DYNAMIC INFLUENCE OF QINGHAI-XIZANG PLATEAU AND ROCKY MOUNTAINS ON THE LEE CYCLONES

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ABSTRACT

Using the operational model (B model) of Beijing Meteorological Center, we do some of numerical experiments of crossing and rounding mountains in all velocity adjustment scheme, and study dynamic effect of Qinghai-Xizang Plateau and Rocky Mountains on lee cyclones. The results show that due to air flow round the Qinghai-Xizang Plateau, divergence is distributed in the shape of confluence which matches cyclogenesis area and cyclonic track in East Asia. In the downstream of the Qinghai-Xizang Plateau, convergence in the upper troposphere restrains cyclone development in the east of China mainland. In North America, air flow primarily crosses over Rocky Mountains. Air is adiabatically cooled when it flows upward in the west flank of Rocky Mountains, while air is warmed when it flows downward in the lee side. The fact is important for the lee cyclogenesis and the lee frontogenesis of Rocky Mountains. Air flow crossing over Rocky Mountains is also the main cause for forming dryline in the mid-west of United States.

I. INTRODUCTION

Dynamic influence of plateau and mountain on the atmosphere, a topic always attracting meteorologists' attention,can be divided into three conditions: 1) natural rounding and crossing, 2) pure rounding and 3) pure crossing. In the world, lee cyclogenesis of Rocky Mountains (RM) and the Alps are the most remarkable, and lee cyclogenesis of the Qinghai-Xizang Plateau (QXP) and Andes Mountains come next. Of course, their features and causes in various areas are very different. The lee cyclogenesis of Rocky Mountains (RM) can be explained by the classical theory on the conservation of potential vorticity, i. e., surface cyclones are associated with the divergence field in the upper troposphere, and lee cylones generate in the area where the low-level vortex extending upward due to upper divergence overlaps on the flow downward in lee side. The Alps lee cyclogenesis involves the blocking of low-level cold air by mountains. Lee cyclones of QXP are often formed in the coast of East China Sea where there is no downward flow, therefore, there is no vertical stretching of air column. The cause for the lee cyclogenesis there should be explained by other mechanism.

Using model-B of Beijing Meteorological Center. we have done numerical experiments in various schemes, such as natural rounding and crossing, pure rounding and pure crossing, in order to understand dynamic influence of QXP on cyclogenesis in East Asia and that of RM on cyclogenesis in North America. Meanwhile, the sensitive experiment of topography is also carried out. Using zonal mean flow as initial data we have run the model-B for 72 hours and analyzed mass flux of various longitudes and eddy momentum in North America and East Asia.

II. EXPERIMENTAL SCHEMES

We have devised an adjustment scheme of all wind speed, that is, direction of air is adjusted to the gradient of topography (crossing) or to shear direction of the gradient of topography (rounding).

1. *Rounding Mountain*

Rounding horizontal wind speed is governed by two equations as follows:

$$\boldsymbol{V}_r \cdot \nabla Z_s = 0, \tag{1}$$

$$|\boldsymbol{V}_r| = |\boldsymbol{V}_s|, \tag{2}$$

where $\boldsymbol{V}_s$ is wind vector near the ground, and $\boldsymbol{V}_r$ is wind vector of rounding flow. From the simultaneous equations (1) and (2), we derive the following equations for components of $\boldsymbol{V}_r$.

$$u_r = -v_r\left(\frac{\partial z_s}{\partial y} \Big/ \frac{\partial z_s}{\partial x}\right), \tag{3}$$

$$v_r = \sqrt{(u_s^2 + v_s^2) \Big/ \left[1 + \left(\frac{\partial z_s}{\partial y} \Big/ \frac{\partial z_s}{\partial x}\right)^2\right]}, \tag{4}$$

where z_s is topographic height above the sea level, and u_r and v_r are components of $\boldsymbol{V}_r$.

2. *Crossing Mountain*

Crossing horizontal wind speed is governed by Eqs. (5) and (6) as follows:

$$\boldsymbol{V}_p \times \nabla z_s = 0, \tag{5}$$

$$|\boldsymbol{V}_p| = |\boldsymbol{V}_s|, \tag{6}$$

where $\boldsymbol{V}_p$ is wind vector of crossing. Combining Eqs. (5) with (6), we can derive the equations for components (u_p and v_p) of $\boldsymbol{V}_p$:

$$u_p = v_p\left(\frac{\partial z_s}{\partial x} \Big/ \frac{\partial z_s}{\partial y}\right), \tag{7}$$

$$v_p = \sqrt{(u_s^2 + v_s^2) \Big/ \left[1 + \left(\frac{\partial z_s}{\partial x} \Big/ \frac{\partial z_s}{\partial x}\right)^2\right]} \quad . \tag{8}$$

During the experiment, when topographic gradient at grid points is bigger or equal to 10^{-3}, we will deal with wind for every time step. Furthermore, if topographic height (z_s) is higher than 800 m and lower than 3000 m, we will adjust winds of the fifth level of the model; if z_s is higher than 3000 m, we will adjust winds of the fourth and fifth level of the model.

