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**Journal of Atmospheric Science Research**
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ARTICLE

# Climatology of Winter Extratropical Cyclones over the Coastal Waters of China

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ARTICLE INFO

*Article history*
Received: 7 March 2019
Accepted: 28 March 2019
Published Online: 12 April 2019

*Keywords:*
Extratropical cyclones
Atmospheric circulation
Cluster analysis
Precipitation

ABSTRACT

The East China coast is one major cyclogenesis region of extratropical cyclones (ETCs) in boreal winter. In this study, the climatological characteristics of winter ETCs passing over the coastal water of China are analyzed by using clustering and composite analysis. Automated cyclone detection and tracking algorithm are used to identify the ETCs, which are further classified into subgroups according to their trajectory features by using the probabilistic clustering algorithm. Six distinct types of straight moving or recurving trajectories with different climatological characteristics are identified in the clustering analysis. Accordingly, the composite analyses also present six distinct synoptic patterns corresponding to cyclogenesis as well as the impact of ETCs on terrestrial precipitation. The spatio-temporal characteristics of winter ETCs' origination, movement, and impact are revealed by the clustering and composite analyses.

## 1. Introduction

Extratropical cyclone (ETC), also called wave cyclone or midlatitude cyclone, is a type of storm system in middle or high latitudes that transports huge amounts of moisture and energy poleward to reduce the meridional temperature gradient [1-2]. The passage of ETC is usually associated with strong winds, excessive precipitation, and temperature changes [3-5]. Therefore, studying the characteristics and paths of ETCs are of great importance both in terms of understanding variations of local weather and for a characterization of climate [3].

There have been a lot of studies on ETCs including their life cycle from initiation, growing, to their impacts as well as the identification, tracking, and clustering algorithms [3-10]. The formation and evolution mechanisms of ETCs have been extensively studied using a wide range of observational, theoretical, and modeling approaches (reviewed in [4]). The main focus of this study start from the identification and tracking of winter ETCs to their climatological characteristics and impacts.

In the early times, the identification and tracking of cyclones were based on manual analysis of synoptic weather charts [11, 12]. Such analysis was very time-consuming, and could only be applied to a limited number of maps. With the increase of computer capacity in recent decades, new automatic and semi-automatic meth-

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 DOI: https://doi.org/10.30564/jasr.v2i2.919

ods are developed to objectively detect ETCs based on sea level pressure, geopotential height, or vorticity fields [13-17]. The tracked ETCs are usually described as a set of moving objects that follow various tracks and have distinct individual lifecycle characteristics. Cluster analysis provides a natural way to analyze sets of trajectories and their relationships with the larger-scale atmospheric circulation, by decomposing large sets of trajectories into subgroups with similar spatio-temporal characteristics [18,19]. Then, the synoptic characteristics of the clustered ETCs could be easily revealed by the following composite analysis [20, 21].

East Asia, especially the East China coast, is a major cyclogenesis region in the Northern Hemisphere [22, 23]. These ETCs move mainly eastward over the coastal waters of China and Northern Pacific [22]. A few of recent studies have focused on the climatological characteristics of ETCs, particularly those generated at East China coast. Objective identification and tracking methods were widely used to study the features of ETCs in spring [24-26]. ETCs over East Asia and Western Pacific exhibit obvious seasonal variability, and stronger ETCs more frequently occurred in winter and spring than in summer and autumn [9]. Qin et al. [25] found that China's offshore ETC tracks tend to shift northward in recent decades, characterized by increased (decreased) cyclone number at the northern (southern) part of the East China Sea. Zhang et al. [26] applied the k-means clustering method to identify the dominating trajectories of ETCs over East Asia, and studied their climatological characteristics in the period 1958-2001. Due to the spatio-temporal homogeneity of ETCs, the k-means clustering method was not the proper algorithm for clustering ETC trajectories [18]. Zhang et al. [23] proposed to classify the developing of ETCs into two types according to the central pressure deepening rate, and studied the inter-annual variability of ETC number and the possible causes.

This study firstly applies an improved winter ETC detection and tracking algorithm based on vorticity fields to identify the ETCs over the coastal waters of China. Then, the probabilistic clustering method is used to classify the ETCs according to their trajectory features. The climatological characteristics as well as the larger-scale atmospheric circulations are also analyzed by using the composite analysis. Moreover, the impacts of ETCs on terrestrial precipitation are also studied. The study is organized as follows: Section 2 presents the data and methodology used in this study. The ETC identification, tracking, and classification along with the composite daily means and anomalies of the synoptic pattern, are presented as results in Section 3. Finally the discussion and conclusions are given in Section 4 and Section 5, respectively.

