Classification of Development Mechanisms of Explosive Cyclones in the Kuroshio Current Area

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Abstract Based on the ERA-5 reanalysis data provided by the European Centre for Medium-range Weather Forecasts (ECMWF), the development mechanisms of explosive cyclones in the Kuroshio Current area from 2000 to 2015 were classified, and the characteristics of these explosive cyclones were analyzed by using diagnostic analysis, statistical analysis and linear fitting analysis methods. The results show that absolute vorticity advection, temperature advection, and non-adiabatic heating were the three main factors affecting the explosive development of cyclones. The development mechanisms of explosive cyclones in the Kuroshio Current area can be classified into three major categories, that is, the explosive cyclones were dominated by a single factor, two factors, or multiple factors. The explosive cyclones dominated by a single factor were mainly weak or medium, while there were fewer strong explosive cyclones and no super explosive cyclones. Among these explosive cyclones, the explosive cyclones dominated by absolute vorticity advection were the weakest, while the strongest explosive cyclones were dominated by non-adiabatic heating. The proportion of strong and supper explosive cyclones dominated by two factors was over 60%. The combination of two factors was more likely to generate strong explosive cyclones than the single-factor dominant type and the combination of three factors, among which the impact was the greatest under the combined effect of temperature advection and non-adiabatic heating. Through statistical analysis, it is concluded that non-adiabatic heating contributed the most to the explosive development of cyclones in the Kuroshio Current area, while vorticity advection had the least impact, and temperature advection had a considerable effect. In terms of seasonal characteristics, the explosive cyclones in the Kuroshio Current area mostly appeared in spring, followed by winter, while there were basically no explosive cyclones in summer and autumn.

Key words Kuroshio Current area; Explosive cyclones; Development mechanisms

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An explosive cyclone is a cyclone developing explosively, in which the central pressure (the geostrophy is adjusted to 60° N) of the cyclone drops by more than 24 hPa within 24 h, that is, the deepening rate of the central pressure is greater than 1 hPa/h[1]. Explosive cyclones are characterized by a rapid decrease in the central pressure and a sharp increase in intensity within a short period of time. Therefore, they are vividly called "weather bombs"[2]. Their horizontal scale is approximately 2 000 – 3 000 km, and their life cycle is about 2 – 5 d. The wind speed of explosive cyclones is relatively high, and can reach more than 30 m/s within an extremely short period of time[3]. They have extremely strong destructive power, and often cause disastrous weather such as huge sea waves and heavy precipitation. Their interaction with large-scale frontal systems will lead to very serious maritime accidents[4].

Many scholars at home and abroad have conducted research on the development mechanisms of explosive cyclones. Generally speaking, they can be divided into two major categories: one is the sub-weather scale dynamic development mechanism with latent heat heating as the research direction[5 – 7]. Another one focuses on the tropospheric apex folding above explosive cyclones as the research direction, with the rapid downward propagation as the dynamic development mechanism[8 – 10]. Zwack and Okossi (1986) proposed the Zwack – Okossi diagnostic equation, and provided its quasi-geodetic form. Lupo *et al.* extended the equation, and proposed the generalized form of the Zwack – Okossi equation. Many scholars at home and abroad have used the extended Zwack – Okoss equation to diagnose and analyze explosive cyclones and study their development mechanisms. Wang Jinsong *et al.*[11] used the diagnostic equations to diagnose and analyze an explosive cyclone, and explained that the explosive development of this cyclone originated from the combination of positive vorticity advection and non-ground transition fields. Among them, the contribution of vorticity advection was the greatest, while the influence of temperature advection was relatively small. Moreover, both vorticity advection and temperature advection played major roles in the upper troposphere, while non-ground transition fields play a major role in the lower troposphere. Zhang Shuqin[12] studied the most intense super-explosive cyclone cases among the explosive cyclones over the Sea of Japan and the Northwest Pacific during the cold season from 2000 to 2015, and it was concluded that the absolute vorticity advancation term, temperature advancation term and non-adiabatic term were the initiating factors for their explosive development through the diagnostic analysis of the Zwack – Okossi equation.

Studies show that the eastern part of the Sea of Japan and the northwest Pacific Ocean adjacent to the Kuroshio Current area are prone to explosive cyclones[13]. Explosive cyclones have had a severe impact on maritime navigation, production and life in the Kuroshio Current area. The interaction between the sea and the atmosphere in the Kuroshio Current area is intense, and the factors

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influencing the development of explosive cyclones are diverse. Different explosive cyclones have different dominant factors for their development. In this paper, the development mechanisms of explosive cyclones were classified, and the statistical characteristics and development mechanisms of various explosive cyclones were studied, which can provide new understanding of the occurrence and development laws of explosive cyclones. In addition, conducting in-depth research on the occurrence and development mechanisms of explosive cyclones in the Kuroshio Current area and making corresponding classifications is conducive to classifying and comparing explosive cyclones with the same development mechanism in the future, reduce and prevent natural disasters, is a guarantee for China's national defense and military activities, maritime resource development, and maritime navigation safety, and has a significant research value.

1 Data and methods

1.1 Data The data adopted in this paper are the ERA5 reanalysis data provided by the European Centre for Medium-range Weather Forecasts (ECMWF). The horizontal resolution is 0.5° ×0.5°, and the vertical section is divided into 29 layers. Data at 00:00, 06:00, 12:00, and 18:00 on the day before yesterday, the current day, and the day after tomorrow when explosive cyclones reached the maximum deepening rate were selected. The variables included seven variables such as temperature, relative humidity, vertical velocity, and absolute humidity.