Using FGGE data (1200 GMT 11 May 1979) as initial data we have done numerical experiments according to various schemes in Table 1, then have discussed the dynamic influence of QXP on lee cyclogenesis and development in the valley of Changjiang River as well as that of RM on lee cyclones in North America.

3. *Zonal Mean Flow as Initial Data*

Using the data of 21 March 1979 which is zonally averaged as initial data, we integrate the model for 72 hours and compute mass flux at various longitudes and eddy

Table 1. Experimental Schemes

	Natural Rounding and Crossing	Rounding	Crossing	No Mountain
East Asia	CRT	RT1 RT2*	CT	NOT
North America	CRR	RR	CR	NOR

* adding the precipitation on various scales

momentum transport, as well as analyze the perturbation of surface pressure and wind field at 700 hPa. Therefore different dynamic influences of QXP and RM on the atmosphere can be studied.

$$M=\int_{\phi_1}^{\phi_2} \rho u dl, \tag{9}$$

$$I=u'v', \qquad u'=u-[u], \qquad v'=v-[v], \tag{10}$$

where M is latitudinal mass flux at some latitude belt, ϕ_1 and ϕ_2 are latitudes, square brockets represent the zonal average for a circle, and I is eddy momentum transport.

III. NUMERICAL EXPERIMENT OF DYNAMIC INFLUENCE OF QXP ON LEE CYCLOGENESIS AND ITS DEVELOPMENT

1. *Natural Crossing and Rounding (CRT)*

In the initial field at 1200 GMT 11 May 1979, there is a trough area in the southwest of China. We integrate the model for 36 hours, there appears a depression which moves northeastward continually toward the sea surface. On the 48 h prediction chart (Fig. 1a), the depression has already moved over the East China Sea, which is consistent with the observational pressure field. In spite of the fact that none of diabatic processes is added to the model, the cyclone is still generated in the area of Changjiang Estuary. This indicates that dynamic influence of the plateau is very important for lee cyclogenesis.

In predicated height and thickness fields of 500 hPa (Fig. 2a), there is a dense area of thickness near 30°N in which the isobars and isotherms almost are parallel, indicating that the baroclinicity of cyclone is not obvious when the cyclone forms in the area of Changjiang and Huaihe Rivers. Thus it can be seen that the explanation by Manabe and Terpstra (1974) for the cause of cyclogenesis in China east coast is not consistent with synoptic facts. The cyclones in the Changjiang-Huaihe Valley are usually formed in a quasi-stationary front.

2. *Rounding*

(1) *Rounding without precipitation (RT1)*

Using rounding scheme without precipitation (RT1), we integrate the model for 24 hours. There appears a vortex in the southwest of China and a high-pressure in the northeast of Plateau.

