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Study on cut-off low-pressure systems with floods over Northeast Asia

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With 24 Figures

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Summary

The cut-off lows (COLs) during the period from June to August 1998 leading to the record flood in Northeast Asia, especially in Northeast China, has been investigated in this paper. The results are as follows: the blocking highs benefited significantly the formation and maintenance of COLs over Northeast China; an obvious frontogenesis zone existed in Northeast China and it implies that baroclinity played an important role in the initiation of COLs, especially in middle and upper troposphere; the maxima of the potential vorticity anomaly were located in the upper troposphere, then extended downwards to the middle and the lower troposphere. The pronounced interaction between systems in upper-middle and low troposphere can be revealed; the moisture supply was from South China, and even from East China Sea and South China Sea. The strong southerly current transported very rich moisture to Northeast China. The maximum of the convergence of moisture flux was below 850 hPa. Obvious interaction between the middle and lower latitude systems was found in the study. Also, the summer monsoon showed significant impacts on the sustained heavy rainfalls related with the COLs over Northeast China; the upward motion could be caused by the lifting of the large scale dynamic forcing and there was no obvious releasing of latent heating in the upper-middle troposphere. The cold dome in the COLs was quite different both from the warm core in tropical cyclone and from the weaker warm core in Meiyu (Baiu) front low. The calculation of vorticity budget shows that both the horizontal advection term and horizontal divergence term contributed importantly to the maintenance and the strengthening of positive relative vorticity. Finally, the complex dynamical characteristics regarding the COLs are discussed and further investigation is proposed.

1. Introduction

East Asia, especially Northeast China experienced its worst floods on record during June–August, 1998. On average, much of the Nenjiang River and Songhuajiang River in Northeast China received in excess of 400 mm of precipitation during this period. In Zalantun (at 48.0° N, 122.6° E) and Arongqi (at 48.2° N, 123.5° E), the two maxima of the precipitation amount of 952.4 and 808.1 mm were reported, respectively. In most areas of Northeast China, the precipitation amount was 100 to 150% more than the seasonal average in history. The heavy rainfalls resulted in the record floods and very serious damages to the local economy and societies. Figure 1 shows the locations of the rivers and the cities mentioned-above.

During the periods of the floods, the atmospheric circulation was dominated by an anomalously deep trough over Siberia and by a stronger ridge than normal over Okhotsk Sea. There were obvious blocking highs in West Pacific and COLs in Mongolia and Northeast China. The so-called

Fig. 1. The locations of the major rivers and related cities in Northeast China

COLs over Northeast China are the synoptic scale low pressure systems which have closed circulation mainly in the upper-middle troposphere, for example, 500 hPa, even up to 200 hPa, and usually associate with a deep trough in the westerlies of upper troposphere. At the surface level, it is not necessary for them to be accompanied by a cold front or closed isoline. COLs are one of the important weather systems that affect Northeast China. Occasionally, the moderate and heavy rainfall associates with COLs. It is generally believed that the most active area for the genesis of COLs in North China is located over the Northeast region and that the most of COLs move eastward or northeastward. Some of them move quickly, whereas the others move quite slowly and can stay in a region for up to five days or even longer. In June and August 1998, the COLs not only moved slowly, but also formed one by one almost in the same region. It is the reason why the severe floods happened, even though the intensity of rainfall each day was not very strong.

Generally, there are three main kinds of rainfall patterns in East Asia: (1) the rainfall caused by summer monsoon, including Meiyu (Changma, Baiu), (2) the rainfall associated with the tropical cyclones, including typhoon, and (3) the precipitation related with the westerlies systems, including COLs. The summer monsoon rainfall in East Asia in 1998 has been investigated (Zhao et al, 1998, 2004; Bei et al, 2002; Lee et al, 2002; Sun and Lee, 2002; Lee, 2004; Zhang and Zhao, 2004). The severe tropical cyclone rainfall in China and Australia has also been studied (Zhao and Mills, 1991; Qi and Zhao, 2003). However, only a few heavy rainfall events related to the westerlies systems have been analyzed, especially during the recent years (Zhao et al, 1980; Matsumoto et al, 1982; Price and Vaughan, 1992; Kentarchos and Davis, 1998; Nieto et al, 2005). Moreover, the most of them are the results of climatologic research.

