# ANALYSIS OF COMPOSITE DIAGNOSIS OF OCEANIC EXPLOSIVE CYCLONES*

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ABSTRACT

Using the data of ECMWF (European Center for Medium-range Weather Forecasts) to undertake composite diagnoses of 16 explosive cyclones occurring at the Atlantic and the Pacific Oceans, it is found that there are a lot of obvious discrepancies on the basic fields between these strong and weak explosive cyclones. The major reasons why the explosive cyclones over the Atlantic are stronger than those over the Pacific Ocean are that the non-zonal upper jet and the low-level warm moist flow over the Atlantic are stronger. The non-zonal upper jet offers stronger divergence, baroclinicity and baroclinic instability fields for explosive cyclones. Anticyclonic curvature at the high level of strong explosive cyclones is easy to make the inertia-gravitational wave developing at the moment of northward transfer of energy and stimulate the cyclones deepening quickly. Warm advection and diabatic heating can cause the upper isobaric surface lifting, as a result, the anticyclone curvature of cyclones enlarges, and wave energy develops easily as well. The most powerful period of the development of explosive cyclones is just the time when the positive vorticity advection center is located over the low vortex. At the upper level, when the distribution of potential vorticity contours changes suddenly from rareness to denseness, and the large values of the potential vorticity both in the west and north sides of cyclones extend downwards together, then cyclones are easy to explosively develop. The formation of strong explosive cyclones is closely related with the non-zonality of upper jet and the anticyclonic curvature.

**Key words**: explosive cyclones, the Pacific Ocean, the Atlantic Ocean, composite diagnoses, non-zonal upper jet

## I. INTRODUCTION

The concept of explosive cyclones was first proposed by Sanders and Gyakum (1980) who viewed the extratropical cyclones with a sea level pressure falling to or below a value of $24\sin\varphi/\sin 60°$hPa ($\varphi$ is the latitude of the cyclone center) within 24 hours as explosive cyclones. Their characteristics are that their surface central pressure decreases sharply in a short time and usually falls over 24 hPa within 24 hours. Some even fall by 27 hPa within 6 hours (Reed and Albright 1986). The wind speed near cyclones increases quickly to 30 m/s or more. The occurrence of explosive cyclones comes along with blizzard and other

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severe weather, and often does serious damage to sailing and working on the sea. Therefore, more attention has been paid to explosive cyclones by scientists.

At the early stage, the study of explosive cyclones was based on statistical analysis (Sanders and Gyakum 1980; Murty et al. 1983; Zhang and Chen 1992). The primary conclusions were the following: explosive cyclones mainly occurred over the Pacific Ocean and the west coast of the Atlantic Ocean; explosive cyclones were more frequent over the Pacific; but comparatively the strong explosive cyclones mainly occurred over the Atlantic Ocean. The recent statistical analysis came to the similar conclusions (Ding et al. 1998).

In the past 20 years, the physical causes for the occurrence and the development of explosive cyclones have been very well researched by a lot of scholars. The study by Robert et al. (1996) showed that the composite roles among the positive vorticity advection over the middle level of the troposphere, the warm advection, the diabatic heating process and the surface energy flux were the essential factors to influence the developing of explosive cyclones. Anthes et al. (1983) emphasized the important role of baroclinic instability to explosive cyclones. Rogers and Bogart (1986) emphasized the function of baroclinicity and latent heating of convection condensation in their study of the Atlantic cyclones. Uccellini and Keyser (1985) pointed out that the divergence area at the north of upper jet offered dynamic conditions to the development of explosive cyclones. Through the studies of explosive cyclones in two different tracks, Lu and Sun (1996) suggested that the downward extending of the flow with high potential vorticity in the upper troposphere was an important factor for the explosive developing of cyclones. Cyclones moved towards the upper-level high potential vorticity center during the explosive period and developed in the area where the potential vorticity of upper and lower levels joined up. Xu et al. (1996) showed that the dominant factor for the explosive development of cyclones was the maximum heating level which was relevant to latent heating, while the total amount of heating, i. e. the degree of heating, was in a subordinate position. The lower height of maximum heating level of oceanic cyclones was favorable to the explosive development of cyclones.

To sum up, researchers have made plenty of studies on the extrotropical oceanic explosive cyclones and have gotten a lot of accomplishments. But these studies are focused on the Atlantic and usually analyzed a single example. Comparatively speaking, little study is carried out on the similarities and differences of explosive cyclones between the Pacific and the Atlantic Oceans. This paper will use the method of composite analysis to research the general characteristics of explosive cyclones. Based on the comparative analysis, the discrepancies of explosive cyclones between the Pacific and the Atlantic Oceans and the causes for discrepancies have been studied, and the formation mechanism of the explosive cyclones have been analyzed according to both the above studies and the discrepancies between strong and weak explosive cyclones.

## II. SAMPLES, DATA AND COMPOSITE METHOD

Sixteen samples with intensity over 1. 1 Bergeron (1 Bergeron $= \Delta P_{24} \sin 60° / (24 \sin \varphi)$), were chosen over the Pacific and the Atlantic Oceans in the Northern Hemisphere. Here $\Delta P_{24}$ is the decreased value of surface pressure in 24 hours, $\varphi$ is ditto, and Bergeron is abbreviated to B hereinafter. Composite diagnosis and contrastive analysis are carried out for these 16 samples (each 8 samples over the Pacific and the Atlantic Oceans respectively). The data of selected samples are all grid points of ECMWF at 0012 UTC of 2.5°×2.5° longitude and latitude grid and have been interpolated to 90 km square grid.

According to the definition of explosive cyclones, the time when the decreased value of the surface pressure reaches the explosive standard is called as "Explosion", 24 hours before the Explosion is called "Pre-Explosion", and 24 hours after the Explosion is called "Post-Explosion". Table 1 lists locations and intensities of 16 surface cyclones at the three periods. Explosive cyclones over 1.5B are simply called as "strong cyclones", and those from 1.1B to 1.5B are called as "weak cyclones". And we diagnose the cyclones over the Pacific and the Atlantic Oceans according to their classifications.

**Table 1.** Intensities and Locations in the Stage of Pre-Explosion, Explosion, and Post-Explosion

| Region | Date | Intensity | Location of cyclone center | | |
|---|---|---|---|---|---|
| | | | Pre-Explosion | Explosion | Post-Explosion |
| The Pacific | 3—5 Apr., 1984 | 1.3B | 56°N, 172°E | 52°N, 179°W | 54°N, 179°E |
| | 22—24 Mar., 1986 | 1.5B | 30°N, 133°E | 35°N, 142°E | 40°N, 156°E |
| | 14—16 Jan., 1984 | 1.5B | 43°N, 135°E | 46°N, 143°E | 49°N, 154°E |
| | 7—9 Jan., 1983 | 1.7B | 42°N, 131°E | 47°N, 145°E | 52°N, 151°E |
| | 25—27 Mar., 1985 | 1.8B | 32°N, 170°E | 32°N, 179°E | 45°N, 180 |
| | 5—7 Feb., 1980 | 1.9B | 40°N, 145°E | 41°N, 160°E | 45°N, 179°E |
| | 9—11 Oct., 1982 | 2.1B | 45°N, 173°E | 47°N, 173°W | 55°N, 160°W |
| | 10—12 Mar., 1984 | 2.2B | 35°N, 145°E | 41°N, 154°E | 44°N, 171°E |
| The Atlantic | 10—12 Jan., 1981 | 1.1B | 35°N, 70°W | 51°N, 66°W | 64°N, 60°W |
| | 17—19 Jan., 1981 | 1.2B | 37°N, 66°W | 46°N, 60°W | 51°N, 55°W |
| | 25—27 Jan., 1985 | 1.2B | 41°N, 85°W | 40°N, 62°W | 49°N, 45°W |
| | 13—15 Feb., 1982 | 1.3B | 37°N, 74°W | 44°N, 53°W | 54°N, 40°W |
| | 8—10 Nov., 1982 | 1.6B | 46°N, 40°W | 55°N, 27°W | 62°N, 10°W |
| | 15—17 Feb., 1986 | 1.6B | 40°N, 66°W | 45°N, 55°W | 51°N, 50°W |
| | 14—16 Jan., 1982 | 2.1B | 30°N, 82°W | 40°N, 63°W | 49°N, 54°W |
| | 17—19 Dec., 1982 | 2.2B | 45°N, 61°W | 60°N, 30°W | 58°N, 15°W |

The method of composite analysis has the following procedures. First of all, 16 samples are classified into two kinds according to their locations (the Atlantic or the Pacific Oceans), then they are further classified into "strong cyclones" and "weak cyclones", and are finally classified into "Pre-Explosion", "Explosion" and "Post-Explosion" according to the cyclones' explosive time. The position of the center of each surface cyclone is regarded as a center, then 17 grid points with a grid spacing of 90 km are extended along east-west and south-north directions from the center respectively, namely a domain of 35×35 is obtained. Composite average of the basic fields in the domain is conducted, and composite data are used to calculate the physical quantities of the compound cyclones, such as the divergence, vorticity, thermal advection, vorticity advection, potential equivalent temperature, and the upper as well as lower jets. When cross-section analysis is done, the physical quantities are interpolated into the 18 levels in the vertical by use of the Lagrange interpolation formula (spacing: 50 hPa).