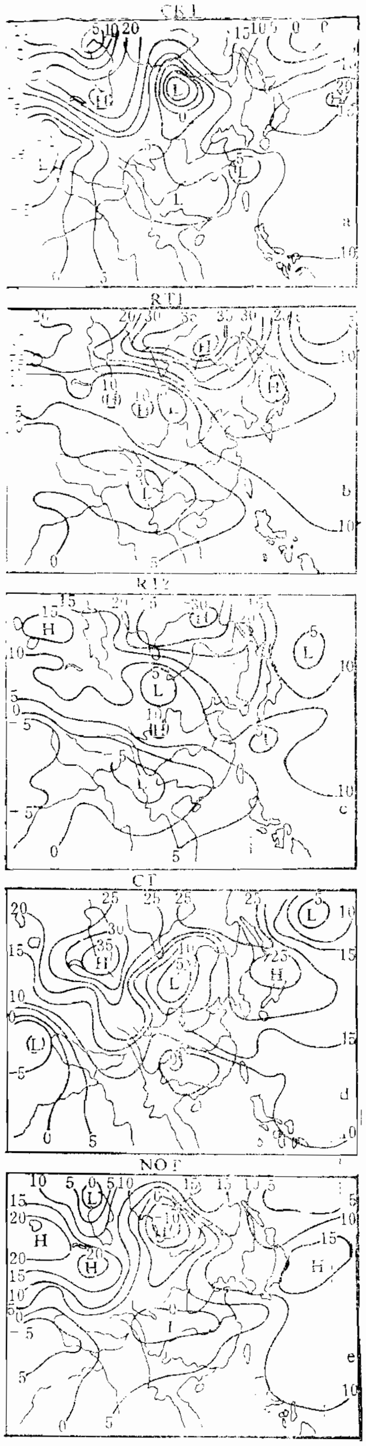

Fig. 1. The 48 h predicated sea level maps as experimental results from various schemes in East Asia (numerals on maps are subtracted by 1000 and in units of hPa).

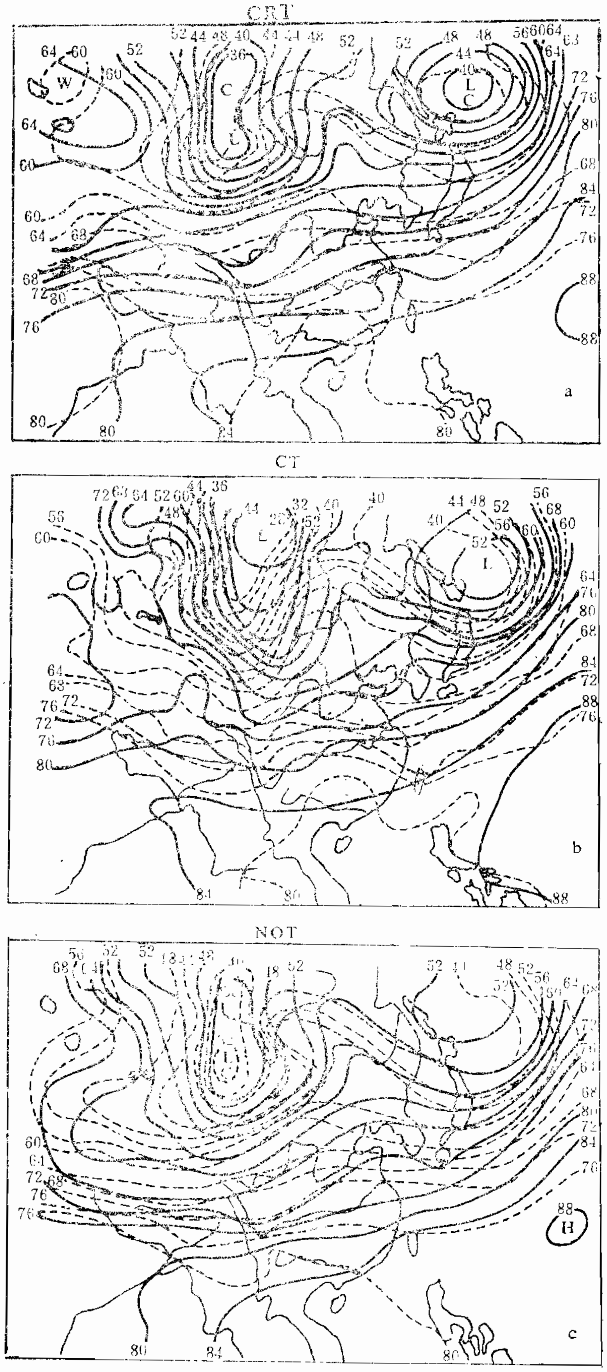

Fig. 2. The 48 h predicated height (solid) and thickness (dashed) field of 500 hPa in East Asia from three schemes (numerals on maps are subtracted by 500 and in units of 10 gpm).

The southwest vortex in China is usually considered as that resulting from lateral friction, while our results show that the air flow rounding the plateau is one of the causes for generation of southwest vortex (Fig. 1b). In the flow field of 700 hPa and 500 hPa (Fig. 3a, b), there is a cyclonic circulation near Jiulong County, Sichuan Province and an anticyclonic circulation north of the QXP. A shear airflow is formed in middle and lower reaches of the Changjiang River. There are often the above-mentioned situations in East Asia. In addition, the 700 hPa wind speed in the southwest of China is larger than 12 m/s. and the low-level jet in East Asia is closely associated with air flow rounding mountain. Southwest monsoon rounding the Plateau plays an important role in the formation of low-level jet.