## 2. Data and Methods

### 2.1 Data

This study adopts the European Centre for Medium range Weather Forecasts (ECMWF) re-analysis data (ERA-Interim for 1979–2017), with a 0.75°×0.75° horizontal resolution and 6-h time interval [27]. The vorticity fields at 850 hPa level within the region of 20°–60°N, 60°–160°E extracted from the ERA-I reanalysis dataset are used for ETC identification and tracking. Other synoptic variables related to large scale atmospheric circulations are 500hPa zonal and meridional wind, geopotential height, air temperature at 850 hPa level, and mean seal level pressure. The daily anomaly fields of all synoptic variables are calculated by subtracting the seasonal cycles (calendar-day mean) for each grid cell. The seasonal cycle is defined from 1979 to 2017, and a 5-day running average is applied to reduce day to day variation.

The daily total precipitation data on a 0.5°×0.5° grid within the study area EAME are provided by the National Oceanic and Atmospheric Administration Climate Prediction Center (U.S.A.). The daily mean climatology for precipitation has been firstly calculated for each grid during the period 1979-2017, and a 5-day running average is also applied for the purpose of reducing the day to day variation. Then, the smoothed mean precipitation is divided by the daily precipitation, and the ratio represents the precipitation anomaly [28].

### 2.2 Methods

In this study, the objective algorithm presented in [17] is used to identify and track winter ETCs (Dec., Jan., and Feb.) based on the vorticity fields at 850 hPa level. The algorithm includes two independent steps, where the first step is devoted to the identification of the cyclone centers, which are combined into a track in the second step. A Matlab toolbox named CycloTRACK (v1.0) could be accessed from the corresponding author of reference [17]. The spurious paths of cyclones moving upstream/westward over five longitude degrees or having a lifetime less than 24 h are eliminated for the purpose of getting rid of local warm season thermal lows [29] and some tropical cyclones moving westward from Northern Pacific [30]. Moreover, only ETCs originating or entering the regions 35- 41°N, 117-127° E and 25-35° N, 120-130° E are considered in this study. Besides the latitude and longitude of cyclone centers, the lifetime, central sea

  DOI: https://doi.org/10.30564/jasr.v2i2.919

level pressure, and travel distances of all ETCs are also recorded. The normalized central pressure deepening rate is also computed using the following equation [31]:

$$R = (P_{t-12}-P_{t-12})/24hPa\times[(\sin 60°)/\sin\varphi], \quad (1)$$

where $P_{t-12}$ and $P_{t+12}$ are the central pressures of the cyclone before 12h and 12h after current time, respectively; the parameter φ denotes the latitude of the cyclone center. The unit of R is "bergeron" (referred to as B). A positive value of R corresponds to developing cyclone, and more specifically the cyclone with R exceeding 1 B is considered as an explosive cyclone [23, 25, 26, 31].

Like Gaffney et al. [18], the probabilistic clustering algorithm is used to classify the identified winter ETCs. In this algorithm, a regression mixture model is applied to describe the longitude-time and latitude-time propagation of the ETCs. Each ETC track is assumed to be generated by one of K different regression models. The clustering problem is actually to assign each track to the mixture component (and thus the cluster) that is most likely to have generated that track. Sometimes, the latitude and longitude measurements are normalized before clustering. In this study, we omit the preprocessing step such as the normalization of ETC tracks. Instead, the ETC tracks are clustered directly, so that the produced results become easy to interpret [20]. The optimum number of clusters is determined by balancing inter-cluster and within cluster variability. The log-likelihood values are also computed as the goodness-of-fit metric [18]. The procedure for model selection is as follows: we randomly select the training sets of trajectories, and then compute the log-probability of unseen ''test'' trajectories under each model. This calculation has been repeated ten times over multiple training-test partitions of the data to generate average out-of-sample log-probability (or log-likelihood) scores as the basis of model selection. Here, we only give a simple summary of the clustering algorithm, and detailed description can be found in references [18, 20] with an application of the clustering method to ETCs over the North Atlantic. A Matlab toolbox of the above-mentioned clustering algorithm for trajectory clustering is available online at http://www.datalab.uci.edu/resources/CCT