1.2 Methods The generalized form of the Zwack – Okossi equation is as follows:

$$\frac{\partial \zeta_{gl}}{\partial t}=\frac{1}{p_l-p_t}\int_{p_t}^{p_l}-\vec{V}\cdot\nabla\zeta_a dp-\frac{1}{p_l-p_t}\int_{p_t}^{p_l}\left[\frac{R}{f}\int_{p}^{p_l}\nabla^2\left(-\vec{V}\cdot\nabla T+\frac{\dot{Q}}{C_p}+s\omega\right)d\ln p\right]dp+\frac{1}{p_l-p_t}\int_{p_t}^{p_l}-\vec{k}\cdot\nabla\times\vec{F}dp-\frac{1}{p_l-p_t}\int_{p_t}^{p_l}\frac{\partial\zeta_{ag}}{\partial t}dp-\frac{1}{p_l-p_t}\int_{p_t}^{p_l}\omega\frac{\partial\zeta_a}{\partial p}dp-\frac{1}{p_l-p_t}\int_{p_t}^{p_l}\left(\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p}-\frac{\partial\omega}{\partial y}\frac{\partial u}{\partial p}\right)dp+\frac{1}{p_l-p_t}\int_{p_t}^{p_l}\zeta_a\frac{\partial\omega}{\partial p}dp$$

In the formula, p_l represents the air pressure near the ground; p_t means the air pressure at the top of the atmosphere; ζ_{gl} stands for the geostrophic vorticity near the ground; $\vec{V}$ is horizontal wind vector; ζ_a represents absolute vorticity; R represents the specific gas constant of dry air; f means Coriolis parameter; $\dot{Q}$ stands for non-adiabatic heating rate; C_p is the specific heat capacity of dry air at constant pressure; S represents static stability parameter ($S=-\frac{T}{\theta}\frac{\partial\theta}{\partial p}$, where θ is potential temperature); ω means the vertical velocity in the P coordinate system; $\vec{F}$ stands for friction force; ζ_{ag} represents non-geostrophic vorticity; the rest are common meteorological symbols. The left side of the equation $\frac{\partial\zeta_{gl}}{\partial t}$ represents the tendency of geostrophic vorticity near the ground; the first three items on the right side of the diagnostic equation are absolute vorticity advection term $\frac{1}{p_l-p_t}\int_{p_t}^{p_l}-\vec{V}\cdot\nabla\zeta_a dp$, temperature advection term $-\frac{1}{p_l-p_t}\int_{p_t}^{p_l}\left[\frac{R}{f}\int_{p}^{p_l}\nabla^2(-\vec{V}\cdot\nabla T)d\ln p\right]dp$, and non-adiabatic term $-\frac{1}{p_l-p_t}\int_{p_t}^{p_l}\left[\frac{R}{f}\int_{p}^{p_l}\nabla^2\left(\frac{\dot{Q}}{C_p}\right)d\ln p\right]dp$.

Research shows that the above three items are the main factors for the eruption and development of explosive cyclones. In this paper, these three items of each explosive cyclone in the Kuroshio Current area from 2000 to 2015 were calculated by the diagnostic equation, and statistical analysis was conducted by using the K-means clustering method.

2 Classification and characteristics of the development mechanisms of explosive cyclones in the Kuroshio Current area

A total of 269 explosive cyclones in the Kuroshio Current area from 2000 to 2015 were studied based on the Zwack – Okossi diagnostic equation. After the data were standardized, 218 representative explosive cyclones were selected. Since the absolute vorticity advection term, temperature advection term and non-adiabatic term at the right end of the equation were the main factors for the explosive development of the cyclones, the average of each term was calculated based on the regional data of 10° ×10° around the cyclone center. Each average was used as the classification factor, and the proportion of each term in the total of the three terms was defined as contribution rate. K-means clustering analysis of contribution rate was conducted to obtain the classification results of the following development mechanisms.

2.1 Single-factor dominance The statistical results show that from 2000 to 2015, a total of 25 explosive cyclones in the Kuroshio Current area were dominated by non-adiabatic heating (Fig. 1), accounting for approximately 11.5% of all cyclones. The maximum deepening rate of these explosive cyclones averaged 1.44 Bergeron. Among them, 11 cyclones were weak explosive cyclones, and 9 cyclones were medium explosive cyclones, while 5 cyclones were strong explosive cyclones. The maximum deepening rate of the strongest explosive cyclone reached 2.25 Bergeron. When their deepening rate was the highest, the average of central pressure was 989.8 hPa, and the lowest pressure at the center of the cyclones averaged 967.6 hPa, while the minimum of the minimum pressure was 945.2 hPa. Over the past 16 years, a total of 14 explosive cyclones in the Kuroshio Current area were dominated by temperature advection (Fig. 2), accounting for approximately 6.4% of all cyclones. The average maximum deepening rate of these explosive cyclones was 1.33 Bergeron. Among them, 7 cyclones were weak, and 6 cyclones were medium, while 1 cyclone was strong. The maximum deepening rate of the strongest explosive cyclone was up to 1.73 Bergeron. As their deepening rate was the maximum, the average of central pressure was 993.3 hPa, and the lowest pressure at the center of the cyclones averaged 965.8 hPa, while the minimum of the minimum pressure was 953.6 hPa. From 2000 to 2015, 8 explosive cyclones were dominated by absolute vorticity advection (Fig. 3), with the proportion of about 3.7%. The average maximum deepening rate of these explosive cyclones was 1.23 Bergeron. Among them, there were 5 weak explosive cyclones, 3 medium explosive cyclones, and no strong explosive cyclones. The maximum deepening rate of the strongest explosive cyclone was 1.45 Bergeron. When their deepening rate was the maximum, the average of central pressure was 983.9 hPa, and the lowest pressure at the center of the cyclones averaged 966.6 hPa.

