A NUMERICAL EXPERIMENT OF CYCLOGENESIS AND THE DEVELOPMENT OF DISTURBANCES

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ABSTRACT

A numerical experiment has been carried out to study the mechanism of cyclogenesis and the development of disturbances. First, an idealized field of temperature and pressure is designed, which is very similar to the actual synoptic situation, consisting of the jet-like zonal circulation with some nonzonal waves superimposed on it. Prediction is made by using a six-level splitting primitive model with the idealized field as an initial one. The results show that if a disturbance like a frontal zone in the lower troposphere is superimposed on the zonal circulation, a frontal cyclone will quickly develop and then gradually become an occluded one. Its life cycle is similar to that of the actual frontal cyclone on the synoptic map. However, if there is a disturbance superimposed on the zonal circulation in the middle troposphere, the cyclone with weaker intensity will be slowly formed near the surface. Finally, if the initial disturbance is located at the high-level, a situation like a cut-off low rather than a frontal cyclone will develop.

I. INTRODUCTION

Frontal cyclone generally appears at middle and high latitudes, and may cause disaster. It is an important subject to study the mechanism of cyclogenesis and its development. Mongolia low, Northeast low and Jiang-Huai cyclone frequently appear in China. It was shown in some works that the development of Northeast low mainly depends on the effect of high-level atmosphere[1], and condensational latent heat plays an important role in the development of Jiang-Huai cyclone[2]. Apart from these cyclones mentioned above, most of the cyclogeneses occur in the frontal zone near the ground. It is obvious that the baroclinic effect near the ground is the main condition of cyclogenesis. Such viewpoint is examined by making some numerical experiments on the cyclogenesis, and good results are obtained.

II. THE STRUCTURE OF IDEALIZED FIELD

An idealized field, similar to that of synoptic chart, is constructed with consideration of the frontal zone at middle latitutes and the existence of the tropopause. The initial height disturbances are made from four planetary waves with different amplitudes, and the initial pressure at the ground is uniform. Consequently, the cyclogenesis near the ground depends on the structure of temperature-pressure field. The idealized field is composed of zonal flow and disturbance as follows.

(1) *Zonal Flow*

The zonal temperature can be written as

$$T(r,\zeta)=T_{00}-AG(r)-\gamma Sr(\zeta), \tag{1}$$

where $$G(r)=\begin{cases}\exp(-br^2)-\exp(-br_0^2), & (r<r_0)\\ 0, & (r\geqslant r_0)\end{cases}$$

and $Sr(\zeta)$ has the form:

if $r<r_0$,
$$Sr(\zeta)=\begin{cases}\ln\frac{1}{\zeta}, & \left(\text{when } \ln\frac{1}{\zeta}<\ln\frac{1}{\zeta^*}\right)\\ \ln\frac{1}{\zeta^*}, & \left(\text{when } \ln\frac{1}{\zeta}\geqslant\ln\frac{1}{\zeta^*}\right)\end{cases}$$

and if $r\geqslant r_0$,
$$Sr(\zeta)=\begin{cases}\ln\frac{1}{\zeta}, & \left(\text{when } \ln\frac{1}{\zeta}<\ln\frac{1}{\zeta_0^*}\right)\\ \ln\frac{1}{\zeta_0^*}, & \left(\text{when } \ln\frac{1}{\zeta}\geqslant\ln\frac{1}{\zeta_0^*}\right)\end{cases}$$

where $\ln\frac{1}{\zeta^*}=\ln\frac{1}{\zeta_0^*}-B[\exp(-cr^2)-\exp(-cr_0^2)]$, r is the distance from the calculated point to the North Pole; ζ is the vertical coordinate and has $\zeta=(P-P_t)/(P_s-P_t)$, with P, P_s and P_t being pressures at an arbitrary level, the ground surface and the highest level, respectively; γ is the lapse rate of temperature and taken to be climatological mean value; r_0 is the distance from 25°N to the North Pole; the tropopause is represented by $\ln\frac{1}{\zeta^*}$, and by $\ln\frac{1}{\zeta_0^*}$ at r_0; and T_{00}, A, r, B, b, c, ζ_0^* are all available through calculations.