## III. DIAGNOSIS AND COMPARISON OF THE BASIC FIELDS

The fields of height, temperature and wind are used as the basic fields to analyze the cyclone's situation in the periods Pre-Explosion, Explosion and Post-Explosion over the two oceans.

### 1. *Pre-Explosion*

At 850 hPa (not shown) in the period of Pre-Explosion, it can be seen that the

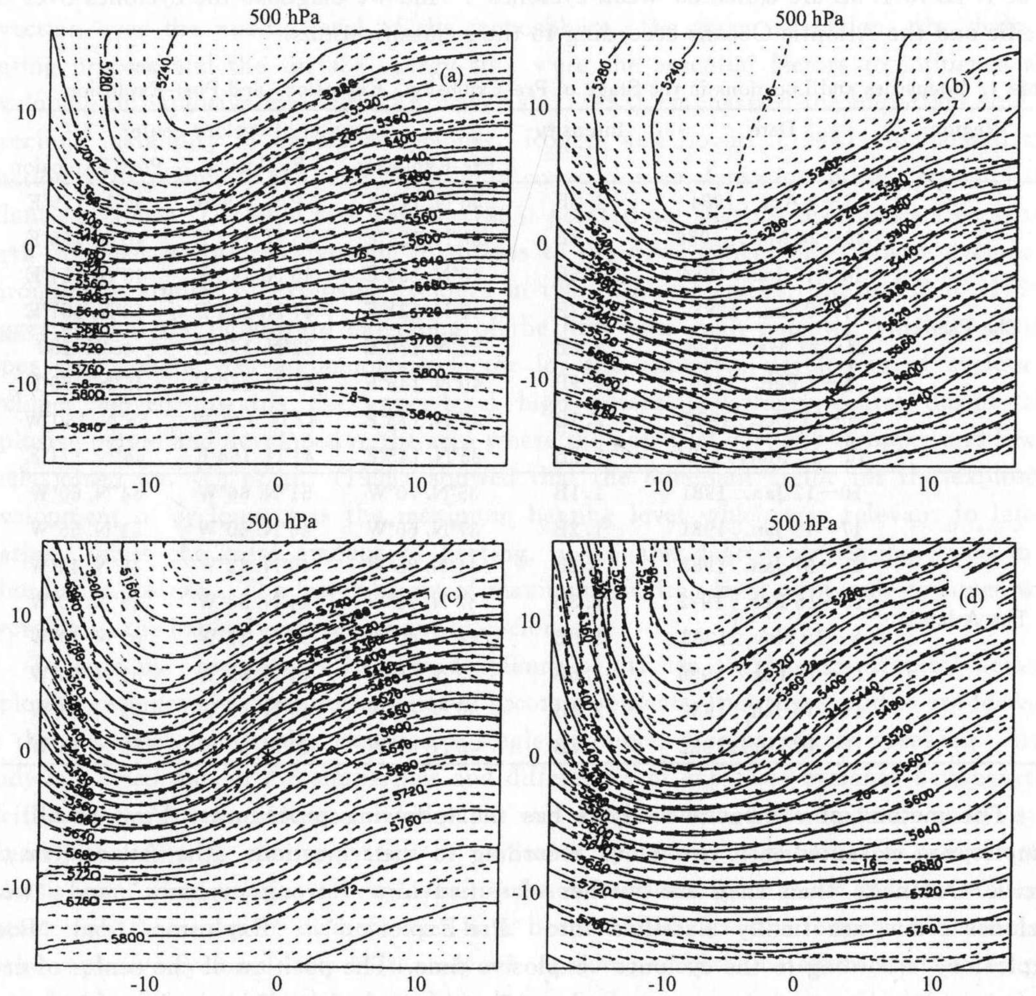


Fig. 1. During Pre-Explosion, 500 hPa temperature (°C, dashed), height (m, solid) and wind vector (m $s^{-1}$, arrow) fields of strong cyclone (left, a, c) and weak cyclone (right, b, d) over the Pacific (top row, a, b) and the Atlantic (bottom row, c, d). The $x$ and $y$-coordinate both denote the distance of departing the cyclone center (×90 km). Cyclone center is shown with asterisk.

gradient of isothermal and the wind speed of strong cyclones are larger than those of weak cyclones over the two oceans. Over the Pacific Ocean, the central maximum wind speed of the strong cyclones is 26 m/s, and that of the weak cyclones is 21 m/s. And it is 28 m/s and 20 m/s over the Atlantic Ocean respectively.

At 500 hPa (Fig. 1), the cyclones of two kinds over the Pacific are all located in front of an upper trough, and the bottom scope of the upper trough is wider. The distance from the strong cyclone's center to the upper trough line is farther than that of the weak cyclones, with a larger curvature of the trough. Over the Atlantic, the trough is located at the rear of the strong cyclones and the southwest wind in front of the trough is strong. The flow of the weak cyclones over the two oceans is even and straight comparatively, and the wind speed is small.

At 200 hPa (Fig. 2), both the strong and weak cyclones over the Pacific are located on the axis of the upper jet ($J_H$) and at the rear of jet center. The corresponding wind speed

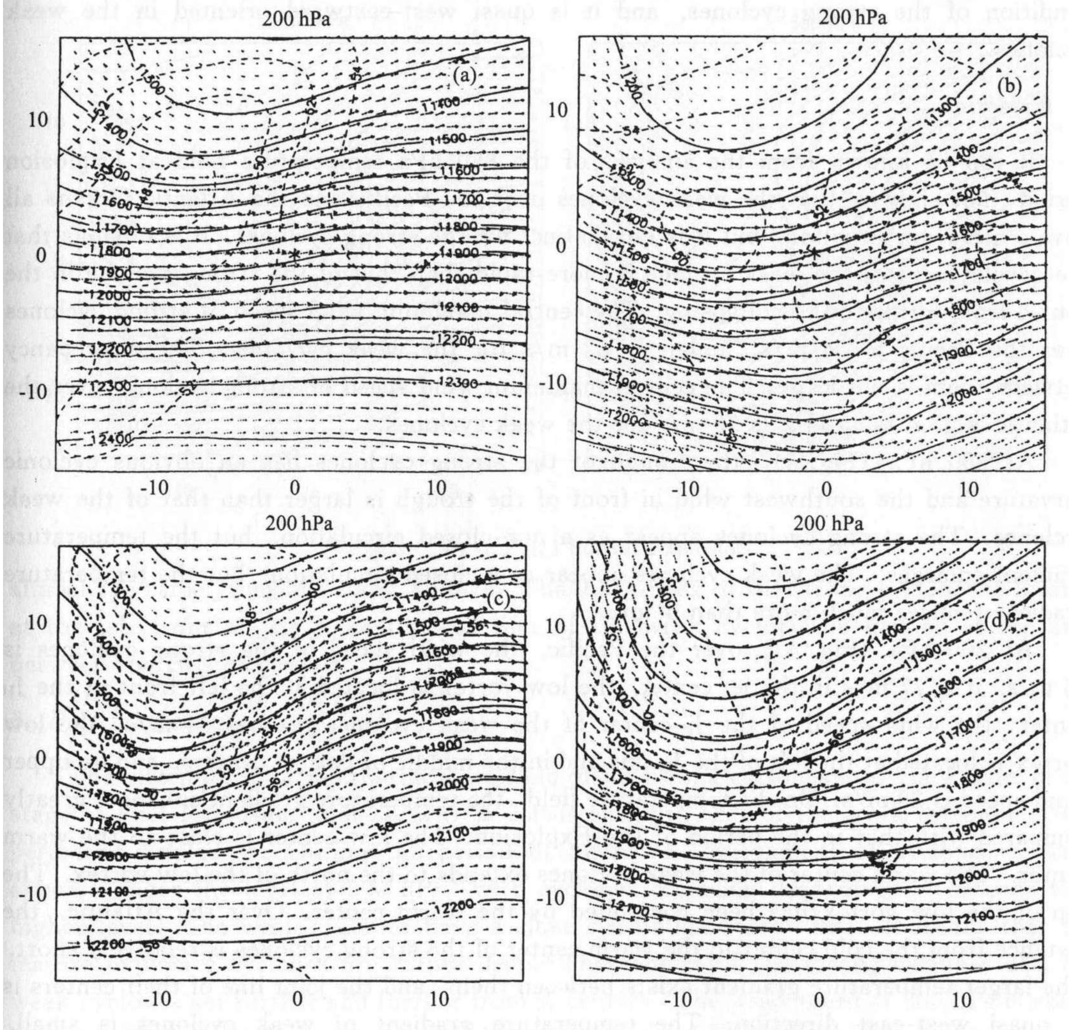


Fig. 2. As in Fig. 1 but for 200 hPa.

of the weak cyclones is 50 m/s, and it is 55 m/s in the $J_H$ center. The corresponding wind speed of the strong cyclones is 72 m/s, and it is 74 m/s in the $J_H$ center. In the temperature field, there are warm centers in the west of the cyclonic centers, and cold centers in the east of the cyclonic centers, and the strong temperature gradient is near the low vortex. But it is obvious that the temperature gradient of the weak cyclones is smaller than that of the strong cyclones. The form of the temperature field over the Atlantic is basically identical with that over the Pacific. But the temperature gradient over the Atlantic is obviously larger than that over the Pacific. The corresponding wind speed of the $J_H$ center of strong cyclones is 58 m/s, and that in the upper area of the low vortex center is 53 m/s, and the low vortex is located at the right back of the $J_H$ center; the corresponding wind speed of the $J_H$ center of the weak cyclones is 55 m/s, and that in the upper area of the low vortex center is 50 m/s, and the low vortex is located at the left front of the $J_H$ center. The upper jet axis is northeast-southwestward oriented under the condition of the strong cyclones, and it is quasi west-eastward oriented in the weak cyclones.