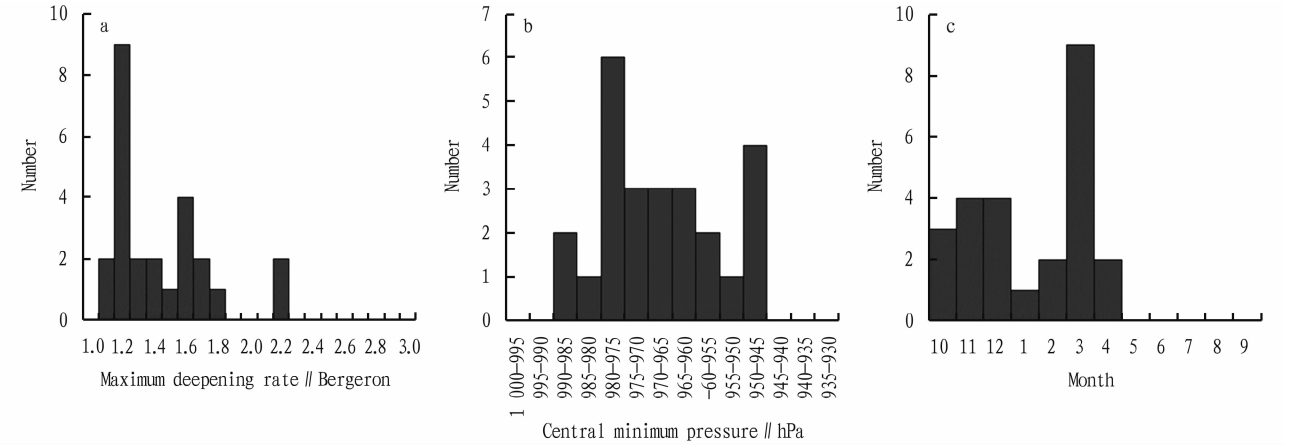


Fig. 1 **Distribution of deepening rate (a) and central minimum pressure (b), and seasonal variation (c) for the explosive cyclones dominated by non-adiabatic heating**

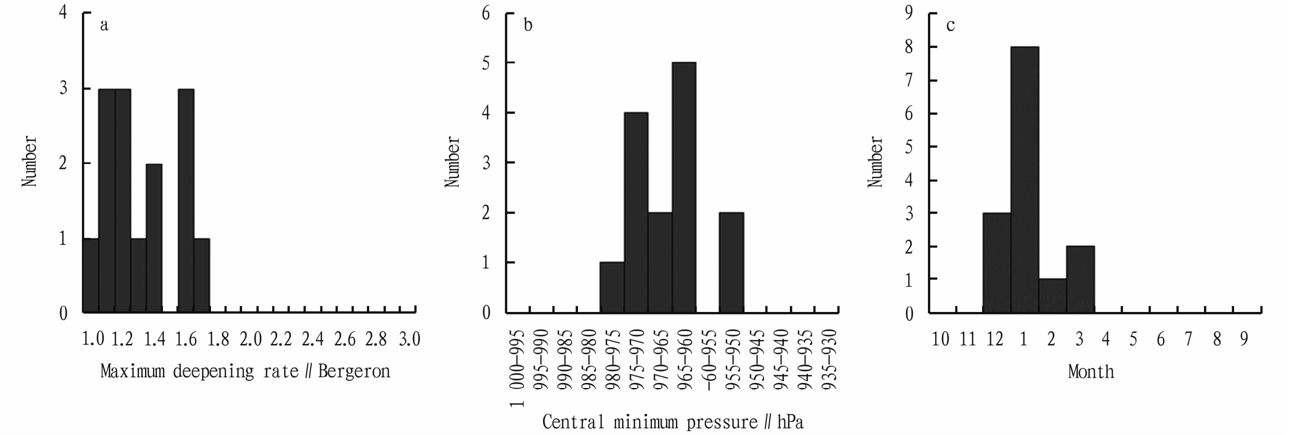


Fig. 2 **Distribution of deepening rate (a) and central minimum pressure (b), and seasonal variation (c) for the explosive cyclones dominated by temperature advection**

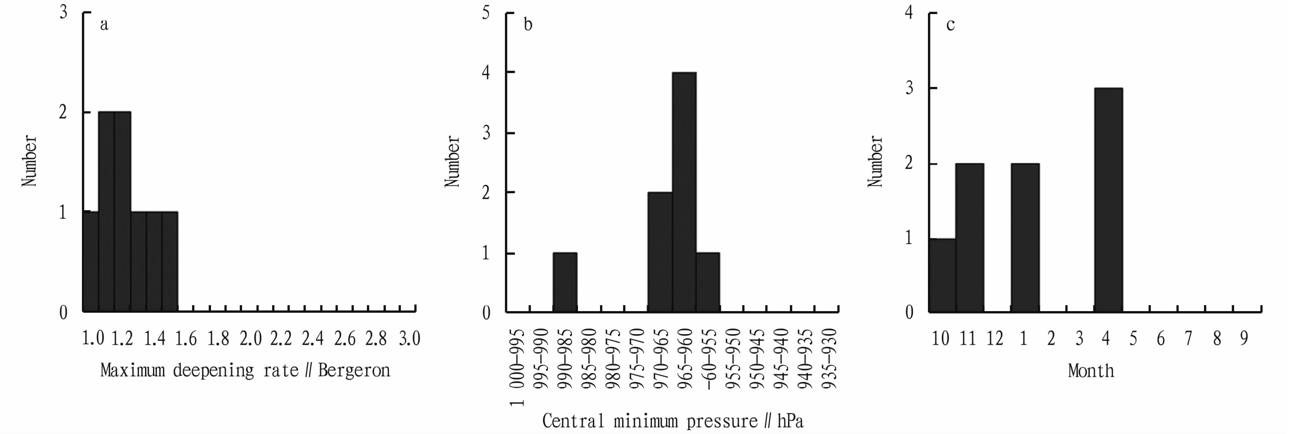


Fig. 3 **Distribution of deepening rate (a) and central minimum pressure (b), and seasonal variation (c) for the explosive cyclones dominated by absolute vorticity advection**