It should be emphasized that cold vortices in North America in earlier spring, and the cold air pools in Europe have been investigated by Hsieh (1949) and by Llasat and Puigcerver (1990), respectively, and COLs in Australia in spring have also been studied by Qi et al (1999). In this paper, the COLs in summer were investigated and it is noticed the related weather situation in summer season was more complicated than that in the other seasons (Ramage, 1971; Tao, 1980; Zeng et al, 1994). In wintertime, strong cold wave and cold surge accompanying with the strong Siberia high moved southeastward and sweep through Northeast China. On average, the East Asia major trough is located in the coast area. Northeast China is situated just behind the major trough, where it is not favorable to the development of upward motion and also not good for formation and maintenance of the COLs. In the transitive seasons, i.e., spring and autumn, the westerlies is just over Northeast China. The small troughs in westerlies are the rapidly moving systems, only resulting in small amount of precipitation that is not likely to cause any floods in this region because of the lack of the moisture supply coming from the lower latitude area before the onset of summer monsoon or after the retreat of summer monsoon. Therefore, not in all seasons, the COLs are favorable to the strong precipitation, whereas in summer there are indeed the favorable conditions of the occurrence of the heavy rainfall and the flood associating with COLs. The previous research has revealed that there are three preferred areas of COLs occurrence and they are, respectively, southern Europe and the eastern Atlantic coast; eastern North Pacific; northern China-Siberian region extending to the northwestern Pacific coast (Nieto et al, 2005). In addition, the statistical results demonstrated that the inter-seasonal variation is also obvious and the COLs form much more frequently in summer than in winter (Price and Vaughan, 1992; Nieto et al, 2005). However, the COLs in Eastern Asia, especially in summer season, have not been clarified completely. Questions that need to be answered included: what kinds of atmospheric circulations are favorable for the formation of COLs? What kinds of dynamical mechanisms are related with the evolution and development of COLs? What kind of structure of COLs can be revealed? Why only a certain amount of COLs are associated with heavy precipitation and where is the moisture source during the precipitation? Is there any interaction between high and lower latitude systems? In addition, it has been noticed that, in some case, the COLs can transfer stratosphere air into the troposphere, namely, stratosphere-troposphere exchange (STE). Chemical effects from STE can, in turn, influence the radiative flux balance in the troposphere and lower stratosphere, therefore, may play a significant role in the radiative forcing of global climate (Kentarchos and Davies, 1998). However, the issue mentioned-above has been beyond the scope of this paper. The main purpose of this paper is to reveal the characteristics of COLs with the heavy rainfalls through the analysis of individual cases of COLs in Northeast China.

In Sect. 1, the background of COLs in Northeast Asia was introduced, the data and methodology employed in this study were described in Sect. 2, and the circulation and the weather related with COLs was mentioned in Sect. 3. In Sect. 4, the detailed analysis of the three cases in June, July and August 1998 were conducted, respectively. A concluding discussion of the relative contributions of atmospheric dynamics and thermodynamics to initiation and maintenance of the COLs associating with the floods were presented in Sect. 5.

2. Data and methodology

In this paper, the NCEP (National Center for Environmental Prediction, US) reanalysis grid $1^\circ \times 1^\circ$ data (Kalnay et al, 1996) and TBB (Black Body Temperature) data from GMS satellite (IR1 10.5–11.5 μm) have been used, respectively. The 24-hour precipitation amount data of around 730 surface stations in China provided by China Meteorological Administration (CMA) has also been utilized.