In 1970s Chinese meteorologists (Ye and Gao, 1979) found from cloud pictures that there were some vortices in the middle of QXP, originating from the west of Plateau. These phenomena make meteorologists puzzled for long time. At present, we know that rounding is one of the causes for generating those vortices, showing that rounding has influences on synoptic systems not only in the vicinity of the plateau, but also over the plateau.

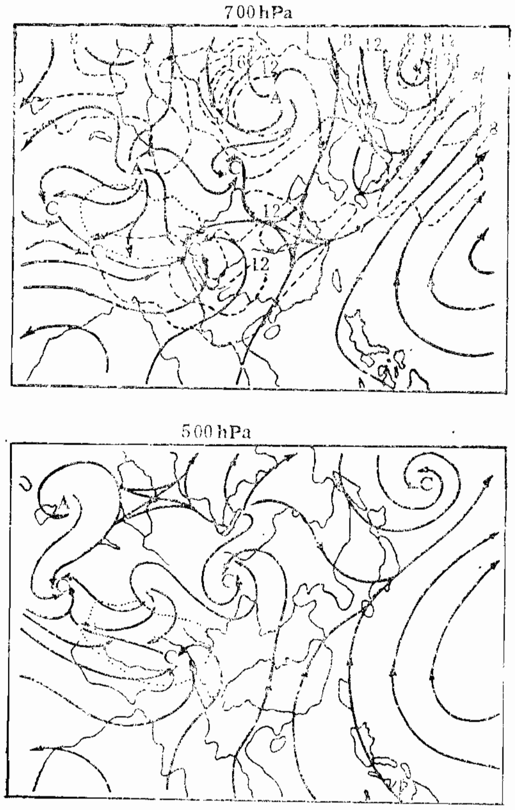

Fig. 3. Predicated field of flow (solid) from the rounding scheme (RT1), the dashed line is isotach.

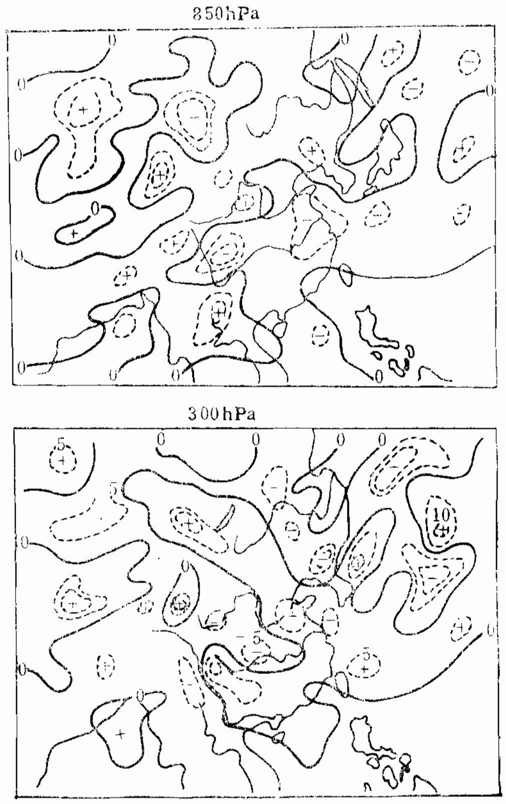

Fig. 4. The 24 h predicated field of divergence from the rounding scheme (RT) in units of $10^{-6}s^{-1}$.

From southwest of China to Japan, there is a convergence belt on 850 hPa and another convergence belt is from Mongolia to Japan (Fig. 4a) . Both confluence near the area of Changjiang Estuary, which corresponds to the divergence belt on 300 hPa. This branching distribution of divergence field is consistent with cyclogenesis area and track in East Asia. In the upper troposphere, due to Taylor column function of QXP, upper air flow converges in the east flank of the Plateau, restraining the strong development of cyclones in China mainland.

(2) *Rounding with precipitation* (*RT*2)

Adding precipitation process on various scales into the model, we have done numerical experiments on rounding. Integrating the model for 18 hours leads the appearance of a cyclone near the Changjiang Estuary. On the 24 h predicted chart its center decreases to 1003 hPa. Due to the release of latent heat, the phase speed of system (Fig. 1c) is modified and the depression becomes stronger. The results show that air flow rounding the Plateau is a characteristic of the general circulation of East Asia. Meanwhile, feedback of latent heat also plays an important part in generation and development of cyclones.