The explosive cyclones dominated by non-adiabatic heating occurred from January to April, October, November and December. Among them, the frequency was the highest in March, up to 9, while it was the lowest in January, only 1. This indicates that the explosive cyclones dominated by non-adiabatic heating in the Kuroshio Current area mostly occurred in spring, followed by winter; the frequency was low in autumn, and there was no explosive cyclones in summer. The explosive cyclones dominated by temperature advance occurred in January, February, March and December. Among them, the frequency was the highest in January, up to 8, while it was the lowest in February, only 1. This reveals that the explosive cyclones dominated by temperature advance in the Kuroshio Current area mostly happened in winter, and the frequency was low in spring, while no explosive cyclones occur in summer and autumn. The explosive cyclones dominated by absolute vorticity advection appeared in January, April, October and November. Among them, the frequency was the highest in April, reaching 3, while it was the lowest in October (only 1). It shows that the explosive cyclones dominated by absolute vorticity advection in the Kuroshio Current area mostly occurred in late spring and autumn, and the frequency was low in winter, while there was no explosive cyclones in summer.

2.2 Two-factor combination The statistical results reveal that from 2000 to 2015, a total of 47 explosive cyclones in the Kuroshio Current area were dominated by temperature advection and non-adiabatic heating (Fig. 4), accounting for approximately 21.6% of all cyclones. The average maximum deepening rate of these explosive cyclones was 1.48 Bergeron. Among them, there were 19 weak explosive cyclones, 17 medium explosive cyclones, 8 strong explosive cyclones, and 3 super explosive cyclones. The maximum deepening rate of the strongest explosive cyclone reached 3.07 Bergeron.

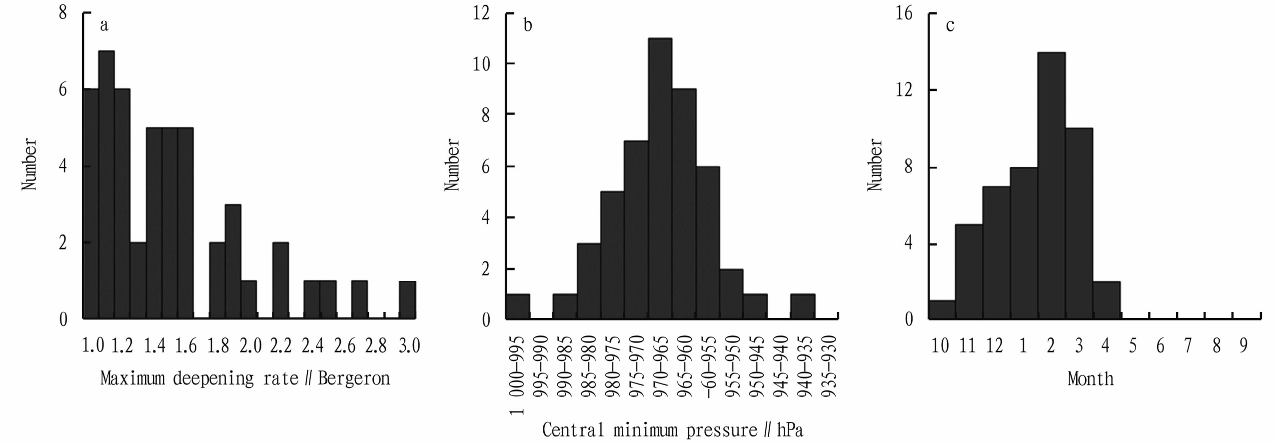


Fig. 4 Distribution of deepening rate (a) and central minimum pressure (b), and seasonal variation (c) for the explosive cyclones dominated by temperature advection and non-adiabatic heating

When the deepening rate of these explosive cyclones was the maximum, the average of central pressure was 991.6 hPa, and the lowest pressure at the center of the cyclones averaged 967.1 hPa, while the minimum of the minimum pressure at the center of the cyclones was 935.2 hPa. During the study period, a total of 45 explosive cyclones were dominated by absolute vorticity advection and non-adiabatic heating (Fig. 5), accounting for approximately 20.6% of all cyclones. The maximum deepening rate of these explosive cyclones averaged 1.48 Bergeron. Among them, these explosive cyclones included 19 weak explosive cyclones, 13 medium explosive cyclones, 12 strong explosive cyclones, and 1 super explosive cyclone. The maximum deepening rate of the strongest explosive cyclone reached 2.72 Bergeron. As the deepening rate of these explosive cyclones was the highest, the average of central pressure was 983.3 hPa, and the lowest pressure at the center of the cyclones averaged 963.7 hPa, while the minimum of the minimum pressure at the center of the cyclones was 933.6 hPa. Over the past 16 years, a total of 21 explosive cyclones in the Kuroshio Current area were dominated by absolute vorticity advection and temperature advection (Fig. 6), accounting for approximately 9.6% of all cyclones. The average maximum deepening rate of these explosive cyclones was 1.43 Bergeron. Among them, 8 cyclones were weak, and 9 cyclones were medium; 3 cyclones were strong, and 1 cyclone was super. The maximum deepening rate of the strongest explosive cyclone was up to 2.48 Bergeron. When the deepening rate of these explosive cyclones was the maximum, the average of central pressure was 986.8 hPa, and the minimum pressure at the center of the cyclones averaged 960.9 hPa, while the minimum of the minimum pressure at the center was 934.2 hPa.