To evaluate the impact of the flood, the total accumulated precipitation amount during three months from June 1 to August 31,1998 and the precipitation amount anomaly from the average (1951–2003) were analyzed. To check the characteristics of the blocking high at 500 hPa, the mean geopotential height field for the cases in June and in August were drawn, respectively. In addition, the 200, 500, 850 hPa and surface map have been analyzed to compare the difference between COLs at the various levels. The meridian and zonal vertical cross sections of potential temperature and potential vorticity across COL center have been drawn in order to understand the vertical structure of the COLs. To explain the maintenance mechanism of the vortex, the vertical profiles of vorticity budget of area mean was discussed and importance of the various terms were investigated.

It should be emphasized that the different horizontal domains, including Asia area (AA), China area (CA) and Northeast Asia area (NE) were chosen in this paper, respectively, for the different purposes. AA covers the most part in Asia from West Siberia to Okhotsk Sea where the two blocking highs were located in, this kind of domain was very useful for analysis of the large scale circulation characteristics. CA was especially for the investigation of the rainy area in China. NE was particularly for studying of the evolution and structure of COLs. In addition, the vertical cross sections were analyzed which followed the centers of the COLs. The positions of the cross sections were selected according to the locations of the COLs, e.g., along 48° or 50° N, along 118° or 130° E, to better the descriptions of the vertical structures in the different cases during the different period.

In order to investigate the formation and the intensification of COLs and check the interaction between the systems in upper troposphere and in lower troposphere, the potential vorticity at different levels was calculated, and it is noticed that appearance of COL seemed to be associated with anormaly zone of the potential vorticity.

The thermal advection was computed, meanwhile to discuss the contribution of cold air to the precipitation. To reveal the interaction between the middle latitude systems and lower latitude systems, the frontogenesis function, defined as the variation with time of horizontal gradient of potential temperature, was calculated. It has been noticed that the impact of warm air from the lower latitude area was also important and, therefore, the warm and moist current should be analyzed. Because no observation data over the ocean area was available, TBB cloud bands which extending from the lower latitude area to Northeast China was employed to represent the current mentioned-above. TBB data at six-hour interval in East China was used. In addition, the water vapor, as an important influencing factor of heavy rainfall, also was calculated, the moisture flux and the divergence of moisture flux have been evaluated to clarify the water vapor supply ability and the source place of moisture during the heavy rainfall in Northeast China. The detailed description of the relevant formulas associated with the methods mentioned-above will be given in Sects. 4, respectively. In this paper, the figures of grid data were drawn by the Grid Analysis and Display System (GrADS) developed by Doty (1995).

3. Circulation pattern and weather systems

During the period from June 1 to August 31, 1998, the sustained precipitation occurred in Northeast China. It can be seen from Fig. 2 that there was a region with precipitation of more than of 400 mm and the maximum of 600 mm in Northeast China. In addition, the deviation analysis results show that the area with the value of 100% above the normal appeared in Northeast China both in June and in August 1998 (in Fig. 3). Two periods from 6 to 23 June and from 1 to 19 August belong to the rich rainfall stages when COLs were very active and frequent. The other period from 17–22 July was related with the less rainfall stage when COLs was inactive.