3. *Crossing Experiment* (*CT*)

On the surface map obtained from crossing experiment (Fig. 1d), there is a depression in the middle reaches of Changjiang River. Integrating for 72 hours, we can see that a depression occupies the entire east plain of China. A situation of high pressure alternating with low pressure in west-east direction appears in East Asia, which is not consistent with

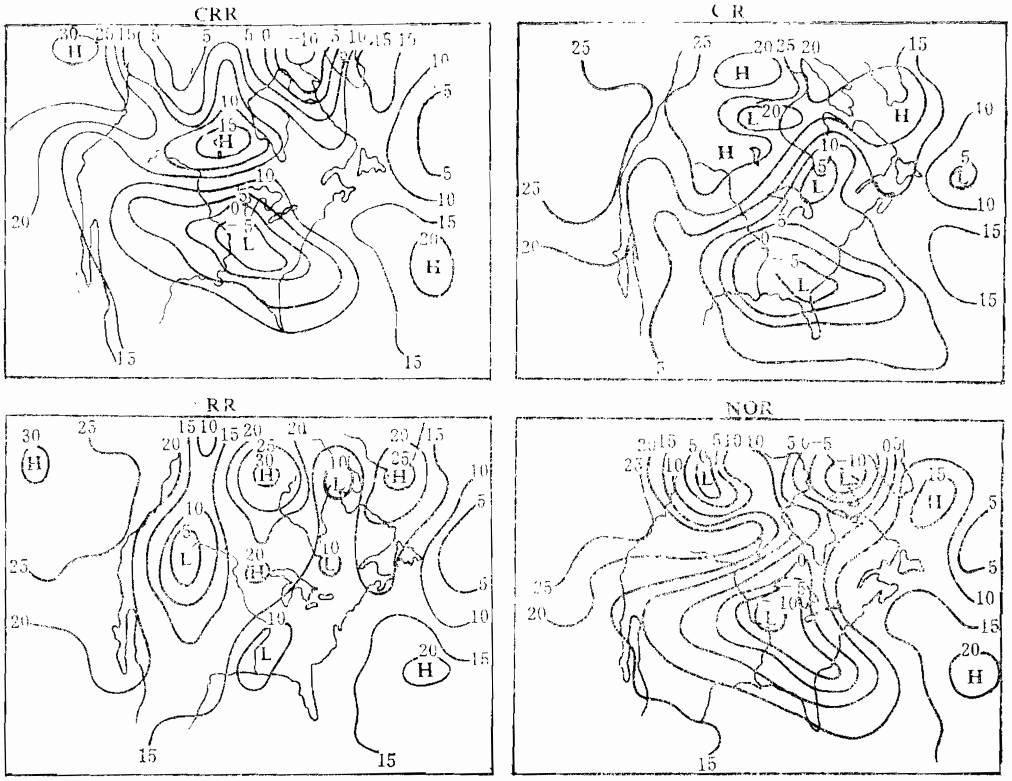

Fig. 5. Surface maps of 72 h integration in terms of various experiments in North America (numerals on maps are subtracted by 1000 and in units of hPa).

observations. In addition, the baroclinicity on 500 hPa chart is very strong in the downstream of QXP (Fig. 2b). A warm ridge with north-south orientation is formed in the east plain of China, which does not accord with actual weather system either.

4. *No Mountain* (*NOT*)

Without the plateau, the depression would cover a larger area with a high intensity, and stays basically in the east continent of China (Fig. 1e). At the same time, the cold air in Xinjiang would moves southeastward directly (Fig. 2c), making baroclinicity stronger. As a result intense cyclone would be formed in China mainland. In fact, it is not the case with the real weather system.

To sum up, synoptic system in Northern America generally moves eastward in shape of high pressure alternating with low pressure in west-east direction, or higher pressure in