2. *Explosion*

It can be known from the analysis of the 850 hPa temperature field at Explosion period (not shown) that the weak cyclones over the Pacific and the Atlantic Oceans all have a occlusion situation, but it is not distinct for the strong cyclones. It is obvious that the development of the weak cyclone is more rapid than that of the strong cyclone in the course from formation to collapsing. The central maximum wind speed of strong cyclones over the Pacific is 34 m/s, and it is 32 m/s for the weak cyclones. The discrepancy between them is not large. The central maximum wind speed of strong cyclones over the Atlantic is 43 m/s, and it is 36 m/s for the weak cyclones.

At 500 hPa (Fig. 3), the trough of the strong cyclones has an obvious cyclonic curvature and the southwest wind in front of the trough is larger than that of the weak cyclones. The strong cyclones appear as a non-closed circulation, but the temperature gradient enlarges. The weak cyclones appear as a closed circulation, but the temperature gradient reduces much more than before.

At 200 hPa (Fig. 4), over the Pacific, the wind speed of the strong cyclones is 45 m/s, it is 77 m/s in the jet center, the low vortex is located at the left front of the $J_H$ center; the wind speed of the $J_H$ center of the weak cyclones reaches 64 m/s, the low vortex is located at the left of the $J_H$ axis and in the middle of two jet centers, and its upper wind speed is 29 m/s. On the temperature field, the temperature gradient enhances greatly compared with that in the period of Pre-Explosion. The low center is close to the warm center. The warm center of the weak cyclones extends to the north of the low vortex. The top of the low vortex has been controlled by the warm center. Over the Atlantic, the distance from the cold center to the warm center of the strong cyclones is relatively short. The larger temperature gradient exists between them, and the joint line of their centers is in quasi west-east direction. The temperature gradient of weak cyclones is small. Compared with the strong cyclones, the weak cyclones' warm center is closer to the cyclone center. The wind speeds in the upper level of the strong and weak cyclones are

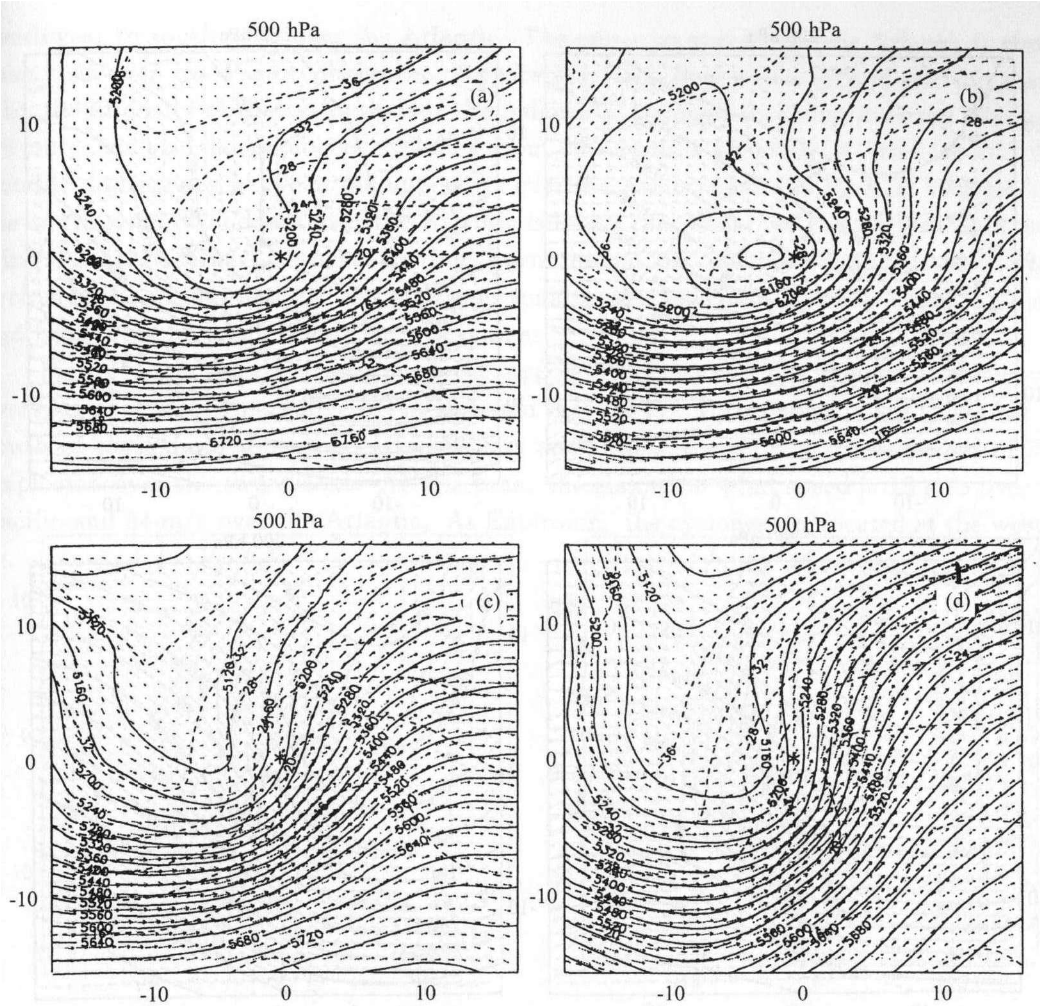


Fig. 3. As in Fig. 1 but for Explosion.

almost the same, they are about 40 m/s. The low vortex of the strong cyclones is located at the left front of the $J_H$ center and that of the weak cyclones is located at the area between the two jet centers.

3. *Post-Explosion*

The distribution of the thermo-baro field of the strong cyclones over the Pacific in the stage of Post-Explosion (not shown) is consistent with that of the weak cyclones in the period of Explosion. During the period of intensive development of cyclones, vortex appears under the level of 500 hPa, with cyclones occlusion deepening, it extends to a higher level. The weak cyclones have a close circulation at 300 hPa. It means that the mature explosive cyclones are rather deep. The centers of the strong cyclones and the weak cyclones get further and further from $J_H$ centers. The wind speed at 200 hPa is about 20 m/s. Over the Atlantic, in the weak cyclones, the closed circulation corresponding to the surface vortex center has come out at 200 hPa. The closed circulation of the strong

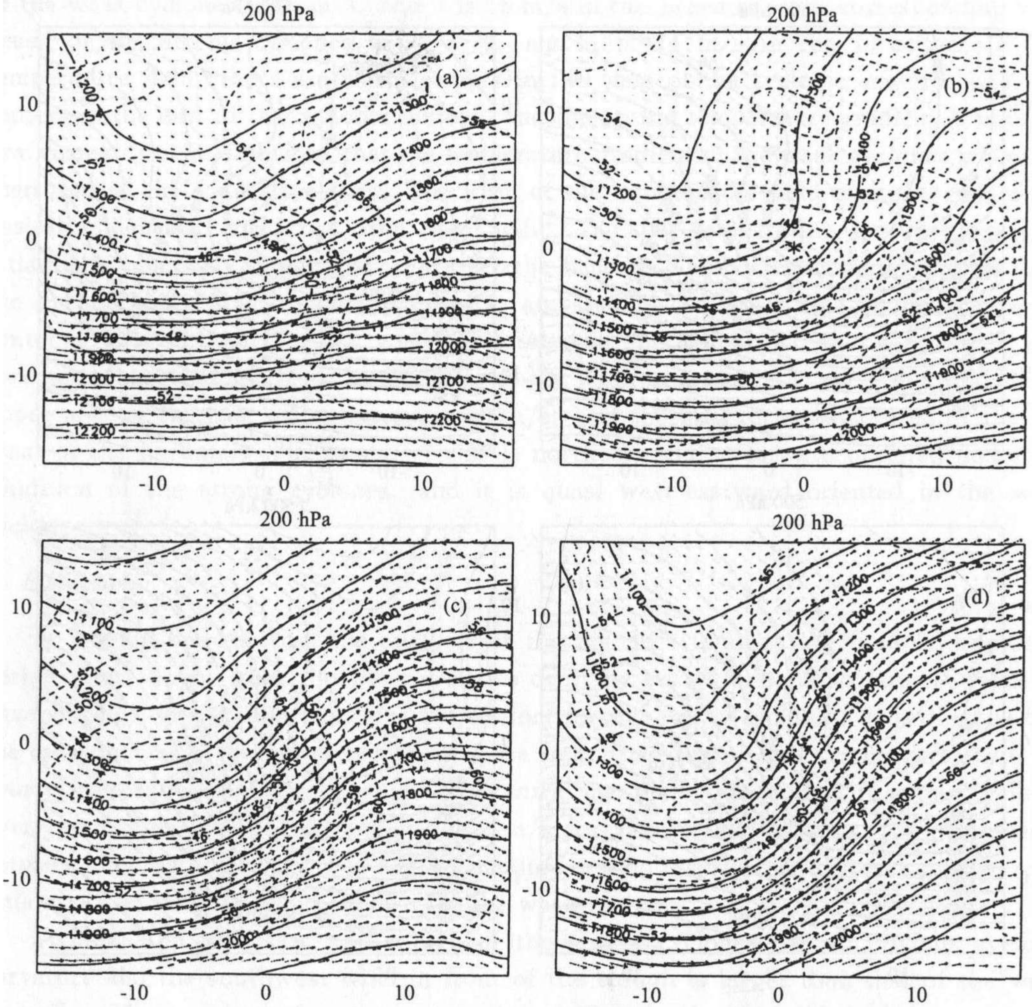

Fig. 4. As in Fig. 1 but for Explosion period and 200 hPa.

cyclones only presents under the level of 300 hPa. In the temperature fields of the strong and weak cyclones, the occlusion situation at low level is apparent. The top of the low vortex is controlled by the warm center. The cold center is located in the north of the warm center. The wind speed over the low vortex decreases greatly.