Year 1998 was a very special year in which the blocking highs maintained persistently over Okhotsk Sea and west Siberia, respectively, in summer that was the most pronounced feature of the atmospheric circulation (Bei et al, 2002; Zhao et al, 2004). At first, the mean circulation during the certain special period was discussed here. Fig. 4a and b were the mean geopotential height at 500 hPa from 6–23 June and 8–13 August, 1998, respectively. The COLs in June lasted for 18 days and the COLs in August maintained at least 6 days. It is noted that the Okhotsk high at 500 hPa was located over the coast area of East Asia and the COLs to west of the high mentioned-above stayed just over Mongolia and Northeast China. The COLs could trigger a series of cloud clusters over Northeast China, resulting in the major floods. In fact, the COLs in Northeast China in average charts at 500 hPa level were composed of the many processes, since the circulation situations at each level were changing with time. It was not good enough if only mean charts were analyzed. Therefore, after two mean COLs were displayed at 500 hPa level in Fig. 4, a total of 14 COLs during the three months from June 1 to August 31 were listed individually in Table 1. According to the tracks, they can be cataloged into the three types: type A, moving southeastward from Lake Baikal; type B, moving eastward from Mongolia and Inner Mongolian Autonomous region, China; type C, moving northeastward from the Yangtze River and Yellow River. Basically, it can be seen that there were 4′, 5′, 5 COLs in June, July, August 1998, respectively. In each type, the COLs were listed in time sequence. Also, it is thought that the case study should be conducted to have a better understanding of the initiation, evolution and structure of COLs, besides investigation of their characteristics from the mean fields.

In this paper, our study concentrated mainly on the three processes of COLs of 6–23 June, 8–13 August and 17–22 July, and they are called as the case in the June, the case in August and the case in July (hereafter), respectively. The case in June belonged to type A, including