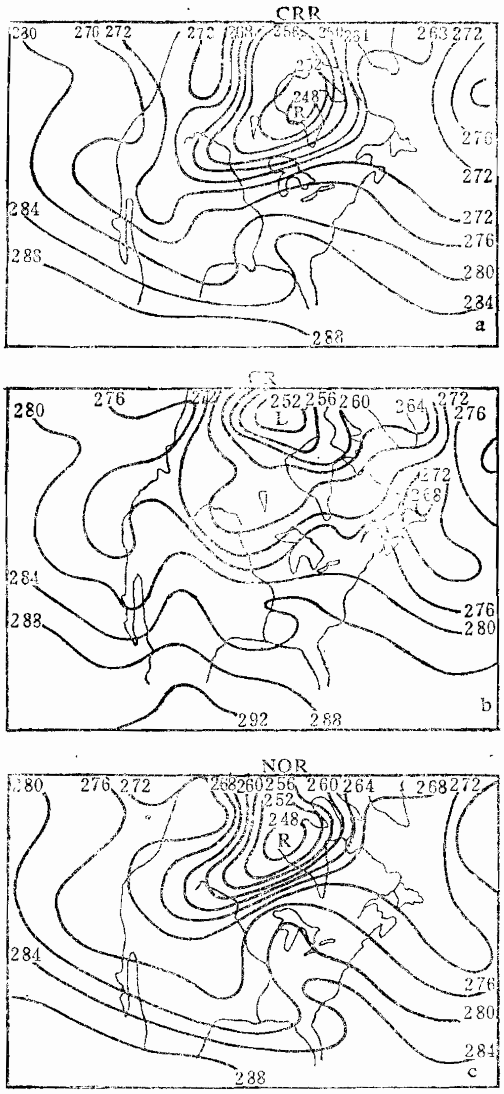

Fig. 6. 850 hPa temperature (K) field of 72 h integration.

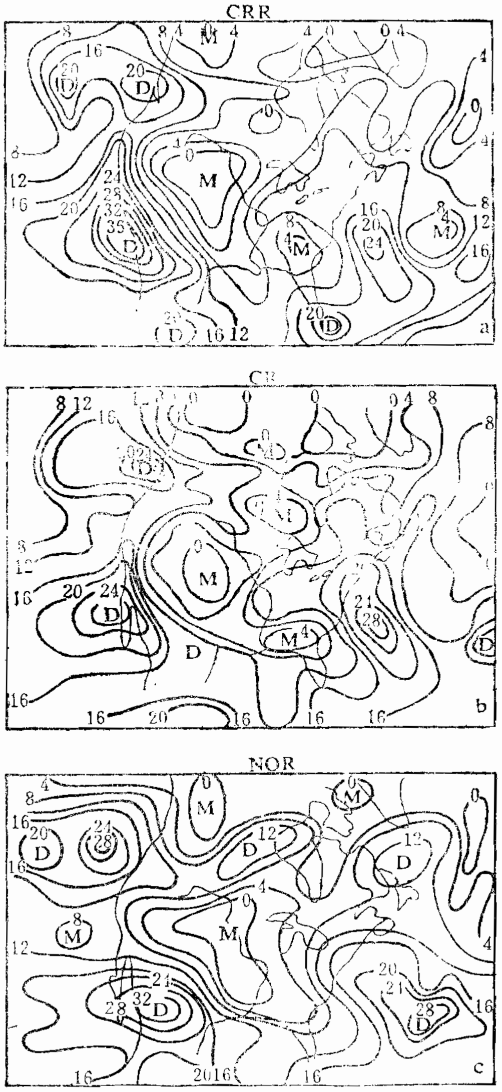

Fig. 7. 700 hPa $T-T_d$(℃) field of 24 h integration (M—moist, D—dry).

the south and lower in the north. Due to the strong polar front, pressure pattern in Europe is similar to that in Northern America. On the contrary, cold high pressures in Siberia always move southeastward one by one. In the initial stage of the cyclone in the Changjiang-Huaihe Valley, pressure situation exhibits the higher in north and lower in south, and appears an inverted trough in South China. Topographic sensitivity experiment and crossing and rounding tests show that these differences result from different dynamic influences of topography on the atmosphere. In East Asia, airflow is primarily around the Plateau.

IV. NUMERICAL EXPERIMENT OF DYNAMIC INFLUENCE OF RM ON CYCLOGENESIS AND ITS DEVELOPMENT

1. *Natural Crossing and Rounding* (*CRR*)

In the initial field of North America, there is an inverted trough area with a west-east orientation in the east flank of Rocky Mountains. After integrating for 48 hours, the depression near Colorado moves to east and develops rapidly. It almost occupies the whole U.S. continent. Then the depression moves slowly and extends its area. Integrating for 72 hours, it shows that intensity and extent of the cyclone approach to the actual state (Fig. 5a).

In the 500 hPa potential height and 500—1000 hPa thickness fields, angles between isohypse and isopach are big, and baroclinicity is remarkable. This is because there is a blocking high in west of North America. Thus trough and cut-off low move slowly. Meanwhile, the height of RM is lower and runs from north to south, which easily causes cold air to intrude southward, and causes baroclinicity in North America to get stronger. Therefore, the cyclone there often develops vigorously.

2. *Rounding Experiment* (*RR*)

Using rounding scheme, and running the model for 72 hours (Fig. 5b), we have cyclones in Colorado and Albert where they are most frequently formed statistically. This shows that part of cyclogenesis there may be related to the air flow rounding mountains.