The obvious discrepancies of cyclones over the Pacific and the Atlantic Oceans in wind field are as follows:

(1) At the lower level, as far as the strong cyclones are concerned, the wind speed over the Atlantic is faster than that over the Pacific in the period of Pre-Explosion and Explosion. At the upper level, no matter the strong or weak cyclones, the wind speed over the Pacific is always faster than that over the Atlantic. The vertical shearing of wind speed at upper level of the low vortex over the Pacific is greater than that over the Atlantic.

(2) The upper jet over the Pacific is quasi-westerly wind and it is southwest wind or

southwest to south wind over the Atlantic. The upper jet speed over the Atlantic is slower than that over the Pacific obviously. Apparently, it is impossible to find out the reason why the intensity of the cyclones over the Atlantic is stronger than that over the Pacific, if we only analyze the explosive cyclones from the vertical shearing of wind speed. The notable discrepancy between the upper jets over the Atlantic and the Pacific Oceans is that the south wind component over the Atlantic is larger than that over the Pacific. Southwest wind jet is beneficial to transporting warm humid air northward and to developing cyclones. Li (1984) pointed out that non-zonal upper jet could intensify air baroclinicity and be of help to the development of cyclones.

Figure 5 shows the changes of the upper level (200 hPa) $v$ fields of the strong cyclones over the two oceans. It can be found that the low vortex centers are located at the south of the axis of $v$ positive value centers and is near the centers in the period of Pre-Explosion over the two oceans. At this time, the maximum wind speed is 18 m/s over the Pacific and 34 m/s over the Atlantic. At Explosion, the cyclones are located at the west of

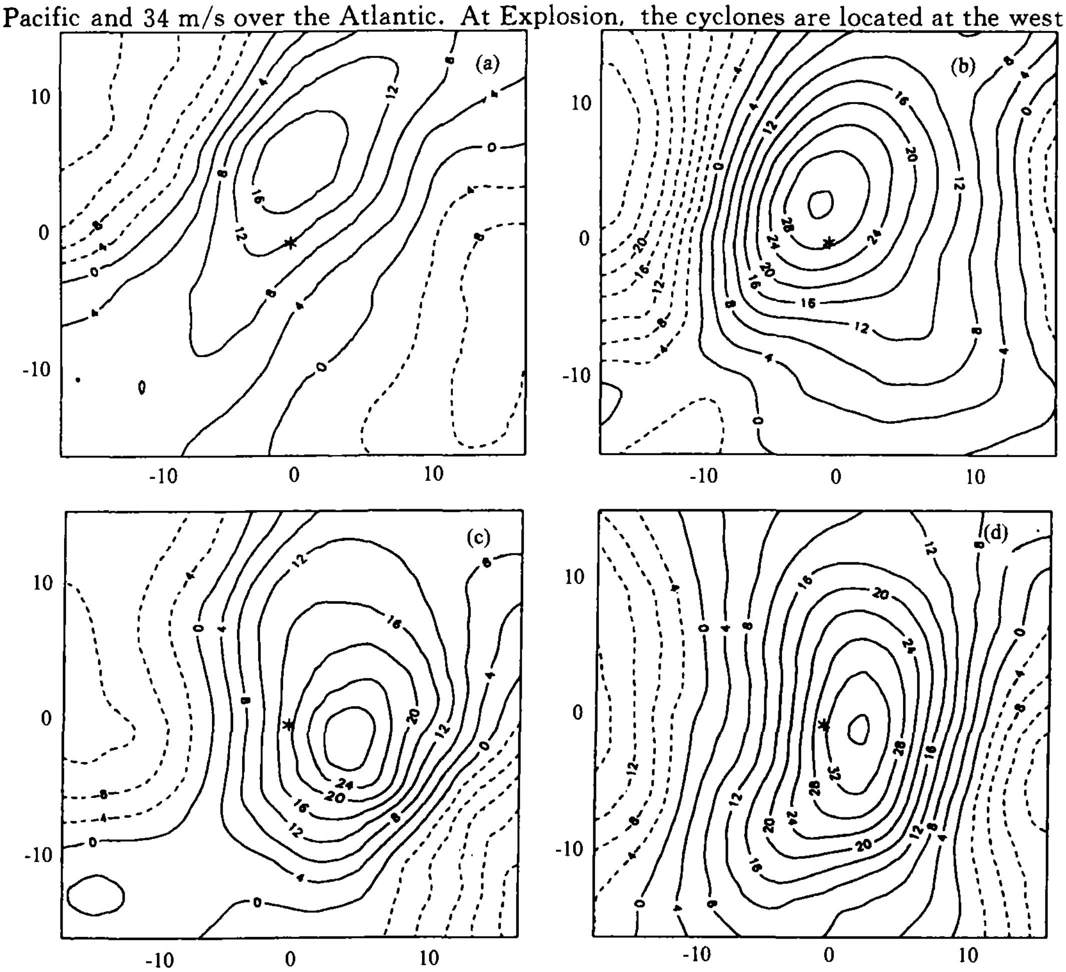


Fig. 5. The distribution of the 200 hPa $v$ field during Pre-Explosion (top row, a and b), Explosion (bottom row, c and d), and over the Pacific (left, a and c), and over the Atlantic (right, b and d). Cyclone center is shown with asterisk.

$v$ centers, the maximum wind speed exceeds 28 m/s over the Pacific and exceeds 36 m/s over the Atlantic. In the stage of Post-Explosion (not shown), cyclones are still located at the west of the $v$ centers, but they are close to the zero line. The value of the $v$ component over the Atlantic is larger than that over the Pacific. It is obvious that the low vortex is easy to develop when it locates at the south of upper positive $v$ component.

From the analysis above, the comparison of the upper wind speed over the two oceans can be shown in Table 2. As shown in Table 2, as far as the Atlantic and the Pacific Oceans are concerned, the development of all the cyclones companions the presence of non-zonal upper jet. But the wind speed of the upper jet over the Pacific is slower than that over the Atlantic.

**Table 2.** Comparison of Full Wind Speed and $v$ Wind Speed Component of Composite Strong Cyclones at 200 hPa during Pre-Explosion (unit: m/s)

| | the Atlantic | the Pacific |
|---|---|---|
| full wind speed | 58 | 72 |
| $v$ wind speed component | 34 | 18 |

In the period of Pre-Explosion, most of the low vortexes over the two oceans are located at the end of the axis of the $J_H$ center, whereas the low vortexes corresponding to the weak cyclones over the Atlantic are located at the left frontage of the $J_H$ center. By the theory of Uccellini et al. (1984), when only the west wind is considered, a field of divergence at upper levels is easy to be formed at the left frontage and the right backside of $J_H$. Why the explosive development of the strong cyclones is not in the two sections? The reason should be related to non-zonality of $J_H$. As shown in Fig. 5, the low vortex is located at south of the south wind center during Pre-Explosion, according to the movement equation:

$$\frac{\mathrm{d}v}{\mathrm{d}t} = - f(u - u_g), \tag{1}$$

at the south of the $v$ center of $J_H$, $\frac{\mathrm{d}v}{\mathrm{d}t}<0$ and $u-u_g>0$; and at the north of the center, $\frac{\mathrm{d}v}{\mathrm{d}t}>0$ and $u-u_g<0$; and at the central place, $\frac{\mathrm{d}v}{\mathrm{d}t}=0$ and $u-u_g=0$. Therefore, the divergence field can be generated by $u-u_g$ near the large value center of the south wind, and the non-zonal upper jet is favorable to form the field of divergence at high levels to develop explosive cyclones.

Based on the comparison between the strong and weak cyclones, we can see that the temperature fields over the two oceans are basically identical and the changes are relatively consistent. The temperature gradient of the strong cyclones is larger than that of the weak cyclones. At 200 hPa, in the stage of the Explosion, the distance from the warm center of the strong cyclones to its center is longer than that for the weak cyclones. Over the Pacific it is more obvious at lower levels that the strength of frontal zone of the strong cyclones is stronger than that of the weak cyclones. Therefore, the strength of the atmospheric baroclinity is related closely to the strength of the cyclones.

In the field of pressure, closed contours come out quite early at the level of 850 hPa for the weak cyclones. The intensity of 500 hPa trough for the strong cyclones is stronger than that for the weak cyclones. The rate of the weak cyclones reaching occlusion is faster than that of strong cyclones.

The conclusion is that the difference of the wind field may be the principal factor for generating different strength cyclones over the two oceans. It also can be seen that the mechanism of the explosive cyclones has a close relationship with that as well.