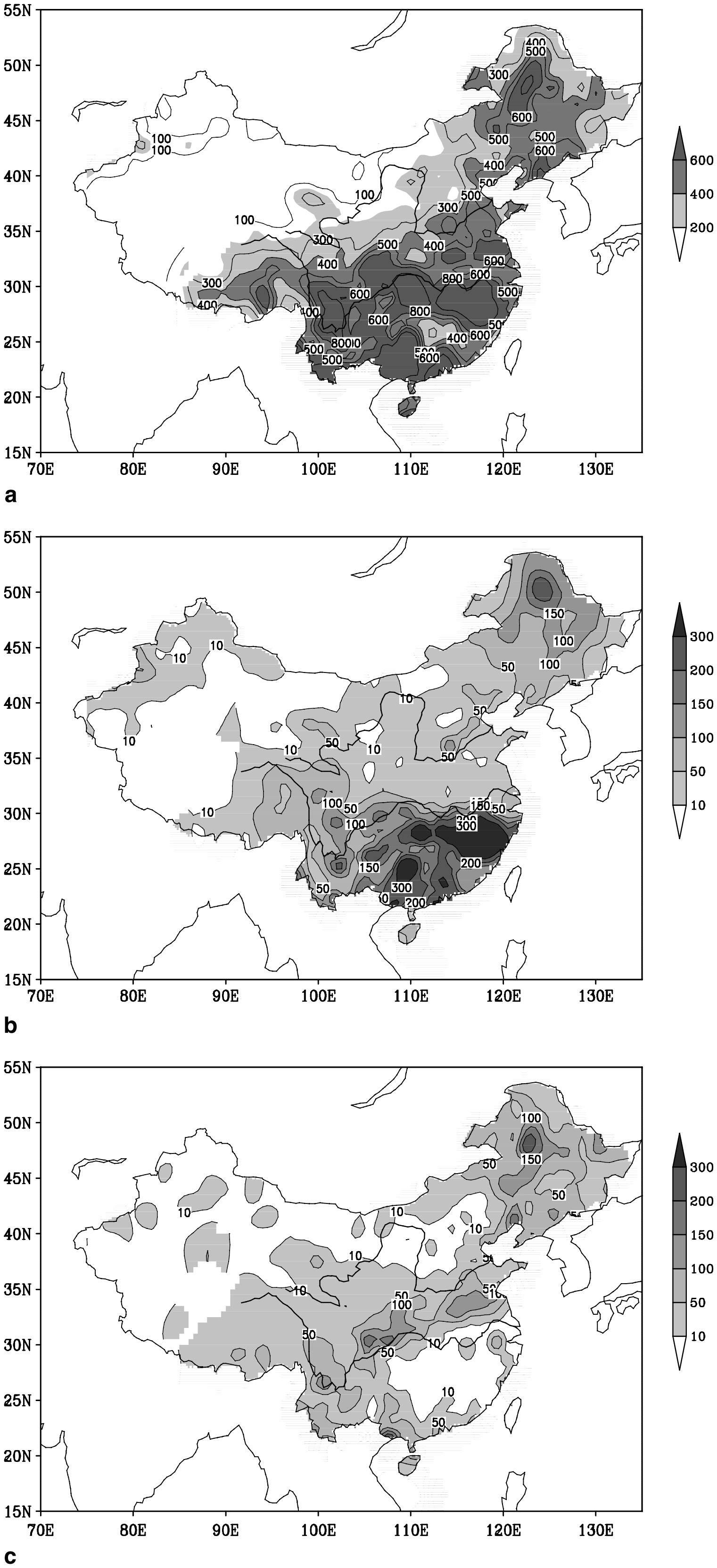

Fig. 2. Total precipitation amount in mm. (**a**) from 1 June to 31 August 1998, (**b**) from 6 to 23 June 1998, and (**c**) from 8 to 13 August 1998

low No. 1 and No. 2 in Table 1, the case in August was type C (No. 11 in Table 1) and the case in July was type B (No. 8 in Table 1). The case in June was composed of COLs No. 1 and No. 2, however, they were studied as one case because they were, in many ways,

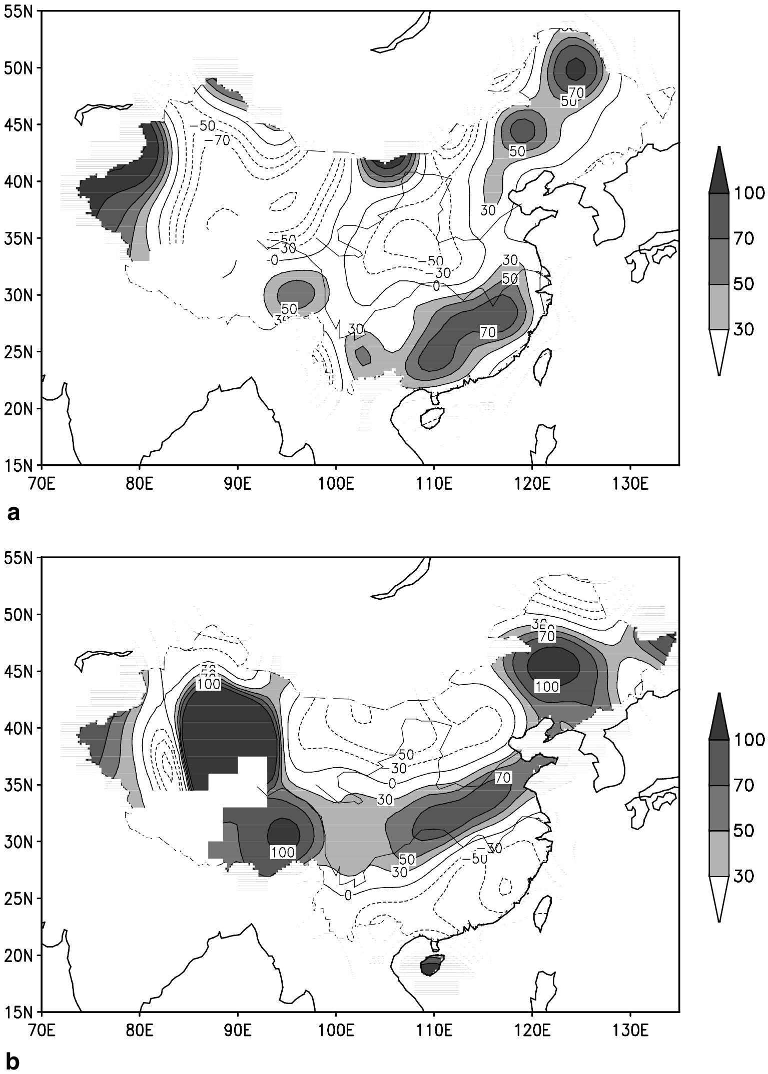

Fig. 3. Precipitation amount anomaly from the average (1951–2003) (in percentage, units: %). (**a**) in June 1998, and (**b**) in August 1998

similar to each other and formed almost in the same circulation background.