The temperature field of zonal flow obtained shows that the gradient of temperature directs towards the North Pole in the troposphere, with the temperature at the North Pole being the lowest, while at the 100 hPa level, it directs towards the equator, with the temperature at the North Pole being the highest. There is a frontal zone at 45°N at every level, and the temperature south of 25°N is equal to that at 25°N.

(2) *Disturbance*

Denoting the disturbance of temperature by $T'(\lambda, r, \zeta)$ yields

$$T'(\lambda,r,\zeta)=-E_0E_1(\lambda)\cdot E_2(r)\cdot E_3(\zeta)\cdot \cos m(\lambda-\lambda_0), \tag{2}$$

where E_0, the amplitude of temperature, is constant and

$$\begin{cases}E_1(\lambda)=\begin{cases}\{\exp[-e_1(\lambda-\lambda_0)^2]-\varepsilon_1\}f_1, & (|\lambda-\lambda_0|<\tilde{\lambda})\\ 0, & (|\lambda-\lambda_0|\geqslant\tilde{\lambda})\end{cases}\\ \varepsilon_1=\exp(-e_1\tilde{\lambda}^2),\ f_1=1/(1-\varepsilon_1),\end{cases}$$

$$\begin{cases}E_2(r)=\begin{cases}\{\exp[-e_2(r-r_0')^2]-\varepsilon_2\}f_2, & (|r-r_0'|<\tilde{r})\\ 0, & (|r-r_0'|\geqslant\tilde{r})\end{cases}\\ \varepsilon_2=\exp(-e_2\tilde{r}^2),\ f_2=1/(1-\varepsilon_2),\end{cases}$$

$$\begin{cases}E_3(\zeta)=\begin{cases}\left\{\exp\left[-e_3\left(\ln\frac{1}{\zeta}-\ln\frac{1}{\zeta_0}\right)^2\right]-\varepsilon_3\right\}f_3, & \left(\left|\ln\frac{1}{\zeta}-\ln\frac{1}{\zeta_0}\right|<\tilde{\xi}\right)\\ 0, & \left(\left|\ln\frac{1}{\zeta}-\ln\frac{1}{\zeta_0}\right|\geqslant\tilde{\xi}\right)\end{cases}\\ \varepsilon_3=\exp(-e_3\tilde{\xi}^2),\ f_3=1/(1-\varepsilon_3),\end{cases}$$

where λ is longitude, λ_0 is taken as $\pi/4$ and $\tilde{\lambda}$ as $3\pi/4$, r_0' is the position of disturbance center, $\tilde{r}$ the range of disturbance along the direction r, ζ_0 the position of disturbance center along the vertical direction, and $\tilde{\xi}$ the range of disturbance along the vertical direction. e_1, e_2, e_3, r_0' and $\tilde{r}$ are all available by calculation. ζ_0 and $\tilde{\xi}$ will be determined according to the requirement of experiments.

The total temperature field mentioned above is shown as

$$T(\lambda,r,\zeta)=\bar{T}(r,\zeta)+T'(\lambda,r,\zeta), \qquad (3)$$

which contains four temperature waves with quite different amplitudes (Fig. 1).

Using different values of $\ln\frac{1}{\zeta_0}$ and $\tilde{\xi}$, we can get different positions and scales of disturbance along the vertical direction. Therefore, we can investigate how the disturbances with different vertical structures affect the formation and the development of surface pressure systems.

III. RESULTS AND DISCUSSION OF NUMERICAL EXPERIMENTS

Some five-day numerical experiments of idealized field mentioned above are performed by use of the six-level implicit primitive model[3].

(1) *Experiment I*

It is assumed that the initial strongest temperature disturbance lies on the ground, and the amplitude of disturbance decreases with altitude, thus it vanishes at 500 hPa.

Such an initial surface temperature field is shown in Fig. 1. For convenience, the strongest trough located at 45°E is known as wave I, two weaker troughs on both sides of wave I as waves II and IV respectively, and the weakest next to wave II as wave III.