## 3. Results

### 3.1 Climatological Characteristics of Winter ETCs

The study identified 291 winter ETCs passing over the coastal water of China in the period 1979-2017, and 171 of them are explosive cyclones. All winter ETCs including the tracks and the genesis locations are shown in Figure 1. The cyclogenesis location ranges from Mongolia to southeast coast of China. More specifically, these winter ETCs passing over the coastal water of China more frequently originate from the east coast of China. In addition, Figure 2 below shows the time series of ETC and explosive ETC numbers in winter seasons. There is obvious inter-annual variation of the number of ETC or explosive ETC. During the period 1979-2017, the average number of ETCs passing over the coastal water of China is 7.5, and 4.3 of them are explosive ones. No significant temporal trend has been detected for either ETC or explosive ETC time series.

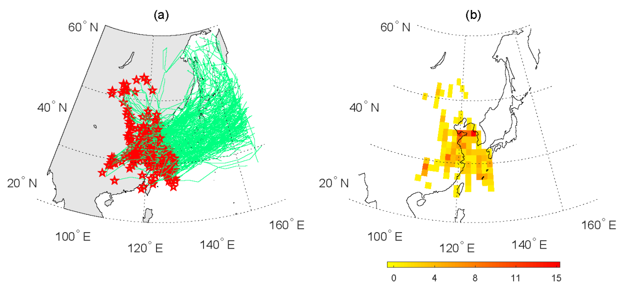


**Figure 1.** (a) Tracks and cyclogenesis positions of winter ETCs passing over the coastal water of China identified from the from the European Centre for Medium range Weather Forecasts (ECMWF) re-analysis data (1979–2017); (b) Spatial distribution of cyclogenesis positions in 1.5°lat×1.75°lon rectangle

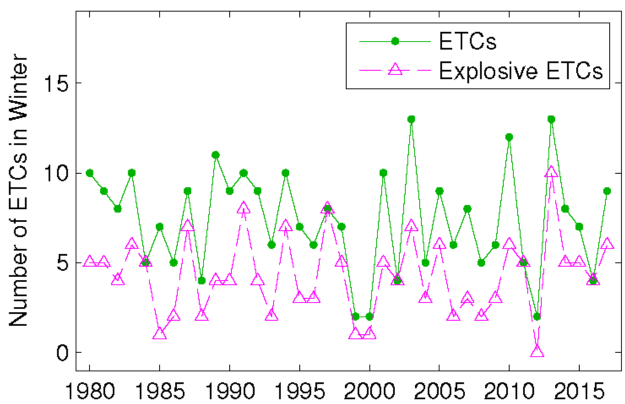


**Figure 2.** Annual time series of winter ETC number and explosive ETC number


DOI: https://doi.org/10.30564/jasr.v2i2.919

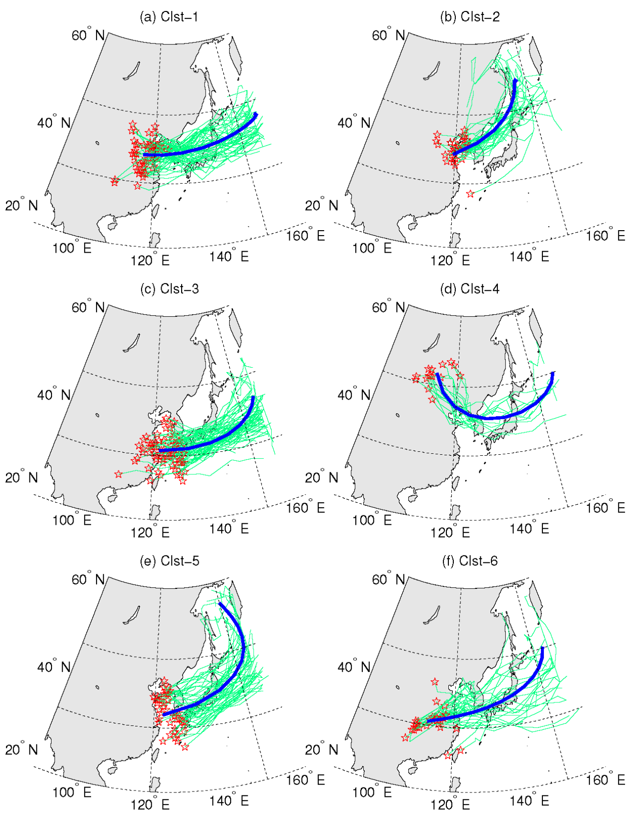


**Figure 3.** The classified Winter ETCs tracks (green) passing over the coastal water of China during the period 1979–2017 and the mean regression curve (blue curves) in each of the six clusters