The explosive cyclones dominated by temperature advection and non-adiabatic heating occurred from January to April and from October to December. Among them, the frequency was the highest in February, up to 14, while it was the lowest in October (only 1). This indicates that in the Kuroshio Current area, the explosive cyclones dominated by temperature advection and non-adiabatic heating mostly happened in spring, while no explosive cyclones occurred in summer. The explosive cyclones dominated by absolute vorticity advection and non-adiabatic heating appeared from January to April and from October to December. Among them, the number of the explosive cyclones were the largest in December, reaching 11, while it was the smallest in October (only 2). It shows that the explosive cyclones dominated by absolute vorticity advection and non-adiabatic heating in the Kuroshio Current area mostly occurred in winter, followed by spring, and no explosive cyclones happened in summer. The explosive cyclones dominated by absolute vorticity advection and temperature advection occurred from January to April and in November and December. Among them, the number of the explosive cyclones was the largest in December, up to 9, while it was the lowest in April (only 1). This reveals that in the Kuroshio Current area, the explosive cyclones dominated by absolute vorticity advection and temperature advection mostly occurred in winter and spring, while no explosive cyclones appeared in summer.

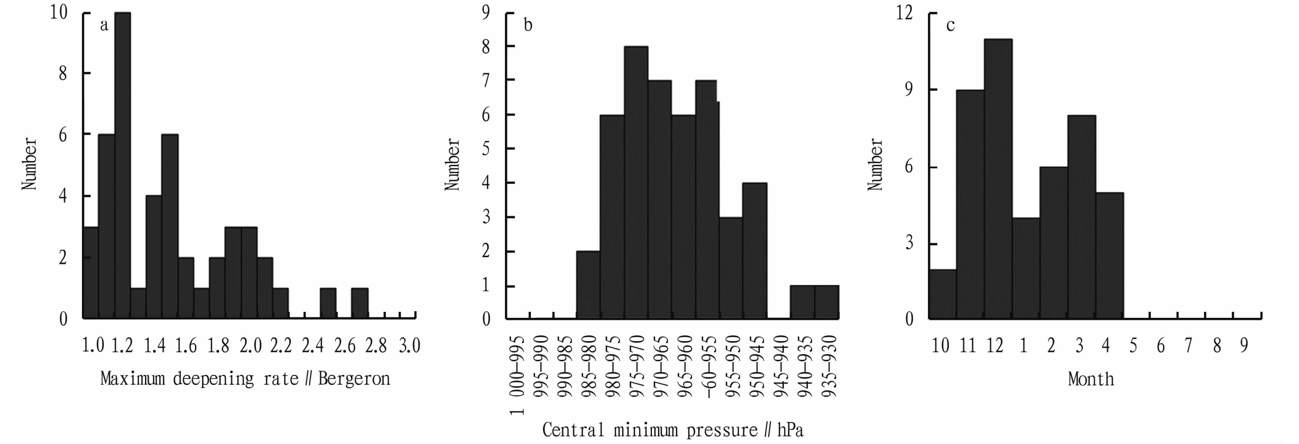


Fig. 5 Distribution of deepening rate (a) and central minimum pressure (b), and seasonal variation (c) for the explosive cyclones dominated by absolute vorticity advection and non-adiabatic heating

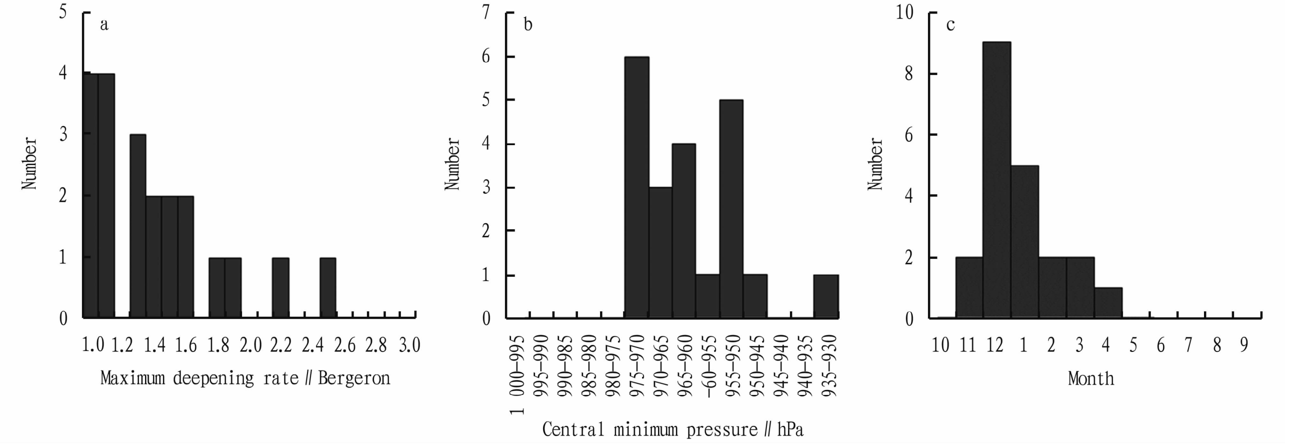


Fig. 6 Distribution of deepening rate (a) and central minimum pressure (b), and seasonal variation (c) for the explosive cyclones dominated by absolute vorticity advection and temperature advection