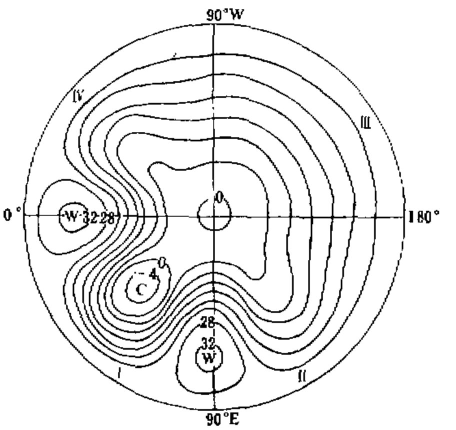

Fig. 1. The idealized temperature field (C: cold, W: warm).

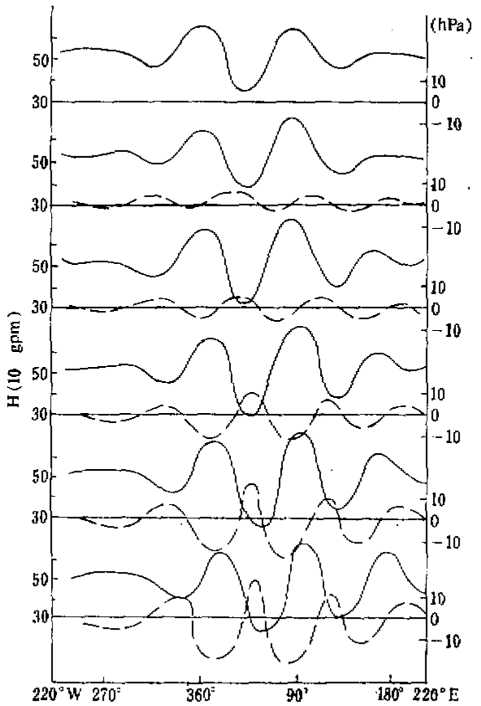

Fig. 2. The daily distributions of the 500 hPa height (solid line) and the surface pressure (dashed line) along 50°N in experiment I. The left ordinate H denotes the 500 hPa height minus 5000 measured in 10 gpm; the right, the difference between the surface pressure and 1000 hPa.

Fig. 2 shows that none of surface pressure disturbance appears at initial time, but the surface systems which match well with the 500 hPa systems take shape at 24 h from the initial time, i. e. there is a cyclone located before the 500 hPa trough and an anticyclone behind it. The result mentioned above agrees very well with the observed situation. Afterwards, the surface pressure systems develop gradually, and there always exists a good corresponding relationship between the surface and the 500 hPa systems. For ease of presentation we put emphasis on the discussion of the course of formation and development of the surface pressure system I. It can be seen from Fig. 2 that this cyclone is the strongest in the North Hemisphere. At first, it is weak, then increasingly deepens to 985 hPa on the third day, then to 975 hPa on the fifth day. Fig. 3 shows the 72 h surface pressure (solid line) and temperature (dashed line). It is clear that the cyclone located at 85°E matches well with the front. The frontal cyclone forms, and develops rapidly. During the following two days, the cyclone and warm tongue stretch gradually towards northwest and the cold high towards southeast, causing the cyclone to deepen. The 500 hPa trough is similar to surface cyclone in phase 5 days later, and the warm tongue becomes narrow, marking the beginning of an occluded stage. This is a typical example which represents the whole course of formation, development and decay of a cyclone. Now we analyse the evolution of the high level systems. The contour of 500 hPa (solid line) along 50°N is day by day given in Fig. 2, which indicates that wave I is strongest and moves eastward by 15 degrees longitude within five days, while its strength increases gradually and begins to decrease on the fourth day.

At the beginning, the strength of waves II and IV on both sides of wave I is the same, though in different tendencies of development. The intensity of wave II increases more quickly than that of wave IV from day to day, and it remains nearly at the original position. The intensity of wave IV increases slowly, but it moves quickly eastward by about 20 degrees longitude within five days. The result mentioned above is due to the effect of dispersion, since wave II is downstream from and nearest to wave I.