It is noticed among all cases that the case in June (type A) and case in August (type C) lasted for the top two longest periods in the table. Moreover, they represented the two different types, one come from North and the other from South. In next section, the two cases mentioned-above were chosen to be investigated first, and then, the case in July (type B) was described briefly.

4. Diagnostic analysis of COLs

From Table 1, the COLs occurred very often during June to August, 1998. But sustained precipitation was found in Northeast China mainly in June and August, respectively. In July the precipitation was not pronounced in Northeast China when the COLs appeared. The main reason seems to be the moisture supply is concentrated over the Yangtze River region rather than Northeast China in July (Zhao et al, 1998, 2004; Bei et al, 2002). Therefore, it can be deduced that moisture supply also played a very important role in occurrence of the precipitation. In this section, the case in June and the case in August are diagnosed first, respectively, because this paper focuses on these COLs associated with the sustained precipitation. Then, the case in July is briefly compared with the two cases mentioned-above. For the detailed diagnosis, the key meteorological parameters, including temperature advection, frontogenesis function, moisture flux, divergence of moisture flux, potential vorticity and vorticity budget were calculated.

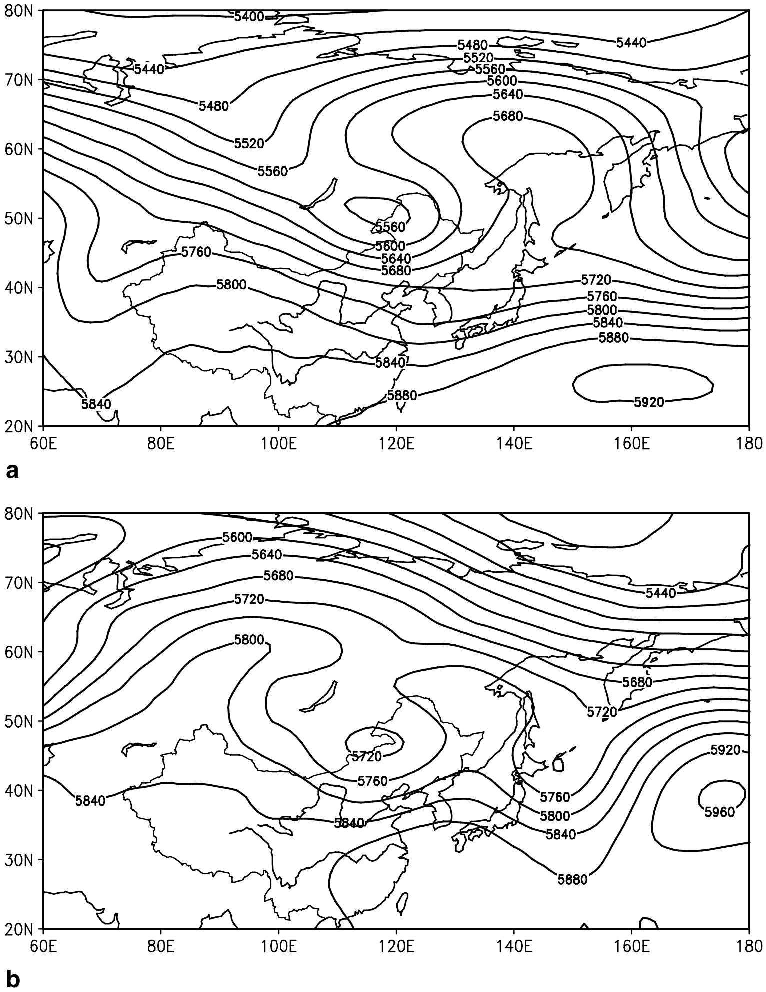

Fig. 4. Mean geopotential height in gpm at 500 hPa. (**a**) 0000 UTC, 6–23 June 1998, and (**b**) 0000 UTC, 8–13 August 1998