## IV. DIAGNOSIS AND COMPARISON OF PHYSICAL FIELDS

### 1. *Vorticity*

Over the Atlantic during Pre-Explosion, in the vertical section of vorticity along the east-west direction of the cyclone's center, it can be seen in Fig. 6 that there is a positive vorticity under 700 hPa and a negative vorticity above 700 hPa for the strong cyclones, and that there is still a positive vorticity above 700 hPa for the weak cyclones. The centers of the positive vorticity of the strong and weak cyclones at or above 700 hPa are both at the west of the low vortex. The center value of the weak cyclones is a little less than that of the strong cyclones. For the strong cyclones, the value of vorticity at 400 hPa is the maximum, the central area of negative vorticity is at the east of cyclones. All levels of low vortex are of positive vorticity whose central axis slightly leans to the west of the low

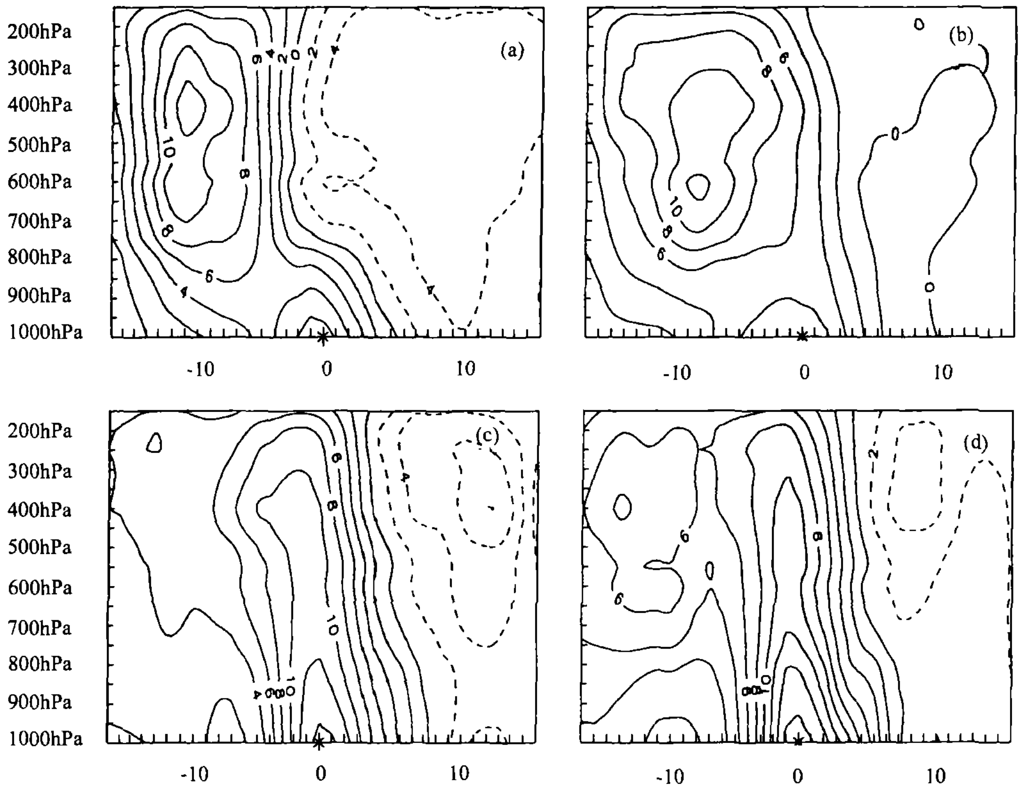


Fig. 6. Over the Atlantic, the vertical section of vorticity ($\times 10^{-5}s^{-1}$) in east-west direction along the center of strong cyclone (left, a and c) and weak cyclone (right, b and d) during Pre-Explosion (top row, a and b) and Explosion (bottom row, c and d). Cyclone center is shown with asterisk. The $x$-coordinate denotes the distance of departing the cyclone center ($\times$ 90 km).

center or near it in the stage of Explosion. The positive vorticity center moves to the east of low vortex in the stage of Post-Explosion (not shown).

Over the Pacific (Fig. 7), it is obvious that the changes of vorticity fields of the strong and weak cyclones are basically identical compared with that over the Atlantic, but the center value is smaller than that over the Atlantic. In the period of Pre-Explosion, the centers of the strong cyclones are located near the vorticity zero line above 700 hPa, and the centers of the weak cyclones are located in the area of positive value.

From the preceding analysis of the flow field of 500 hPa and 200 hPa (Figs. 1 to 4), it can be seen that, in the stage of Pre-Explosion, the anticyclonic current field produces a negative vorticity area at the front of low vortex. The basic current field has anticyclonic curvature. Then, the negative vorticity area moves to the east gradually and becomes further and further from the low vortex. The current field above the low vortex has a cyclonic curvature. Based on the natural coordinate system, Zhou and Chen (1996) pointed out that when the basic current is non-straight and the gradient wind equilibrium relation is not satisfied, the wave packet energy variation would be

$$\frac{\partial E}{\partial T} = -\iint_{\Sigma} \frac{m}{k}\frac{\Phi_0^2}{\lambda^2} f \boldsymbol{C}_g \cdot \nabla (\Delta \bar{U}_{\theta f}) \mathrm{d}Y\mathrm{d}Z - 2\iint_{\Sigma} \frac{m}{k}\frac{\Phi_0^2}{\lambda^2} f C_{gY} \frac{\partial}{\partial Z}(K_S \bar{U}) \mathrm{d}Y\mathrm{d}Z, \tag{2}$$

where $m$ and $k$ are wave numbers of $Y$ and $Z$ directions respectively; $\boldsymbol{C}_g = C_{gY}\boldsymbol{j} + C_{gZ}\boldsymbol{k}$ is the envelope velocity; $\Delta\bar{U}_{\theta f} = \Delta\bar{U}_\theta - \frac{(K_s\bar{U}^2)_z}{f}$ is the non-thermal wind corresponding to the

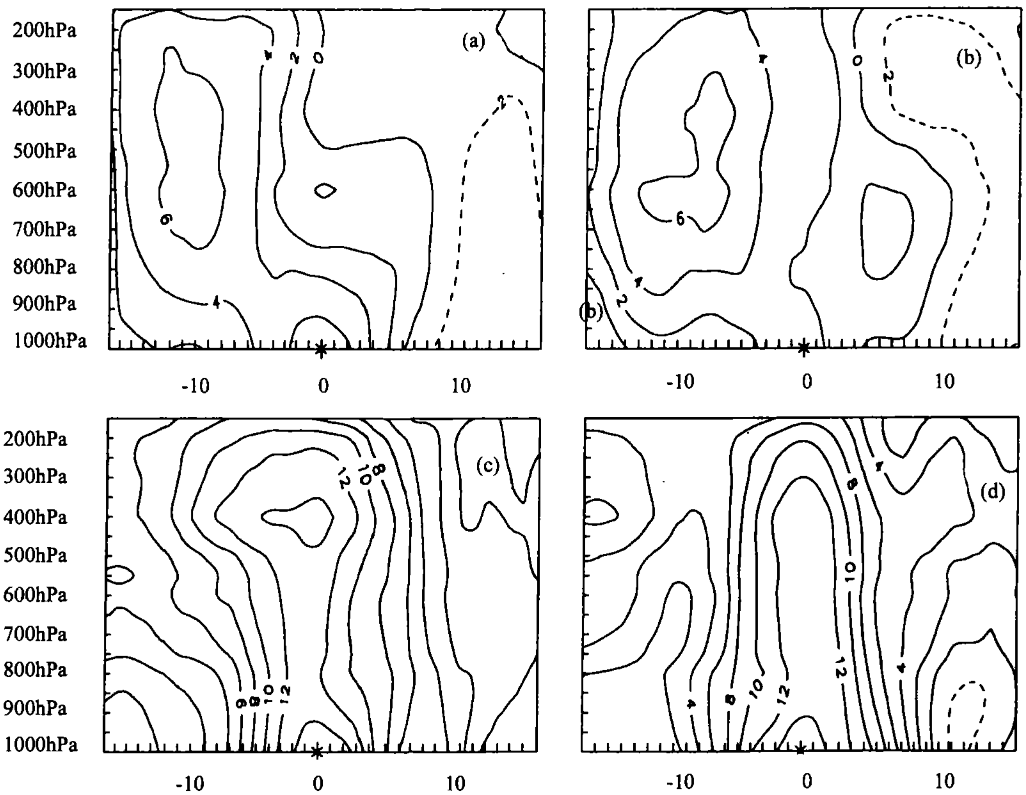


Fig. 7. As in Fig. 6 but for the Pacific.

equilibrium basic current of non-gradient wind; $\Delta\bar{U}_\theta=\bar{U}_\theta-\bar{U}_z$ is the non-thermal wind; $\bar{U}_\theta=-\frac{1}{f}\frac{g}{\theta_0}\frac{\partial\bar{\theta}}{\partial n}$ is the thermal wind of basic temperature field; $\bar{U}_z=\frac{\partial\bar{U}}{\partial z}$ is the vertical shearing of wind; and $K_s$ is the curvature of basic current, a constant.