In this study, a quadratic polynomial in the probabilistic clustering algorithm has been selected for the ETC tracks by visually inspecting the ETC shape (not shown as figures). The candidate cluster numbers from 4 to 9 have been evaluated, and we find that the clustering results are not sensitive to the choices between 6 and 8. The final choice of cluster number is 6 since the trajectory shapes and cyclogenesis positions could be easily distinguished. Figure 3 shows the clustered ETC tracks as well as the mean regression trajectories. The ETC tracks in cluster-1 are typical straight and usually cross Korean Peninsula and Japan. The cyclogenesis positions for ETCs in cluster-2 are similar to those in cluster-1. However, the ETCs in cluster -2 usually move northeastward rather than eastward in cluster-1. ETCs firstly cross the Korean Peninsula, then move to the Japan Sea, and decay over the Okhotsk Sea. The typical ETC tracks in cluster-3 are very similar to those in cluster-1, but the mean curve is localized farther to the south and crossing the south border of Japan. The typical tracks in clusters 4 and 5 are both recurved trajectories. ETCs in cluster-4 originate at Mongolia and move southeastward firstly, then recurve after entering China's coastal water and move eastward similar to ETCs in cluster-1. The recurving cluster-5 is more diffuse since the genesis positions occupy almost the whole east coastal waters including the Bohai Sea, Yellow Sea, and East China Sea. A few of ETCs in this cluster change their directions after entering the Northwest Pacific. The last cluster-6, also the most diffuse cluster, represents ETCs those originate at the Asian continent and move eastward to the Pacific Ocean. Figure 4 below shows all explosive ETCs for each cluster. Most explosive ETCs in winter occur at the Pacific coast or Northwest Pacific. The ratios of explosive ETCs to all ETCs in the 6 clusters are 54%, 69%, 52%, 47%, 92%, and 32%, respectively.

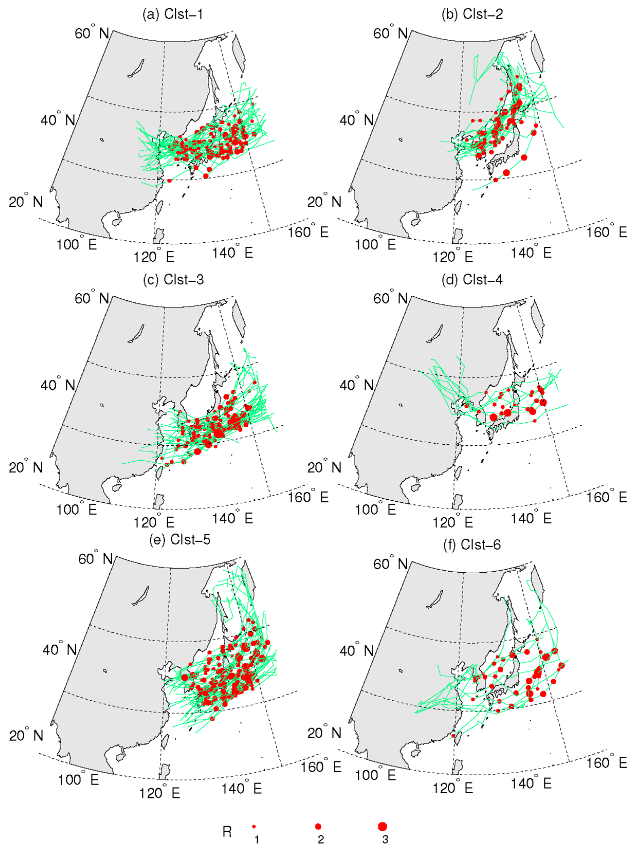


**Figure 4.** The explosive ETCs in each of the six clusters. The red dots indicate the positions with R≥1

The distributions of the ETC's lifetime, track length, minimum central SLP, and maximum deepening rate for each cluster as well as their pairwise correlations are shown in Figure 5. The smoothed probability density functions (PDFs) shown in the diagonal subplots represent the distributions of the 4 climatological characteristics. Except the lifetime and track length in cluster 3 and 5, the other distributions are dissimilar and some PDFs are bio-modal or multi-modal. The lower triangular subplots are the scatterplots, while the upper triangular subplots show the corresponding pairwise spearman correlations for the 6 clusters. Unsurprisingly, the positive correlations