3. *Crossing Experiment* (*CR*)

Prognostic surface map (Fig. 5 c) in terms of crossing scheme is consistent with actual state. In addition, the 700 hPa vertical motion fields of CRR and CR are similar. This illustrates that air flow in North America is primarily the air flow crossing mountain.

Crossing function directly influences lee frontogenesis and cyclogenesis. In the temperature field from CR, there is a warm ridge in the lee side of the Rocky Mountains (Fig. 6b). Obviously, the warm ridge is related to the large-scale descent in the lee side. When there is frontogenesis in the troposphere, air in the warm side sinks in relation to air in the cold side. There appears different adiabatic heating in both sides and momentum transports downward, which is helpful for temperature gradient and vorticity getting stronger. The warm cap area is just where the severe convective weather in the United States often takes place.

Remarkable difference of weather phenomena between North America and East Asia is that there are more severe convective weathers in North America and more heavy rains in East Asia. The severe convective weather in the United States is related not only to warm cap, but also to dry line in the west of the United States. West wind blows towards North America continent from flat ocean, and meets RM extending from south to north, then the air flow climbs the mountain's slope and becomes dry and cold. On the other hand, in the east flank of RM, the warm and moist air at low-level comes from the Gulf of Mexico. From Figs. 7a and 7b, we see that their distributions of $T-T_d$ are very consistent.

4. *No Mountains* (*NOR*)

Comparing Figs. 5a with 5d we have found that, if there is no mountain, cyclone would be stronger and slight further north. In addition, the warm ridge would locate further east than in that of CRR (Fig. 6c), and the dry line in the west of the United States starts deformation (Fig. 7c).

Generally speaking, dynamic influence of RM on the atmosphere is primarily crossing. Due to the airflow crossing the mountains, air ascends up in the west flank of the mountain and becomes dry and cold, while air descends in the lee side and becomes moist and warm. Warm ridge is formed in the east flank, which plays an important part in lee frontogenesis and lee cyclogenesis. At the same time, air crossing is also one of the causes for dry lines in the west of the United States.

V. NUMERICAL EXPERIMENT OF ZONAL MEAN FLOW AS INITIAL DATA

In the above, we have discussed dynamic influences of QXP and RM on lee cyclones using initial fields of various times. Now, we use zonal mean flow as initial data to do numerical experiment and examine mass flux at various longitudes, eddy momentum transport in East Asia and North America, and differences of pressure field and wind field between East Asia and North America.

1. *Mass Flux and Momentum Transport*

It is very clear that QXP makes the air flow of 700 hPa and 500 hPa branching (Fig. 8a) near 80°E, the north branch of jet arrives at the northmost latitude (about 40°N). and the south branch of jet moves southward. Two jets speed up and confluence at about 120°E. It is consistent with actual situation. While maximum mass fluxes in 500 hPa and 700 hPa are basically at the same latitude in North America.

The momentum transport is calculated according to Formula (10), as shown in Fig. 9. In East Asia, when westerly current meets QXP, it gets weaker, and rounds the QXP southward. In the southwest flank of the QXP, $u'v'$ is positive. From Southwest China to the Changjiang Delta, $u'v'$ is also positive. According to Starr' theory on momentum transport, if eddy momentum has meridional convergence, disturbance will decay, and basic flow will become stronger, which is unfavorable for cyclone development in East China continent. On the contrary, in North America, the magnitude of eddy momentum transport is very small so that neither would basic flow speed up nor would disturbance decay.

2. *Pressure and Wind Fields*

In the surface map of North America, pressure disturbances locate in the lee side of RM and low pressure can hardly move. While in East Asia, pressure disturbances are generated in the lower reaches of Changjiang River and then move northeastward.

In the flow field, eddy circulation appears in Southwest China. There is a wind shear