From the above, the $\nabla(\Delta\bar{U}_{\theta f})$ in the first term of the right-hand of the equation can be expressed as

$$\nabla(\Delta\bar{U}_{\theta f})=-\nabla\left(\frac{1}{f}\frac{g}{\theta_0}\frac{\partial\bar{\theta}}{\partial n}\right)-\nabla\left(\frac{\partial\bar{U}}{\partial z}\right)-\nabla\left(\frac{(K_s\bar{U}^2)_z}{f}\right), \tag{3}$$

therefore the distributions of $\theta$ (potential temperature) field and the vertical shearing of wind on the horizontal level can be used to qualitatively discuss the contribution of the first term of the right-hand of Eq. (3) to wave energy.

The distributions of 200 hPa $\bar{\theta}$ and 200−850 hPa $\frac{\partial\bar{U}}{\partial z}$ fields over the Atlantic of the strong cyclones in the stage of Pre-Explosion are shown in Fig. 8. Around the cyclone center, $\frac{\partial\bar{\theta}}{\partial n}>0$, and $\nabla\left(\frac{\partial\bar{\theta}}{\partial n}\right)>0$. Due to the factor that the cyclones generally move to the north when they intensely developed, thus $C_{gY}>0$, it means that the change of the thermal wind has a positive contribution to $\frac{\partial E}{\partial T}$; under the area of $J_H$, $\frac{\partial\bar{U}}{\partial z}>0$, and $\nabla\left(\frac{\partial\bar{U}}{\partial z}\right)>0$ (Fig. 8b), the vertical shearing of wind also makes a positive contribution to $\frac{\partial E}{\partial T}$. If $K_s$ is constant and $K_s<0$, then $K_s\nabla(\bar{U}^2)_z<0$, which makes a negative contribution to $\frac{\partial E}{\partial T}$. From the scale analysis, if $K_S\sim10^{-6}$, the order of $\nabla\left(\frac{(K_s\bar{U}^2)_z}{f}\right)$ is less than that of the first two terms. In both of strong and weak cyclones, the distributions of $\nabla\left(\frac{\partial\bar{\theta}}{\partial n}\right)$ and

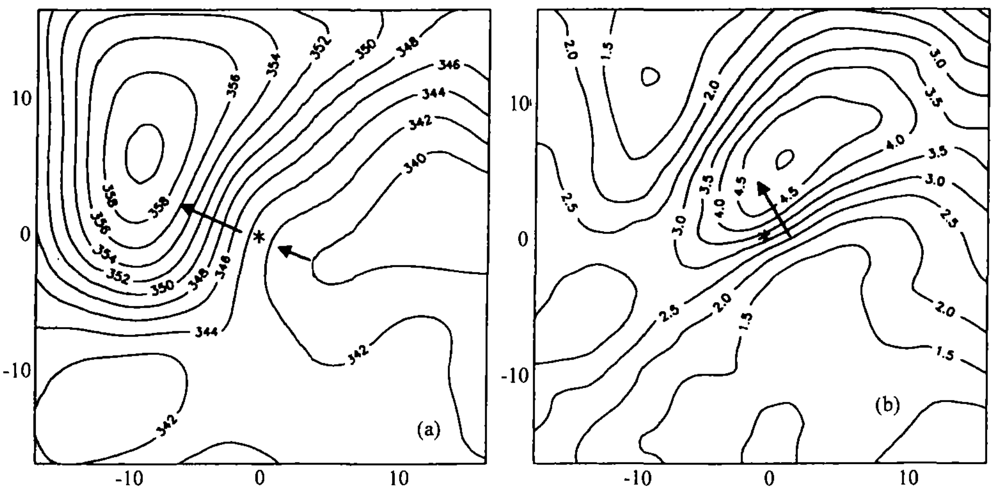


Fig. 8. During Pre-Explosion, the distributions of (a) $\bar{\theta}$ field at 200 hPa (unit: K) and (b) $\frac{\partial\bar{U}}{\partial z}$ of 200−850 hPa (unit: $\times10^{-3}\mathrm{s}^{-1}$) of strong cyclones over the Atlantic. The arrow denotes the direction of $n$ and its length qualitatively represents the size of $\frac{\partial\bar{\theta}}{\partial n}$.

$\nabla\left(\frac{\partial \overline{U}}{\partial z}\right)$ are all identical and have positive contributions to $\frac{\partial E}{\partial T}$. Therefore it can be concluded that the distribution of the non-thermal winds in current field is advantageous to the development of the energy of wave.

For the second term of the right-hand of Eq. (3), under the area of jet, $\frac{\partial \overline{U}}{\partial z}>0$, there are two cases to discuss. (1) When $K_s<0$ and $C_{gY}>0$, the energy of wave will develop. Before the cyclones' explosion, the wave energy propagates northwards ($C_{gY}>0$), and when the front of low vortex is anticyclonic current field ($K_s<0$), it could make the wave energy develop and deepen surface cyclones. (2) When $K_s>0$ and $C_{gY}<0$, it helps to develop the wave energy. During the later period of the development of low vortex, $K_s>0$, the wave energy develops when it propagates to the south. Because the low vortex moves mainly to the north, this is disadvantageous to its development. These negative fields of vorticity are much helpful to the explosively developing of cyclones. Because the negative vorticity area over the Atlantic is wider and nearer to the low vortex center than that over the Pacific, thus the low vortex over the Atlantic develops much more easily.

2. *$\theta_e$ Field*

In the stage of Pre-Explosion, there is an inverted Ω-shaped distribution in the $\theta_e$ field (Fig. 9), near the strong cyclones over the two oceans. The inverted Ω-shaped $\theta_e$ field over the Atlantic is more notable and closer to the low vortex center than that over the Pacific, and the frontal zone is also much stronger than that over the Pacific. This kind of field moves to the east and weakens off during Explosion (not shown). Comparatively, there is no this kind of characteristic $\theta_e$ field in the weak cyclones. This kind of distribution of $\theta_e$ fields in the strong cyclones could bring about convective instability and benefit to the strong cyclones' development obviously. It can be seen from the analysis of the $\theta_e$ value that the weak cyclone has its $\theta_e$ value much less than that of the strong cyclones. The difference at the same height between the centers of the strong and weak cyclones can reach 10 K. This also might be one of the reasons why the weak cyclones cannot intensively develop.

3. *Thermal Advection Field*

The feature of the thermal advection field of the strong cyclones during Pre-Explosion (not shown) is that the cyclones' centers under 500 hPa over the two oceans are near to the advection zero line, and they are controlled by the weak warm advection. The latter enlarges rapidly at the 500 hPa level or higher. The maximum warm advection center at 200—300 hPa is just located at the top of the low vortex. The situation about the weak cyclones is roughly the same, but their value is much less. Subsequently, the warm advection center moves eastwards. Near the low vortex center, the levels under 500 hPa are controlled by cold advection, but the high levels are controlled by warm advection. During Post-Explosion, the all levels near the low vortex center are located nearby the zero line of the advection. Therefore it can be concluded that the thermal advection has the biggest contribution to the development of cyclones during Pre-Explosion, and that the effect of thermal advection on the development of cyclones becomes less in the stages of Explosion and Post-Explosion.

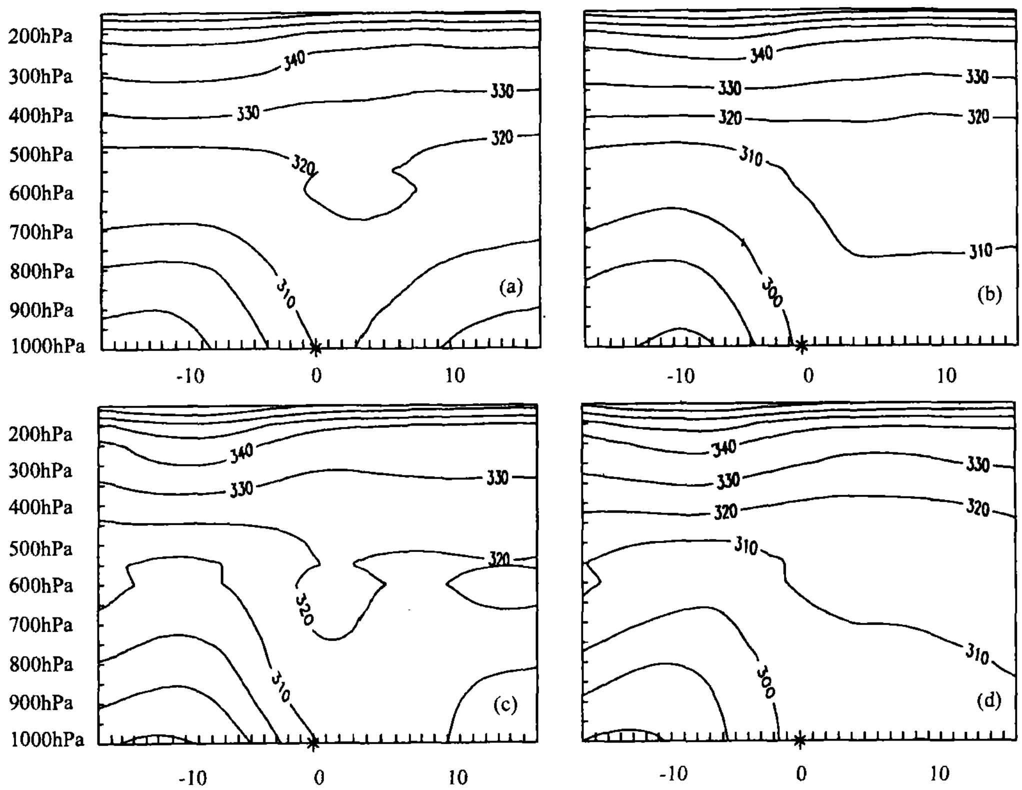


Fig. 9. During Pre-Explosion, the vertical section of $\theta_e$ field (K) in east-west direction along cyclone center of strong (left, a and c) and weak cyclone (right, b and d) over the Pacific (top row, a and b) and the Atlantic (bottom row, c and d). Cyclone center is shown with asterisk. The $x$-coordinate denotes the distance of departing the cyclone center ($\times$ 90 km).