DOI: https://doi.org/10.30564/jasr.v2i2.919

between the lifetime and track length are consistent in all 6 clusters. Significant negative correlations for lifetime vs. minimum central SLP, track length vs. minimum central SLP, and minimum central SLP vs. maximum deepening rate are also identified in all 6 clusters. The maximum deepening rate is also positively correlated to lifetime and track length in 5 clusters except for in cluster-2.

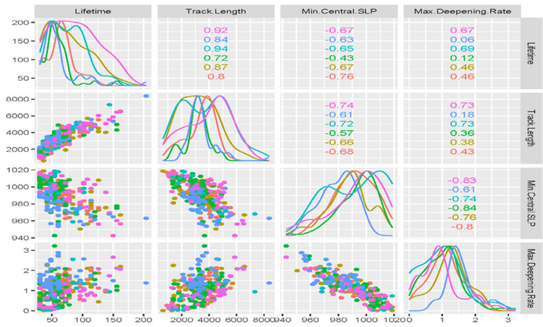


**Figure 5.** The distributions of the ETC's lifetime, track length, minimum central SLP, and maximum deepening rate for each cluster as well as their pairwise correlations. Diagonal subplots: probability distributions of the 4 climatological characteristics; lower triangular subplots: pairwise scatterplots; upper triangular subplots: pairwise spearman correlations for the 6 clusters

## 3.2. Synoptic Patterns of Winter ETCs

In this study, the synoptic patterns associated with each cluster are obtained by constructing the composite maps of atmospheric variables. For each composite map, the time steps that correspond to either the cyclogenesis position or the whole life cycle are composited. Figures 6-8 show the composite anomalies of geopotential height (500hPa level), air temperature (500hPa level), and mean SLP corresponding to the cyclogenesis days, respectively. Obviously, the cyclogenesis positions for each cluster shown in Figure 3 are consistent with the negative anomalies of geopotential height and low pressure shown in Figure 6 and 7. Moreover, the cyclogenesis positions are also consistent with the cold fronts shown in Figure 8. Since the movement of cyclone is largely determined by the large scale steering winds at mid-tropospheric level (700hPa or 500hPa). The anomalous winds composites at 500hPa during the whole life cycle of ETCs in each cluster are shown in Figure 9. The influence of the steering winds on the mean regression trajectory in each cluster is clearly revealed by the composite wind fields.

The influences of ETCs on terrestrial precipitation are also revealed by the composite maps of anomalous terrestrial precipitation during the whole life cycle of ETCs (Figure 10) in each cluster. Generally, the excessive precipitation anomalies are consistent with cyclogenesis positions or tracks. In cluster-1, the region with excessive precipitation is located at the rim of the Bohai Sea and Yellow Sea including the Korean Peninsula. However, no excessive precipitation is brought to Japan. In cluster-2, ETCs cause excessive precipitation to Korean Peninsula when moving northeastward. The influence of ETCs in cluster-3 on terrestrial precipitation is over the East China, Korean Peninsula, and South Japan. ETCs in cluster-4 originate at Mongolia and move southeastward to North China associated with excessive terrestrial precipitation anomalies. ETCs in cluster-5 mainly originate over the whole east coastal waters of China, so the influence of ETCs on precipitation anomalies is only located at the Korean Peninsula and the three southern islands of Japan. On the contrary, ETCs in cluster-6 mainly originate at the Central China and move eastward, so that the influence of ETCs on terrestrial precipitation is located at East China.