Contrasting the solid lines with the dashed ones in Fig. 2, we can see that the surface low corresponding to wave II is not so deep as wave IV despite that wave II develops more quickly than wave IV. Obviously, the surface front plays an important role, and makes the disturbance develop quickly.

(2) *Experiment II*

It is assumed that the centre of temperature disturbance is located at 700 hPa, the strongest disturbance appears at the 500 hPa height, and the surface pressure, 850 hPa temperature and surface temperature are initially constant everywhere.

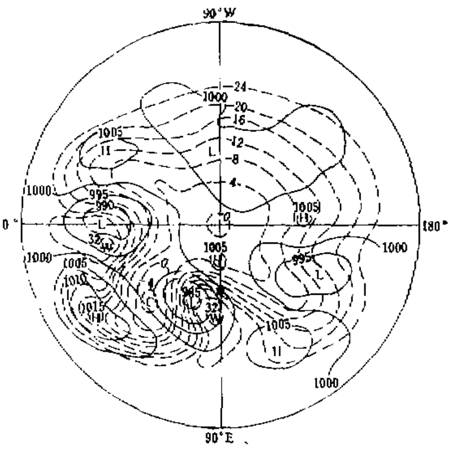

Fig. 3. The distribution of 72 h surface pressure (solid line) and temperature (dashed line) in experiment I.

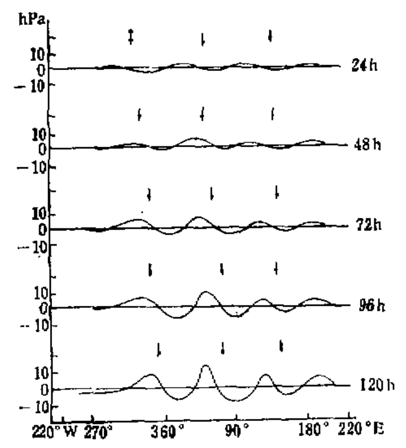

Fig. 4. The daily distribution of surface pressure minus 1000 hPa from experiment II. Arrows represent the position of trough line of 500 hPa.

Fig. 4 shows the computed results. It can be seen that the surface pressure systems are formed after 24 h. They match well with the 500 hPa systems and continue to develop day by day. There exists a good corresponding relationship between the height system and the ground system. Hence the situation mentioned above is the same as that of experiment I. The difference between them is that the systems of 500 hPa in experiment II develop more weakly and move eastward more quickly, the formation and development of surface pressure systems in experiment II are slower than those in experiment I, and the strongest one is 990 hPa on the fifth day. The disturbances of temperature and pressure of the surface and 850 hPa have shaped on the third day, and become more obvious on the fifth day. The surface temperature is in harmony with surface pressure on the fifth day, but the developments of the cyclone and anticyclone are slow, since no obvious front zone exists yet. In view of the tendency of temperature-pressure development, the frontal cyclone can be formed sometime later. The cyclone will develop quickly after the formation of the surface front zone.

(3) *Experiment III*

The centre of temperature disturbance is at 500 hPa, and the strongest height disturbances are at 300 hPa. There is no disturbance of temperature and pressure on the ground initially. The result is quite different from those of experiments I and II. The surface pressure begins to form at 24 h, then increasingly develops and moves eastward. The intensity of pressure systems is weaker. The relationship between the distribution of surface pressure systems and the position of 500 hPa trough line is not like the general situation, but like the cut-off low, the trough of high level corresponds to the surface low.

The phases of the 500 hPa temperature and pressure are always the same within five days. The systems increasingly weaken, and move eastward more quickly than those obtained in experiments I and II. It follows that the frontal cyclone can not be formed when the disturbance centre of temperature-pressure is located at the middle and upper levels of troposphere.

IV. CONCLUSION

From the experiments mentioned above we may reach conclusions as follows:

(1) When there exists a front near the ground, the frontal cyclone will develop quickly.

(2) When there is a strong disturbance at the middle levels of troposphere, it will transmit downward and form cyclone even though no front zone exists near the ground. However, the cyclone evolves slowly.

(3) When the centre of disturbance is located at the high levels of troposphere and no surface front exists there, it is impossible to develop a frontal cyclone on the ground, but cut-off low and suchlike may exist.

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