The upper warm advection and the diabatic heating can cause the upper isobaric surface lifting, making the anticyclonic curvature of cyclones enlarged, and promoting the development of wave energy.

The warm advection of the weak cyclones over the Pacific is less than that over the Atlantic. However, the warm advection at the high levels of strong cyclones over the Pacific is slightly larger than that over the Atlantic (not shown). This may be related with the faster wind speed at the high level of strong cyclones over the Pacific.

To sum up, the stronger southwest wind flow is beneficial to the transport of the warm moist flow, and the development of inertia-gravitational wave as well as instable energy, therefore cyclones are forced to explode intensively.

4. *Potential Vorticity and Vorticity Advection*

Potential vorticity, $-g(\zeta+f)\dfrac{\partial\theta}{\partial p}$, is a physical quantity that denotes air-mass heat power and dynamical characteristics. When the potential vorticity value of the upper air is quite high, it can cause cyclonic circulation at the same height of this air-mass. If the surface potential temperature is homogeneous, a surface cyclone under the maximum value area of the potential vorticity will be generated (Ding 1989). Uccellini et al. (1985)

pointed out that when the large value of potential vorticity in the stratosphere transports down to the troposphere, and when the large value area of potential vorticity at the top level is connected with that at the bottom level, it is most helpful to the explosive development of cyclones. Lu et al. (1996) also suggested that the appearance and the strengthening of the upper level potential vorticity are a very important physical condition for the explosive development of cyclones. The strong potential vorticity area extends downwards unceasingly and the original cyclones move promptly to the area beneath the large potential vorticity. When cyclones are located right under the strong vorticity, or the upper and lower large value areas are connected, cyclones would develop vigorously.

Figures 10 and 11 are the east-west vertical section of the potential vorticity along the cyclone centers over the Pacific and the Atlantic Oceans respectively. It can be seen that the difference of distributions between potential vorticity fields of strong and weak cyclones is not large. During Pre-Explosion, the concentration zone of the potential vorticity contours is located at 200—150 hPa, and there are downward transmission areas of potential vorticity in the west of the surface cyclones. The value of potential vorticity of the weak cyclones is bigger than that of the strong cyclones. In Explosion, the value of potential vorticity at 500 — 300 hPa increases suddenly with the emergence of another concentration zone of the potential vorticity contours, and the potential vorticity down

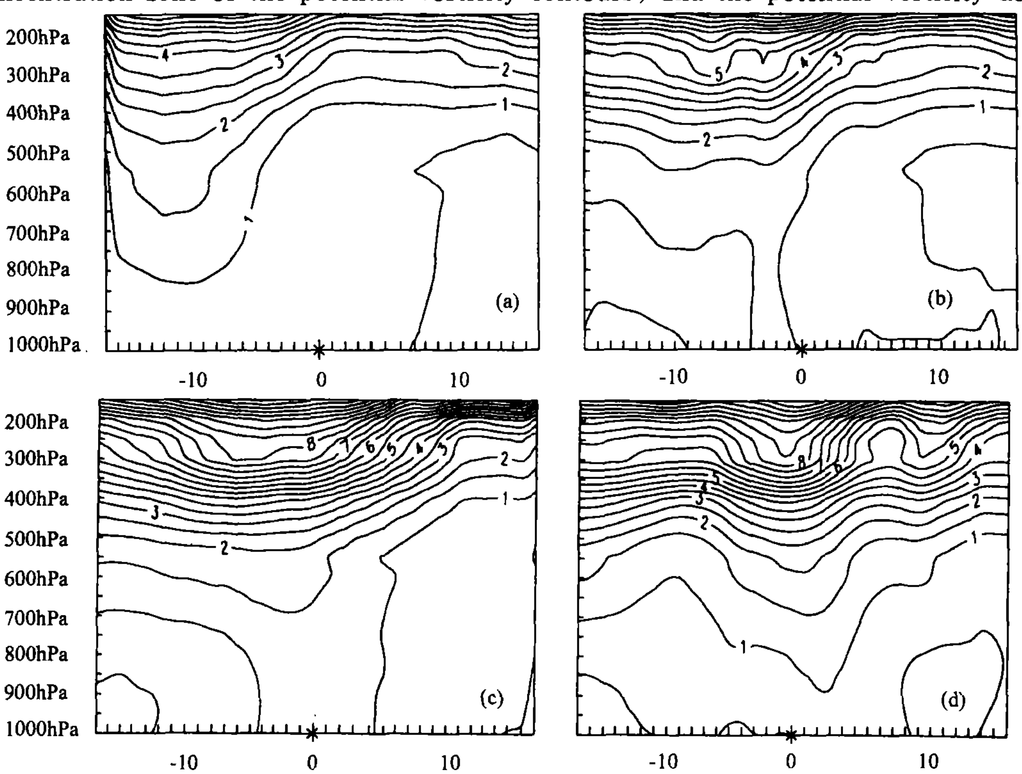


Fig. 10. Over the Pacific, the vertical section of potential vorticity (unit: $\times 10^{-6} m^2 K\ s^{-1}\ kg^{-1}$) in east-west direction along cyclone center of strong (left, a and b) and weak cyclones, (right, b and d) during Pre-Explosion (top row, a and b) and Explosion (bottom row, c and d). Cyclone center is shown with asterisk, The $x$-coordinate denotes the distance of departing the cyclone center ($\times 90$ km).

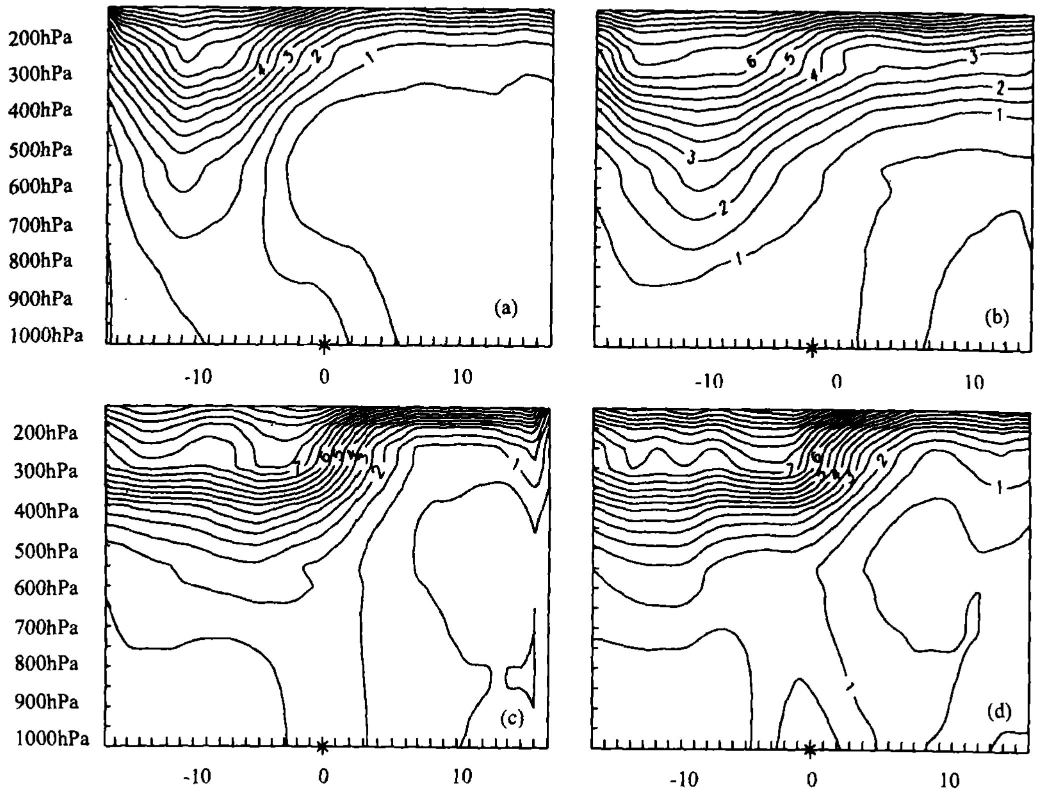


Fig. 11. As in Fig. 10 but for the Atlantic.

transmission area is located at the upper area of cyclones. During Post-Explosion (not shown), the concentration zone of the potential vorticity contours extends downwards obviously and is located at the upper area of cyclones, but its main part deflects to east. Obviously, the process from Pre-Explosion to Post-Explosion for cyclones is a course in which the potential vorticity down transmission area moves from the west of cyclone to its upper levels, and then to its east. The key discrepancy between strong and weak cyclones consists in the value change of potential vorticity of the strong cyclones, which is larger than that of the weak cyclones and the potential vorticity suddenly increases apparently from Pre-Explosion to Post-Explosion.