2.3 Combination of absolute vorticity advection, temperature advection and non-adiabatic heating The statistical results show that over the past 16 years, a total of 59 explosive cyclones in the Kuroshio Current area were dominated by absolute vorticity advection, temperature advection and non-adiabatic heating (Fig. 7), accounting for approximately 27.1% of all cyclones. The maximum deepening rate of these explosive cyclones averaged 1.47 Bergeron. Among them, there were 27 weak explosive cyclones, 20 medium explosive cyclones, 9 strong explosive cyclones, and 2 super explosive cyclones. The maximum deepening rate of the strongest explosive cyclone reached 2.84 Bergeron. As the deepening rate of these explosive cyclones was the maximum, the average of central pressure was 990.2 hPa, and the minimum pressure at the center of the cyclones averaged 966.3 hPa; the minimum of the minimum pressure at the center was 945 hPa, and the maximum of the minimum pressure at the center was 983.2 hPa. In addition, these explosive cyclones occurred from January to April and in November and December. Among them, the number of these explosive cyclones was the largest in February, reaching 18, while it was the smallest in April (only 3). It indicates that in the Kuroshio Current area, the explosive cyclones dominated by absolute vorticity advection, temperature advection and non-adiabatic heating mainly happened in winter and spring, while no explosive cyclones occurred in summer and autumn.

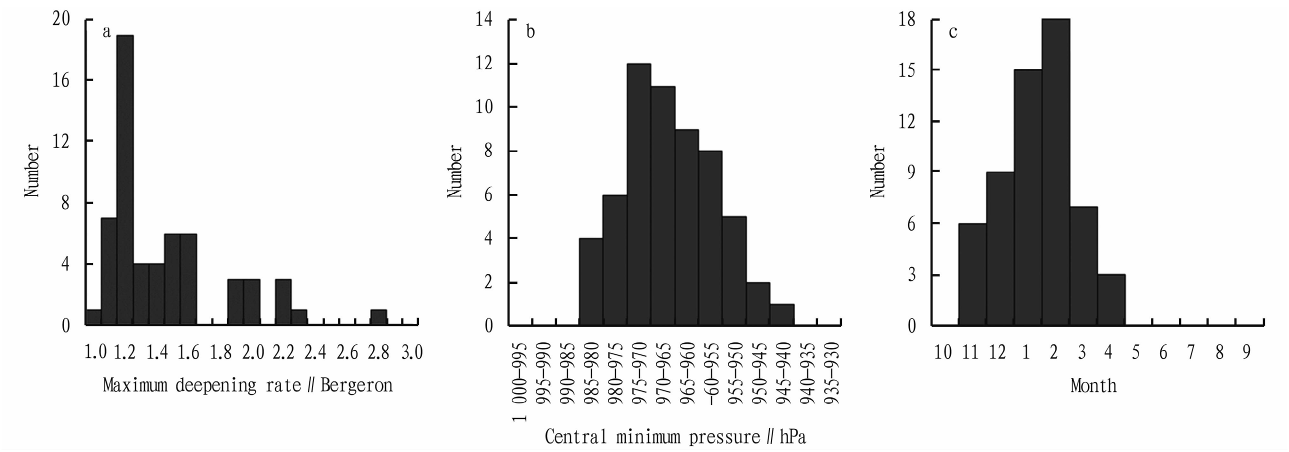


Fig. 7 Distribution of deepening rate (a) and central minimum pressure (b), and seasonal variation (c) for the explosive cyclones dominated by absolute vorticity advection, temperature advection and non-adiabatic heating

2.4 Relationship between the intensity of explosive cyclones and dominant factors According to statistics (Fig. 8), 96 explosive cyclones were weak, accounting for approximately 44% of all cyclones. 23 explosive cyclones were dominated by a single factor, and the number accounted for about 24% of the total number of weak explosive cyclones. Among them, the number of weak explosive cyclones dominated by non-adiabatic heating, temperature advection, and absolute vorticity advection was 11, 7 and 5, respectively. 46 explosive cyclones were dominated by two factors, accounting for approximately 47.9% of the weak explosive cyclones. Among them, the number of weak explosive cyclones dominated by absolute vorticity advection and non-adiabatic heating or temperature advection and non-adiabatic heating was 19, accounting for approximately 82.63% of the total number of explosive cyclones dominated by two factors. 8 explosive cyclones were dominated by absolute vorticity advection and temperature advection. 27 explosive cyclones were dominated by absolute vorticity advection, temperature advection and non-adiabatic heating, and the number accounted for approximately 28.1% of the total number of weak explosive cyclones.