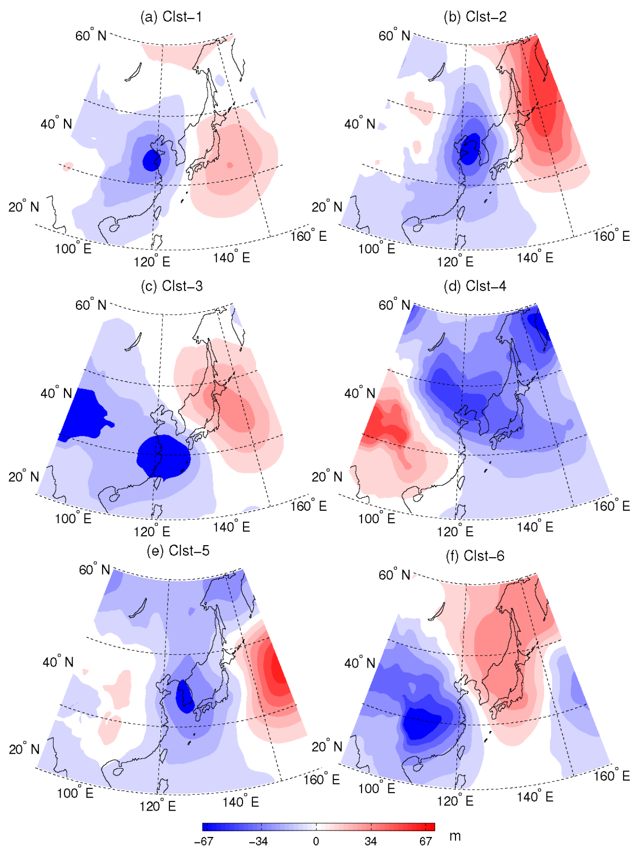


**Figure 6.** Composite of geopotential height anomalies (red and blue shading) at 500hPa level for each cluster in the period 1979-2017, based on genesis day only


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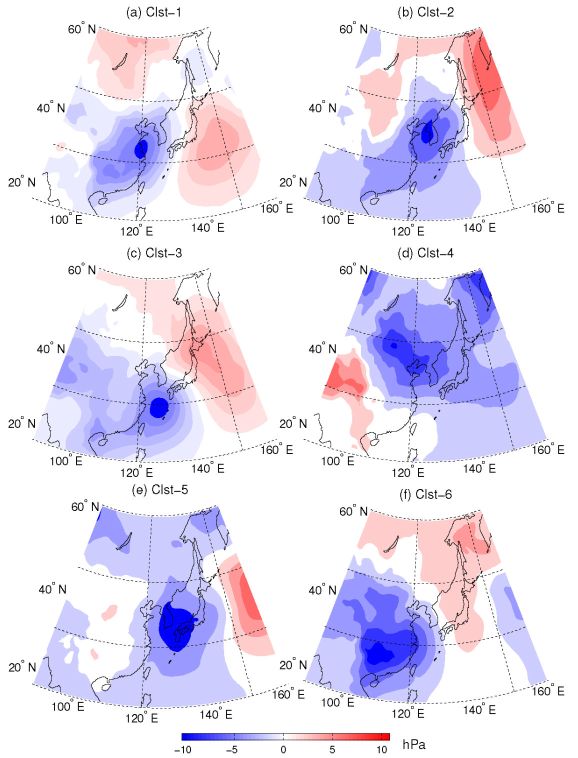


**Figure 7.** Composite of mean sea level pressure anomalies (red and blue shading) for each cluster in the period 1979-2017, based on genesis day only

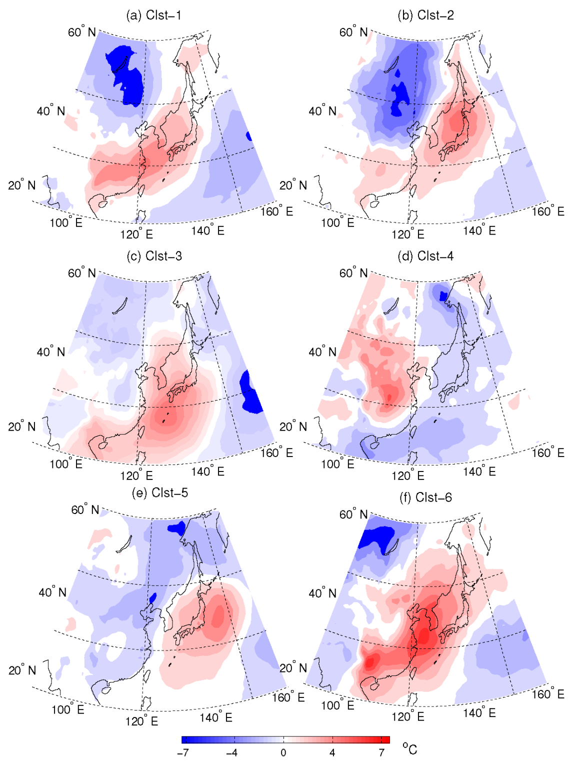


**Figure 8.** Composite of air temperature anomalies (red and blue shading) at 500hPa level for each cluster in the period 1979-2017, based on genesis day only