From the south-north vertical section across the cyclone center (Fig. 12 and Fig. 13), during Pre-Explosion, it can be known that whether the strong or the weak cyclones there are two large concentration zones of the potential vorticity contours at 200—150 hPa and 500 — 300 hPa. Subsequently in Explosion Period, these two areas of large value of potential vorticity still maintain, but the isopleth has obvious subsidence and is located at the upper area of the low vortex. During Post-Explosion (not shown), the potential vorticity subsidence area widens and principal part of it is located at the south of the cyclones.

From the analysis above, it indicates that the downward transmission of potential vorticity is helpful to the development of cyclones. This result is consistent with the early conclusions reached by case study. From the analysis of the vertical section of east-west

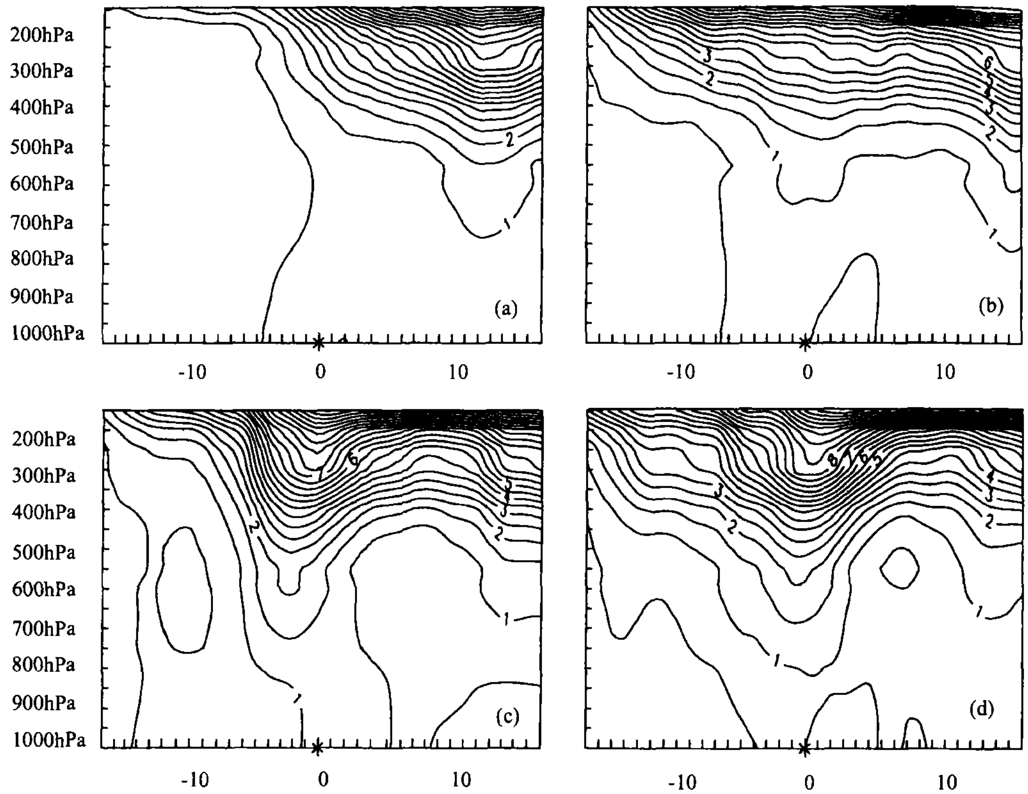


Fig. 12. As in Fig. 10 but for the south-north direction vertical section.

direction, it is deserved to notice that from Pre-Explosion to Explosion, the explosion of cyclones is related to the potential vorticity contours which suddenly change from sparseness to denseness and move to the east and subside to the upper levels of the low vortex. From Explosion to Post-Explosion, although the potential vorticity contours are still quite concentrated, cyclones develop slowly. The south-north vertical section shows the course that cyclones move to the large value area of potential vorticity. From the combined analysis of these two situations, we know that the large value areas of potential vorticity have the course of moving from west to east and the cyclones have the movement from south to north. When the potential vorticity area in the west moves eastwards and overlaps with the north potential vorticity area and subsides in the cyclones area, it is of advantage to explosive development of cyclones.

From the vertical section of the east-west direction of the vorticity advection through cyclones center (not shown), it is known that the distributions of vorticity advection of strong cyclones over the two oceans do not have much difference. Both are the positive vorticity advection area in the west of the low vortex in Pre-Explosion. The positive vorticity advection center moves to the east or the northeast of the cyclones in Explosion. In Post-Explosion, the positive vorticity advection center is far away from the low vortex center. The vorticity advection value of the strong cyclones over the Pacific is larger than that over the Atlantic. The level of the center of the maximum vorticity advection over the Atlantic is located at 300 hPa, and that over the Pacific is located at 200 hPa. The patterns

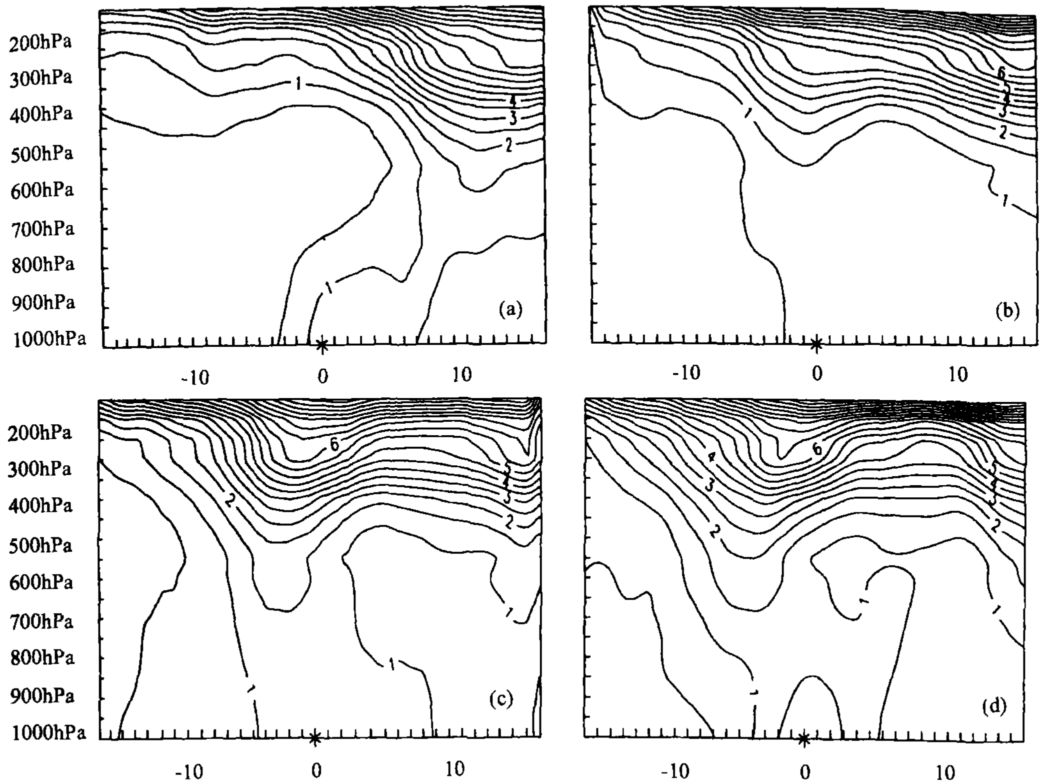


Fig. 13. As in Fig. 10 but for the south-north direction vertical section and over the Atlantic.

of vorticity advection of the weak cyclones are also relatively consistent over the Two oceans. The center of vorticity advection has moved to the east of the low vortex in Pre-Explosion and then it moves to the east obviously. It means that if the center of positive vorticity advection moves to the front of the low vortex too early, the low vortex cannot develop intensely.

V. CONCLUSIONS

The basic flow fields and physical quantity fields of the explosive cyclones over the Pacific and the Atlantic Oceans are analyzed. It can be referred that the probable causes that the explosive cyclones over the Pacific are not as strong as those on the Atlantic are as follows: The Pacific area is an active region for polar front, where the stronger upper jet would occur easily in winter. There are strong baroclinicity and baroclinic instability at the upper jet area and they are easy to cause the surface cyclone to explode. This is the main reason why so many cyclones occur over the Pacific. However, because of the fact that the upper jet over the Pacific is of zonal type in most cases, and the transport of water vapor and heat is weak, it is unfavorable to the development of strong explosive cyclones. On the contrary, many southwest upper jets occur over the Atlantic, this is helpful to baroclinic instability of atmosphere, warm moist instability as well as the development of inertia-gravitational wave. Therefore though the wind speed of upper jet is not large, it can still generate strong explosive cyclones. The development of strong explosive cyclones over the Pacific is also related to the non-zonal upper jet. Obviously, the non-zonal upper jet is the main cause for the genesis of strong explosive cyclones.

From the analysis above, the explosive mechanism of strong cyclones might be below. The non-zonal anticyclonic bend of the upper jet provides an advantageous situation for the development of the explosive cyclones including strong divergence, baroclinicity, baroclinic instability and inertia-gravitational wave energy. Meanwhile, the intensive warm advection at the middle and upper levels can promote this situation. 24 hours before the explosion of cyclone, the existence of inverted $\Omega$-shaped $\theta_e$ field is one of the marks for strong explosive cyclones. This distribution of $\theta_e$ field can result in convective instability, and be obviously beneficial to the development of cyclones. The warm moist air current at lower levels offers instable energy for the explosion of cyclones. The positive vorticity advection and the immigration of the maximum potential vorticity are also helpful to the explosive development of cyclones.

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