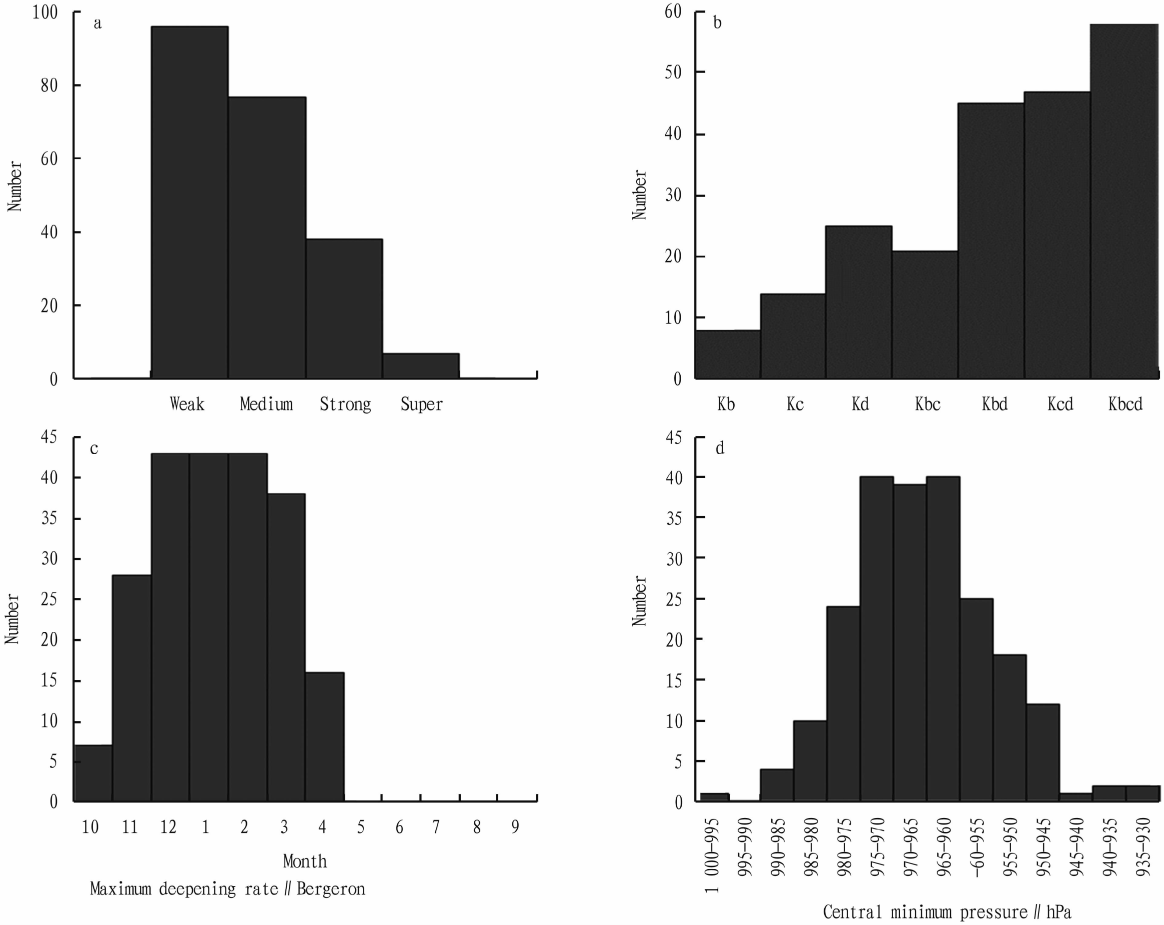
77 explosive cyclones were medium, accounting for approximately 35.3% of all explosive cyclones. 18 explosive cyclones were dominated by a single factor, making up about 23.4% of medium explosive cyclones. Among them, the number of medium explosive cyclones dominated by non-adiabatic heating, temperature advection, and absolute vorticity advection was 9, 6 and 3, respectively. 39 explosive cyclones were dominated by two factors, accounting for approximately 50.6% of the medium explosive cyclones. Among them, the number of medium explosive cyclones dominated by temperature advection and non-adiabatic heating, absolute vorticity advection and non-adiabatic heating, as well as absolute vorticity advection and temperature advection was 17, 13, and 9, respectively. There were 20 medium explosive cyclones dominated by absolute vorticity advection, temperature advection and non-adiabatic heating, and the number accounted for approximately 26% of the total number of medium explosive cyclones.

There were 38 strong explosive cyclones, accounting for approximately 17.4% of all explosive cyclones. There were 6 strong explosive cyclones dominated by a single factor, among which 5 explosive cyclones were dominated by non-adiabatic heating, and 1 explosive cyclone was dominated by temperature advection. 23 strong explosive cyclones were dominated by two factors, accounting for approximately 60.5% of the strong explosive cyclones. There were 12 strong explosive cyclones dominated by absolute vorticity advection and non-adiabatic heating, 8 strong explosive cyclones dominated by temperature advection and non-adiabatic heating, and 3 strong explosive cyclones dominated by absolute vorticity advection and temperature advection. 9 strong explosive cyclones were dominated by absolute vorticity advection, temperature advection and non-adiabatic heating, accounting for approximately 23.7% of the strong explosive cyclones.

There were 7 super explosive cyclones, accounting for 3.3% of all cyclones. The number of super explosive cyclones dominated by two factors was 5, among which there was one super explosive cyclone dominated by absolute vorticity advection and temperature advection or absolute vorticity advection and non-adiabatic heating. 3 super explosive cyclones were dominated by temperature advection and non-adiabatic heating. There were 2 super explosive cyclones dominated by absolute vorticity advection, temperature advection and non-adiabatic heating, accounting for about 28.6% of the super explosive cyclones.

From 2000 to 2015, explosive cyclones in the Kuroshio Current area mainly occurred in spring, followed by winter; there were fewer explosive cyclones in autumn and no explosive cyclones in summer. Among the explosive cyclones dominated by a single factor, the explosive cyclones dominated by absolute vorticity advection, temperature advection or non-adiabatic heating occurred frequently in spring. For the explosive cyclones dominated by two factors, the explosive cyclones dominated by temperature advection and non-adiabatic heating happened frequently in spring. For three factors, the explosive cyclones dominated by absolute vorticity advection, temperature advection and non-adiabatic heating appeared frequently in spring. The explosive cyclones occurring frequently in winter were dominated by two factors, namely absolute vorticity advection and temperature advection, as well as absolute vorticity advection and non-adiabatic heating.