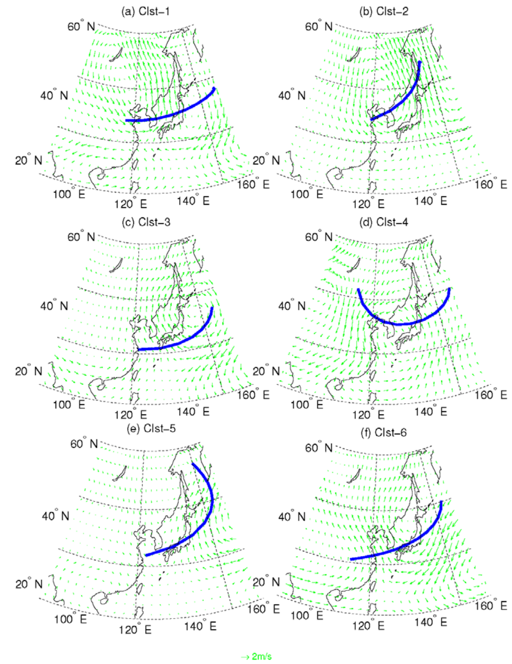


**Figure 9.** Composite of anomalous wind fields (green vectors) at 500hPa level during the whole life cycle of ETCs in each cluster for the period 1979-2017 and the mean regression curve (blue curves)

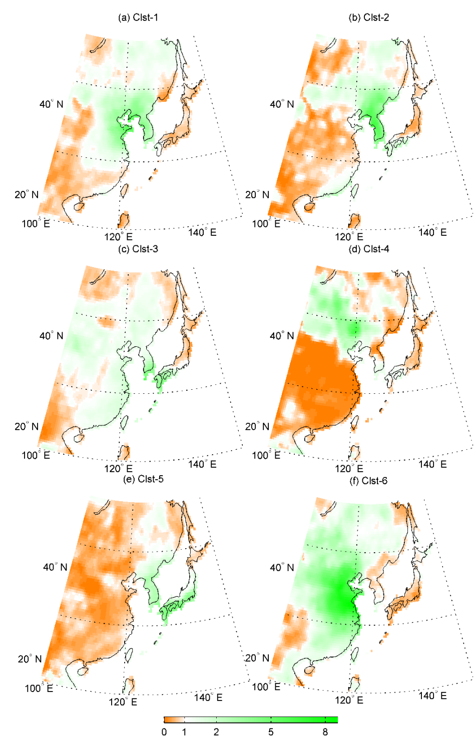


**Figure 10.** Composite of anomalous terrestrial precipitation (orange and green shading) during the whole life cycle of ETCs in each cluster for the period 1979-2017. The value of ratio smaller than one means precipitation is lower than normal years, while the value of ratio larger than one means precipitation is higher than normal years



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## 4. Discussion

The East coast of China is a vital cyclogenesis region in East Asia [22]. The climatological characteristics of ETCs passing over the coastal water of China in winter season and their impacts of terrestrial precipitation were the major objective of this study. Previous studies show that ETCs occur in the strong baroclinic zones and thermal advection often trigger the initial development of ETCs [2-9]. The ETCs developing at the East China coast might be attributable to the atmospheric baroclinicity from continent to ocean.

