse active season.

Figure 5 shows the mean numbers of cyclones per calendar month, for each cluster and all, based on genesis dates. The LLR_C is not active from July to October, which is the active season for the Northwestern Pacific TCs. However, its frequency is higher in the six-month season from November to April. The NWR_C appeared rarely in February to May, but its frequency is relatively uniform in other months. The other three recurving clusters of TCs seldom appeared from December to April. Among them, the WR_C (peak activity in July to September) precedes the ER_C (peak in August to October), while the RNE_C (peak in September and October) is the last one. The two straight-moving clusters persist in every season, like the LLR_C. However, they are not active in the first season. The PWNW_C maintains this status till the second season. The five months from July to November are the active season of these two clusters.

3.5 *Landfall probability*

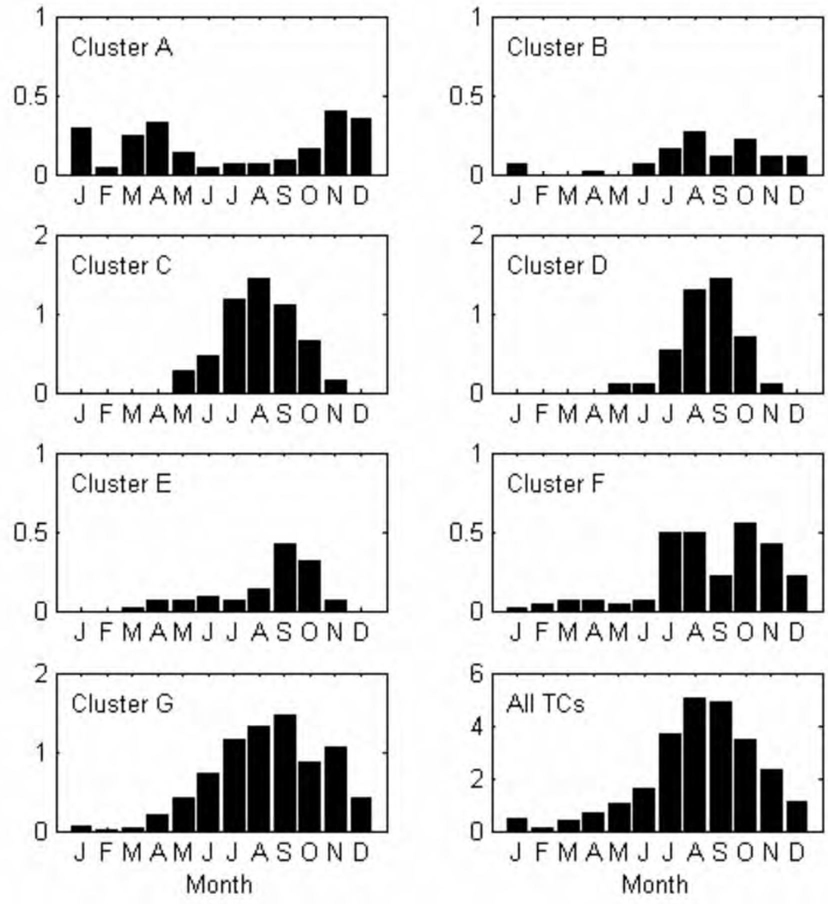

Figure 5. Mean number of cyclones for the month, cluster and all TCs.

Landfall risk is a main concern of the government and the general public. The landfall percentage of all TCs is 59.4% (see Table 2). The landfall probability of two straight moving clusters reaches 89.2%, which is highest. Among the five recurving clusters, because of the western recurving point, the landfall probabilities of the NWR_C and the WR_C are larger than the total mean. However, the landfall probabilities of the other three clusters are very small for they are east-recurving.