Between 2000 and 2015, the central minimum pressure of explosive cyclones in the Kuroshio Current area was basically between 945 and 985 hPa, and the number of these explosive cyclones accounted for 95.4% of the total number. Among them, the majority were concentrated between 960 and 975 hPa, accounting for approximately 54.6% of the total number. The central minimum pressure of the explosive cyclones dominated by a single factor was not lower than 945 hPa, while that of the explosive cyclones dominated by two or three factors was basically lower than 945 hPa.



Note: Kb. Absolute vorticity advection; Kc. Temperature advection; Kd. Non-adiabatic heating; Kbc. Combination of absolute vorticity advection and temperature advection; Kbd. Combination of absolute vorticity advection and non-adiabatic heating; Kcd. Combination of temperature advection and non-adiabatic heating; Kbcd. Combination of absolute vorticity advection, temperature advection, and non-adiabatic heating.

Fig. 8 Intensity (a), type (b), seasonal (c) and central minimum pressure distribution (d) of explosive cyclones in the Kuroshio Current area during 2000 –2015

All three types of the explosive cyclones dominated by two factors had relatively low central pressure. The central minimum pressure of a medium explosive cyclone dominated by absolute vorticity advection and temperature advection was 934.2 hPa, which was the lowest value of the central minimum pressure of this type of explosive cyclones. The central minimum pressure of a supper explosive cyclone dominated by absolute vorticity advection and non-adiabatic heating was 933.6 hPa, which was the lowest value of the central minimum pressure of all explosive cyclones. The central minimum pressure of a supper explosive cyclone dominated by temperature advection and non-adiabatic heating was 935.2 hPa, which was the lowest value of the central minimum pressure of this type of explosive cyclones. The central minimum pressure of explosive cyclone dominated by three factors was relatively stable, fluctuating slightly within the range of 10 hPa around the average of central minimum pressure.

3 Conclusions and discussion

Based on the ERA-5 reanalysis data provided by the European Centre for Medium – Range Weather Forecasts (ECMWF), by using diagnostic analysis, statistical analysis and correlation analysis methods, the explosive cyclones in the Kuroshio Current area from 2000 to 2015 were studied to reveal the diversity of their development mechanisms, and the characteristic of explosive cyclones with different development mechanisms were analyzed. The main conclusions are as follows.

(1) The development mechanisms of explosive cyclones in the Kuroshio Current area can be classified into three types, that is, they were dominated by a singe factor (absolute vorticity advection, temperature advection, or non-adiabatic heating), two factors (the combination of absolute vorticity advection and temperature advection, absolute vorticity advection and non-adiabatic heating, or temperature advection and non-adiabatic heating),

and three factors (absolute vorticity advection, temperature advection, and non-adiabatic heating).

(2) The explosive cyclones dominated by a single factor were generally weak or medium, while the number of strong explosive cyclones was relatively small, and there were no super explosive cyclones. Among these explosive cyclones, the explosive cyclones dominated by absolute vorticity advection were the weakest, while the strongest explosive cyclones were dominated by non-adiabatic heating.

(3) The proportion of strong and supper explosive cyclones dominated by two factors exceeded 60%. The combination of two factors was more likely to generate strong explosive cyclones than the single-factor dominant type and the combination of three factors, among which the influence was the greatest under the combined effect of temperature advection and non-adiabatic heating.

(4) In terms of seasonal characteristics, the explosive cyclones in the Kuroshio Current area mostly occurred in spring, followed by winter. There were basically no explosive cyclones in summer and autumn.

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termination indicators suitable for Yushu area were extracted.

(1) Within the range of 50 km, short-term heavy precipitation mostly occurred at night. The central intensity of the echoes was generally ⩾45 dBZ (with the maximum of 60 dBZ), and the top height of the echoes was ⩾8 km (with the average of about 12 km). VIL was mainly 8 – 12 kg/m^2, and radial velocity often exceeded 22 m/s. If dual polarization parameters show the presence of dense flat large particles, it can be determined that short-term heavy precipitation may occur. When VIL is lower than 8 kg/m^2, a comprehensive judgment should be made in combination with the movement speed and trigger conditions.

(2) When the detection range was 100 km, precipitation was concentrated after dusk. The echo intensity was generally ⩾ 40 dBZ (the maximum exceeded 50 dBZ), and the top height of the echoes was ⩾8 km (averaging 13 km). VIL was ⩾8 kg/m^2 (the average maximum was 15 kg/m^2), and movement speed was ⩾22 m/s. As the influence of strong echoes lasts for more than six times of scanning and dual polarization parameters show dense flat large particles, short-term heavy precipitation may happen. The above two indicators can be used as key judgment bases.

(3) Within the range of 150 km, heavy precipitation mainly occurred in the evening. The echo intensity was ⩾45 dBZ (the maximum was up to 58 dBZ), and the top height of the echoes was ⩾15 km. VIL was ⩾7 kg/m^2 (the average maximum was 17 kg/m^2), and movement speed was ⩾22 m/s. Short-term heavy precipitation may appear as the continuous influence of the strong echoes and high VIL lasts for more than 3 times of scanning and there are dense flat large particle signals. The two phenomena can be used as judgment conditions.

(4) In areas over 150 km away, precipitation mostly occurred at night, and flat large particles appeared in some processes. Due to the limitations of integrity and accuracy of radar data, it is necessary to comprehensively assess the possibility of short-term heavy precipitation under the conditions of echo intensity ⩾45 dBZ, the top height of the echoess ⩾13 km, and significant changes in VIL based on other monitoring data.

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