In this study, the ETC centers were defined in terms of relative vorticity and the tracks are obtained by combining the cyclone centers. The advantage and disadvantage of the use of relative vorticity for cyclone identification and tracking have been discussed in numerous studies [10, 17, 32, 33]. Vorticity allows for more accurate identification of the cyclone generation at stages earlier than those revealed by SLP. However, the relative vorticity is sensitive to the horizontal resolution of the data set since it is a wind-based field. The algorithm for ETC identification and tracking in this study was presented in reference [17], where all potential disadvantages have been properly considered and corrected. Zhang et al. [26] showed that there were two major cyclogenesis regions for winter ETCs in East Asia. In this study, our results are basically consistent with the previous findings. ETCs passing over China's coastal water mainly originate at the East coast of China. Other ETCs are from Mongolia and moving southeastward to the Bohai Sea and Yellow Sea. There was no significant temporal trend for the annual time series of ETC number or explosive ETC number, although there were evidence for the change of ETC frequencies and characteristics over the world [3]. Wang et al. [8] found that there was no trend over Northern Europe in the winter. Actually, the changes of ETCs were very complex including the interannual variability of ETC number and the spatial shift of ETC tracks. The changes of ETC frequencies and characteristics for a larger region, i.e. the East Asia or North Hemisphere, deserve a deeper study to a better understanding of the impacts of global climate change on cyclone activities.

ETCs have localized coherent spatial structures that generally propagate toward the east driven by the westerly [34]. The ETC population is thus most naturally described as a set of moving objects that follow various tracks and have differing individual lifecycle characteristics [18]. However, the commonly used method in atmospheric sciences such as the principal component analysis (PCA) is not suitable to analyze the cyclone trajectories, which are inherently localized in space in any given timeframe [18]. On the contrary, cluster analysis provides a natural way to analyze sets of ETC tracks and their relationships with the larger-scale atmospheric circulations, by classifying cyclone tracks into subgroups with homogeneous spatio-temporal characteristics [18,19]. Several studies have applied clustering to classify cyclone tracks including tropical cyclones and ETCs. A proper classification of ETCs is helpful to reduce case-to-case variability and allows for a highly realistic representation of specific cyclone features in composite analysis. The roles of atmospheric baroclinicity and thermal advection in triggering the development of ETCs were confirmed by the composite maps for each cluster. Previous studies also verified the passive role of sea surface temperature (SST) gradient in triggering the ETCs originating over the Gulf Stream [33]. Over China's coastal water, the influence of SST anomalies on ETC activities was verified in [9, 10, 22]. The role of SST anomalies especially the Kuroshio extension on ETC activities were not covered in this study. Much more detailed and in-depth work should be done in the future. In addition, the composite analysis also showed that anomalous wind fields at mid-tropospheric level partly explained the shapes of mean regression trajectory. An interesting finding of this study was that ETCs did not always cause excessive terrestrial precipitation during their whole lifespan. This question will be answered by a simultaneous analysis of ETC movement and vapor transportation in the next work.

## 5. Conclusions

In this study, the climatological characteristics of winter ETCs over the coastal water of China are analyzed by using clustering analysis and composite analysis. Using an objective cyclone detection and tracking algorithm, 291 ETCs have been identified from the ERA-I reanalysis dataset (1979-2017) in the study area. The ETCs are classified into 6 clusters according to their trajectory features by using the probabilistic clustering method. The synoptic patterns as well as the impact of ETC on terrestrial precipitation are presented by the composite maps. Major conclusions are summarized as follows.

The cyclogenesis positions of winter ETCs passing over the coastal water of China range from Mongolia to southeast coast of China. Most ETCs are usually weak over the coastal waters but deepening after entering the Pacific coast or Northwest Pacific. No significant temporal trend has been detected in the annual time series of ETC number. There are obvious differences for the features of ETCs in the 6 clusters. Generally, the ETC lifetime is positively correlated to track length and maximum deepening rate, but negatively correlated to minimum central


DOI: https://doi.org/10.30564/jasr.v2i2.919

SLP (Figure 5). The composite analyses show that the cyclogenesis positions are consistent with the strong baroclinic zones and cold fronts. The large scale steering winds at mid-tropospheric level partly determine the ETC movement. The composite analysis also reveals the tight association between ETCs and excessive precipitation. In summary, the clustering of ETCs is basically successful since ETCs with similar spatio-temporal characteristics have been classified into one cluster.

## Author Contributions

Conceptualization, M.G.; methodology, M.G. and N.X.; software, M.G. and N.X.; validation, M.G., N.X. and Z.G.; formal analysis, M.G.; data curation, M.G.; writing—original draft preparation, M.G; writing—review and editing, N.X. and Z.G.; supervision, M.G and Z.G.

## Funding

This work was partly supported by the Youth Innovation Promotion Association of CAS (2016195) and National Natural Science Foundation of China (31570423).

## Conflicts of Interest

The authors declare no conflict of interest.

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 DOI: https://doi.org/10.30564/jasr.v2i2.919