3.6 *Trends*

Figure 6 shows the annual TC number and its binomial curve for each cluster and all TCs, with the fitness rate at 95%. It shows that all TCs' frequency decreases in the mass, which accords with the research results of Chen et al.[9], He et al.[10] and Huang et al.[11]. It was indicated that the number of tropical cyclones in the western Pacific are more (or less) than the normal year, when the subsurface ocean temperature of the equatorial Western Pacific Warm Pool persistently shows positive (or negative) anomaly (WU et al.[12]). According to WANG et al.[13], the variation characteristics of ocean temperature in the Western Pacific Warm Pool are such that subsurface ocean temperatures have descended 0.72℃ in the 47 years from 1958 to 2004. The frequencies of the RNE_C, the PWNW_C and the LLR_C have declined. The NWR_C and the ER_C have no obvious variation. The frequency of the ONW_C decreased before 1990 but changed little after 1990. On the contrary, the TC number of the WR_C increased in its totality. GONG et al.[14] analyzed the interdecadal change of the Western Pacific Subtropical High. Since the 1980s, the Subtropical High has enlarged, intensified, and shifted southwestward. The reinforced and westward shift of the Subtropical High lead to the westward shift of TCs' recurving points. As a result, the TC number of the WR_C increased.

The annual mean intensity (maximum wind speed)

Table 2. TC number, landfalls and their percentages for each cluster.

Cluster	TC number	percentage	landfalls	Landfall percentage
A	100	9.0	4	4.0
B	51	4.6	35	68.6
C	237	21.3	161	67.9
D	194	17.5	23	11.9
E	56	5.0	15	26.8
F	122	11.0	112	91.8
G	351	31.6	310	88.3
All	1111	100.0	660	59.4

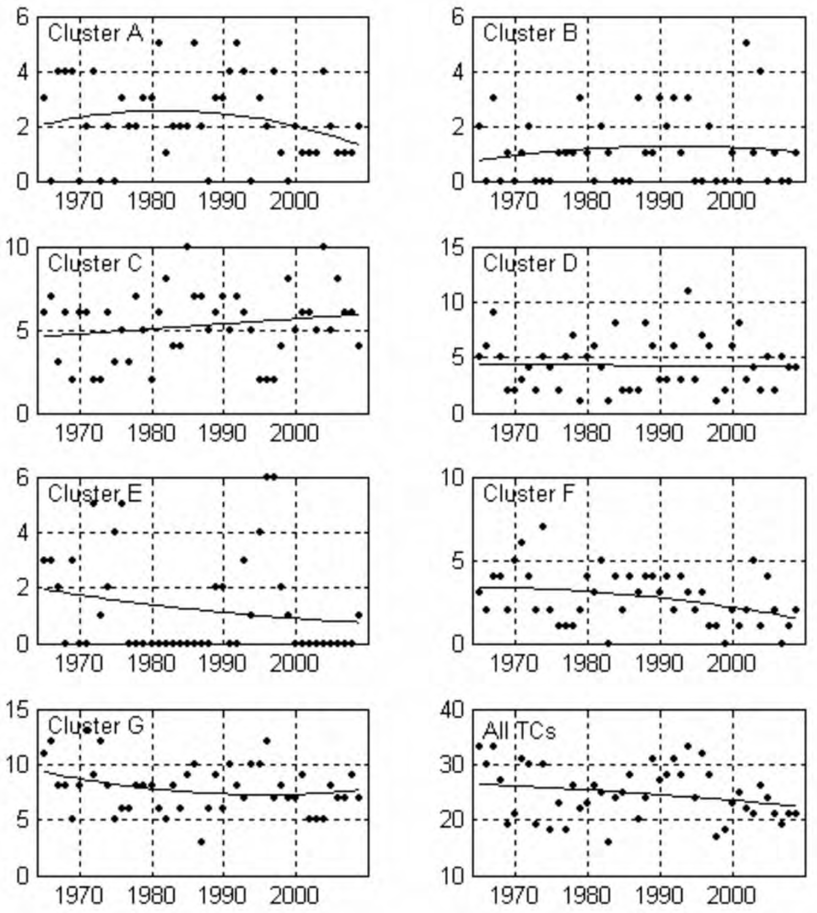

Figure 6. The annual TC number (dots) and its binomial curve for each cluster and as a whole.

and its binomial curve (the fitness figure is 95%) for each cluster and as a whole (figure omitted) is analyzed. In the last two decades, the intensity trend weakened for the RNE_C, changed rarely for the LLR_C, and enhanced for the other five clusters (among them, the NWR_C and the WR_C enlarged and enhanced obviously).