Table 1. Statistics of activities of the COLs over Northeast China from 1 June to 31 August, 1998. Three types of COLs are divided according to the different tracks. Type A: moving southeastwards from Lake Baikal; Type B, moving eastward from Mongolia and Mongolian Autonomous region, China; Type C, moving northeastward from the Yangtze River and the Yellow River

Track type	Series	Developing time	Period of influence over Northeast China	Intensity (close center value at 850/500/200 hPa, unit : gpm)
A	1	6 June	6–13 June	1340/5400/11680
	2	15 June	18–20 June	1300/5400/11760
	3	13 July	14–16 July	1340/5760/–
	4	26 July	29–30 July	1400/5680/12040
B	5	14 June	15–16 June	1340/5600/11880
	6	23 June	24 June	1360/5600/–
	7	6 July	7–9 July	1320/5680/–
	8	17 July	19–22 July	1360//5640/12140
	9	1 Aug.	5–6 Aug.	1400/5720/12160
C	10	30 July	1–3 Aug.	1400/5720/–
	11	7 Aug.	8–13 Aug.	1380/5680/–
	12	17 Aug.	19–20 Aug.	1400/5680/–
	13	22 Aug.	23–25 Aug.	1380/5680/–
	14	26 Aug.	27–30 Aug.	1440/5640/11920

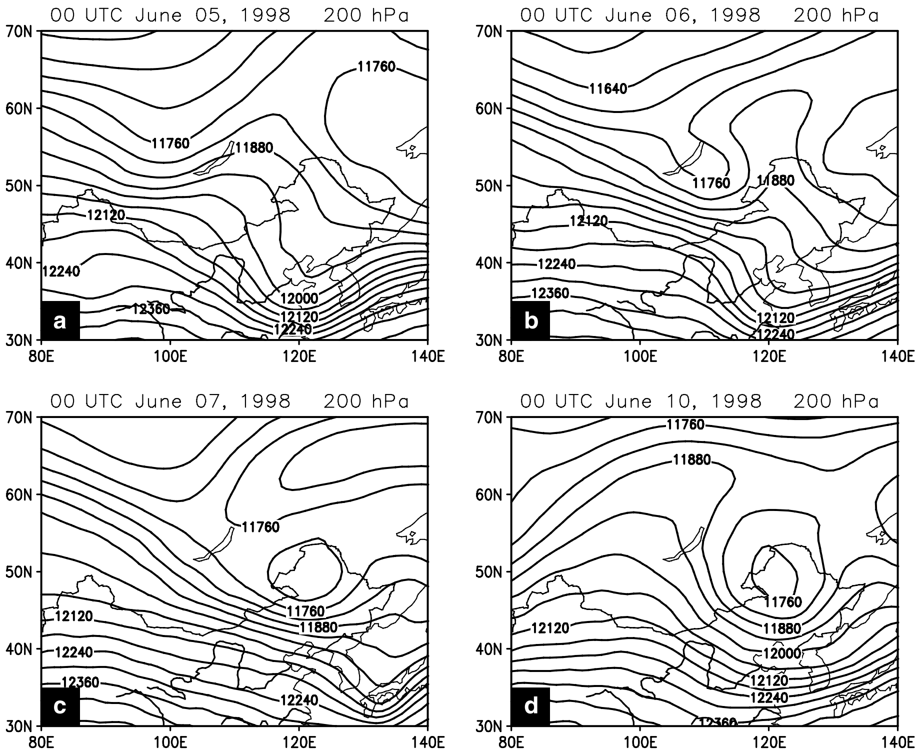

Fig. 5. Geopotential height in gpm at 200 hPa. (**a**) 0000 UTC 5 June 1998, (**b**) 0000 UTC 6 June 1998, (**c**) 0000 UTC 7 June 1998, and (**d**) 0000 UTC 10 June 1998