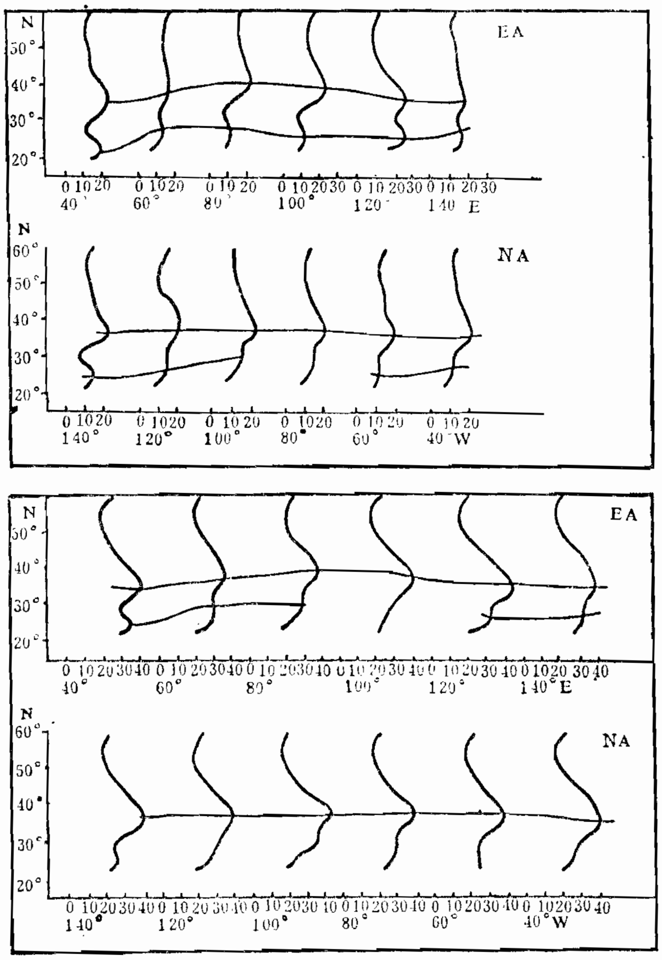

Fig. 8. Mass flux at various longitudes (unit: 10 m^2s^{-1}, EA—East Asia, NA—North America).

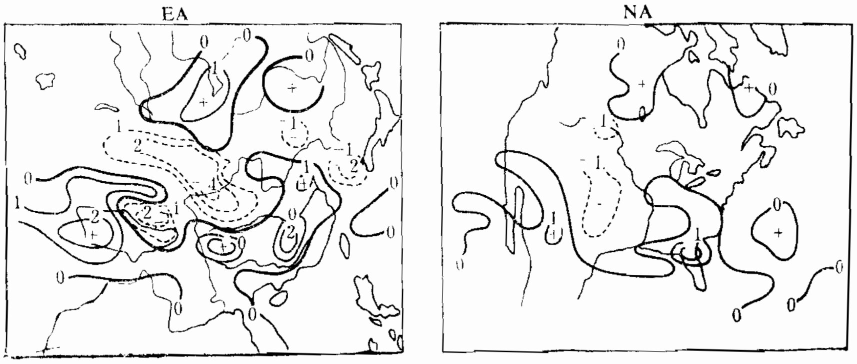

Fig. 9. Eddy momentum transport $u'v'$ (m^2s^{-2}, 700 hPa).

line in East Asia and also a wind shear over the QXP, but no wind shear can be found out in North America.

VI. CONCLUSION

We devise an adjustment scheme of all wind speed and conduct various numerical experiments of rounding and crossing. The results show that due to air flow rounding the QXP, the convergence belt in the lower troposphere is distributed in the shape of confluence which corresponds to divergence field in the upper troposphere. These match with high frequency area of cyclogenesis and cyclone track in East Asia. But in the downstream of the QXP, the convergence in the upper troposphere restrains cyclone development in the east of China mainland. Therefore, there is no intense cyclones in East Asia unlike in Europe and North America.

Because air flow rounds the Plateau, it is easier to form vortices in Southwest China, and in the Changjiang Delta often to form inverted trough. Meanwhile, southwest wind speeds up. All these are the background of cyclogenesis in the Changjiang-Huaihe Valley. Because of air flow rounding, small vortices and shears are often formed over the Plateau. This illustrates that rounding has influences on weather systems not only in the vicinity of the Plateau, but also over the Plateau.

In North America, the influence of RM on the atmosphere is primarily by way of crossing. Due to the air flow ascending along slope, air mass cools adiabatically and gets dry, meanwhile descends down in the lee side of RM on large-scale. Warm ridge is formed in the lower troposphere. This is favorable for lee frontogenesis and lee cyclogenesis. Crossing of air flow is one of the causes for generation of dry line in the west of the United States. Severe convective weather is closely related to the dry line and the warm ridge.

Analysis of mass flux and eddy momentum shows that air flow is blocked by the QXP, thus jet is branched into two subjects which speed up and converge near 120°E. This phenomenon is absent in North America. In the downstream of the Plateau, there is an eddy momentum meridional convergence, so that basic flow speeds up near 120°E. This is the cause that no strong cyclone develops in East China continent.

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