Analysis of the annual lifespan and its binomial curve (the fitness figure is 95%) for each cluster (figure omitted) reveals that the mean lifespan had no obvious change for most clusters. Only the WR_C tended to increase lightly. The other clusters decreased or changed little in the last two decades.

The annual PDI and its binomial curve (the fitness figure is 95%) for each cluster and as a whole (figure omitted) is analyzed. The LLR_C tended to enlarge before 1980, and changed slightly since 1980. The NWR_C increased on the whole. The WR_C had no obvious changes before 1980 but tended to enlarge since then. The ER_C had no obvious chance in the previous three decades, and tended to enlarge since the late 1990s. The RNE_C and the PWNW_C tended to decrease. The ONW_C and the whole TCs tended to decrease before the mid-1980s, and tended to increase since the late 1980s. Although the total TCs annual number tended to decrease, but the annual total PDI increased in the last two decades, suggesting that PDI of single TC tended to enlarge obviously.

According to the definition of the annual PDI, it depends on the TC number, intensity, and lifespan of each cluster. The variation tendencies of these parameters of each cluster in the last two decades were contrastively analyzed in this paper. The variation of annual total PDI in each cluster was decided mainly by the changes of intensity and frequency while the proportion of intensity was larger. The variations of annual PDI in most clusters were consistent with intensity. In the NWR_C and the PWNW_C, the variation of annual PDI were decided mainly by frequency.

4 CONCLUSIONS AND DISCUSSIONS

Table 3. The trends of the annual PDI and its three parameters of each cluster in the last two decades.

Cluster	Annual TC number	Intensity	Lifespan	Annual PDI
A	−−	0	0	0
B	0	++	−	0
C	++	++	+	++
D	0	+	0	+
E	−−	−−	−−	−−
F	−−	+	0	−−
G	0	+	−	++
All	−	++	−	+

Based on the improved *k*-means method, the Northwestern Pacific TC tracks are classified objectively by the TCs' centroid and variance. The centroid indicated the mean position. The variance indicated the track's shape, length, and direction. The main conclusions are as follows:

(1) The cluster number of TC tracks is confirmed by the mean silhouette values and the number of negative silhouette values. Based on the TC track samples between 1965 and 2009, we classified tracks into 7 clusters, including 5 recurving clusters and 2 straight-moving clusters. The energy, lifespan, active season, and landfall of cyclones have quite obvious differences among the clusters, though they are not used in the clustering algorithm.

(2) There is obvious positive correlation between maximum wind speed and lifespan. These two parameters are coincident in sequence: the NWR_C is largest, the RNE_C and the PWNW_C take second or third place, WR_C is slightly larger than the total mean, the LLR_C and ER_C are slightly smaller than the total mean, and the ONW_C is the smallest.

(3) The LLR_C is active from November to April. The NWR_C rarely survives from February to May. Its frequency is uniform relatively in other months. The WR_C (peak activity in JAS) precedes the ER_C (peak in August to October), the RNE_C (peak in September and October) is posterior. The two straight-moving clusters are active in the five-month season from July to November.

(4) The two straight moving clusters lead in the landfall risk, their total risk reaches up to 89.2%. Among the five recurving clusters, landfall probabilities are diverse. Because of the western recurving point, the landfall probabilities of the NWR_C and the WR_C are greater than that of the total mean. The landfall probabilities of three other clusters are very small for their eastern recurving point.

(5) In the last two decades, frequencies of the RNE_C, PWNW_C and LLR_C had lessened trends while the frequency of the WR_C increased in the mass. Because the West Pacific Subtropical High intensified and shifted westward after 1980s, TCs' recurving point shifted westward. The intensity weakened for the RNE_C, changed rarely for the LLR_C, and enhanced for the other five clusters. The lifespan tended to increase lightly in the WR_C, and decreased or changed rarely for other clusters. The trend of annual PDI increased for the WR_C, ER_C, and ONW_C; but decreased in the RNE_C and the PWNW_C. The trends of annual PDI in most clusters were consistent with that of intensity. In the NWR_C and PWNW_C, however, the trends of the annual PDI were mainly decided by frequency.

The factors that affect the TC tracks are very complex. The circulation characteristics of seven track clusters classified in this paper will be discussed in our other work.

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