4.1 Case in June (type A)

First, in geopotential height field at 200 hPa at 0000 UTC 5 June 1998 (in Fig. 5), a blocking high over Okhotsk Sea implied that the troughs and the ridges in the westerlies were quasi-stationary. To the west of the Okhotsk high, a small trough was located near the national boundary between Russia and Mongolia, west to Lake Baikal. 24 hour later, at 0000 UTC 6 June the trough moved slightly to Northeast Mongolia, deepened and no closed isoline in the trough was found. At 0000 UTC 7 June, a minimum of central value of 11700 gpm with the closed isoline shifted eastward to North Part of Northeast China. After that the closed low maintained persistently for a long period in the same region. Up to 0000 UTC 22 June, the Okhotsk high weakened and at 0000 UTC 23 June, it moved eastward. Then, the COLs in Northeast China disappeared. The COLs mentioned-above lasted almost 18 days in total.

It is also very interesting to analyze the circulation at 500 hPa (in Fig. 6) during this period. At 0000 UTC 5 June, similar to the situation at 200 hPa, the small trough was situated west to Lake Baikal and near the boundary between Russia and Mongolia. However, at 0000 UTC 6 June, different from that at 200 hPa, a closed isoline with the minimum of 5440 gpm can be identified at 500 hPa. It was one day earlier than the appearance of the closed isoline at 200 hPa. Then, the COL maintained in Northeast China. The continuous evolution process of the COLs at 500 hPa on 5–10, 12, 14, 16, 18, 20, and 22 June can be clearly seen in Fig. 6, respectively.

At 850 hPa (in Fig. 7), it was also noticed that at 0000 UTC 6 June, a closed isoline with the central value of 1360 gpm was in Northeast China. It implies again that the low with closed circulation formed first in the middle and lower troposphere and then, up to the upper troposphere. The formation of the COLs in northeast China can be found earlier in the middle-lower troposphere, and then up to the upper troposphere, the results are, to a certain extent, similar to the COLs in Europe (Nieto et al, 2005).

To investigate the contribution of cold air activities in case in June, pseudo-equivalent potential temperature and the temperature advection were calculated first and the results were shown in Fig. 8.

Temperature advection T_a is computed by the following formula (Zhao and Zeng, 2005):

$$T_a = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} \qquad (1)$$

In Fig. 8a and b, the pseudo-equivalent potential temperature θ_{se} and temperature advection at 850 hPa were given and the weak cold advection can be detected. Pseudo-equivalent potential temperature is recognized more suitable to the weather system in East Asia monsoon area (Tao, 1980; Zhao et al, 2004). Form Fig. 8a and b, isoline of 312 K at 850 hPa was in central Mongolia at 0000 UTC 16 June, then isoline of 312 K moved eastwards and at 0000 UTC 18 June, the cold air advanced to Northeast China. In Fig. 8c and d, isoline of 320 K at 500 hPa also extended into Northeast China. And however, the cold advection at 500 hPa was stronger than that at 850 hPa. Therefore, the cold air in the middle troposphere could play more important role in initiating and maintaining COLs than that in the lower troposphere. The reason may be that the cold air in the middle troposphere could strengthen the potential instability in the atmospheric stratification.

For discussing the influence of baroclinity, the frontogenesis function F_g was calculated.

$$F_g = \frac{d}{dt}|\nabla\theta| = F_{g1} + F_{g2} + F_{g3} + F_{g4}$$

$$F_{g1} = \frac{1}{|\nabla\theta|}\left[(\nabla\theta)\cdot\nabla\left(\frac{d\theta}{dt}\right)\right],$$

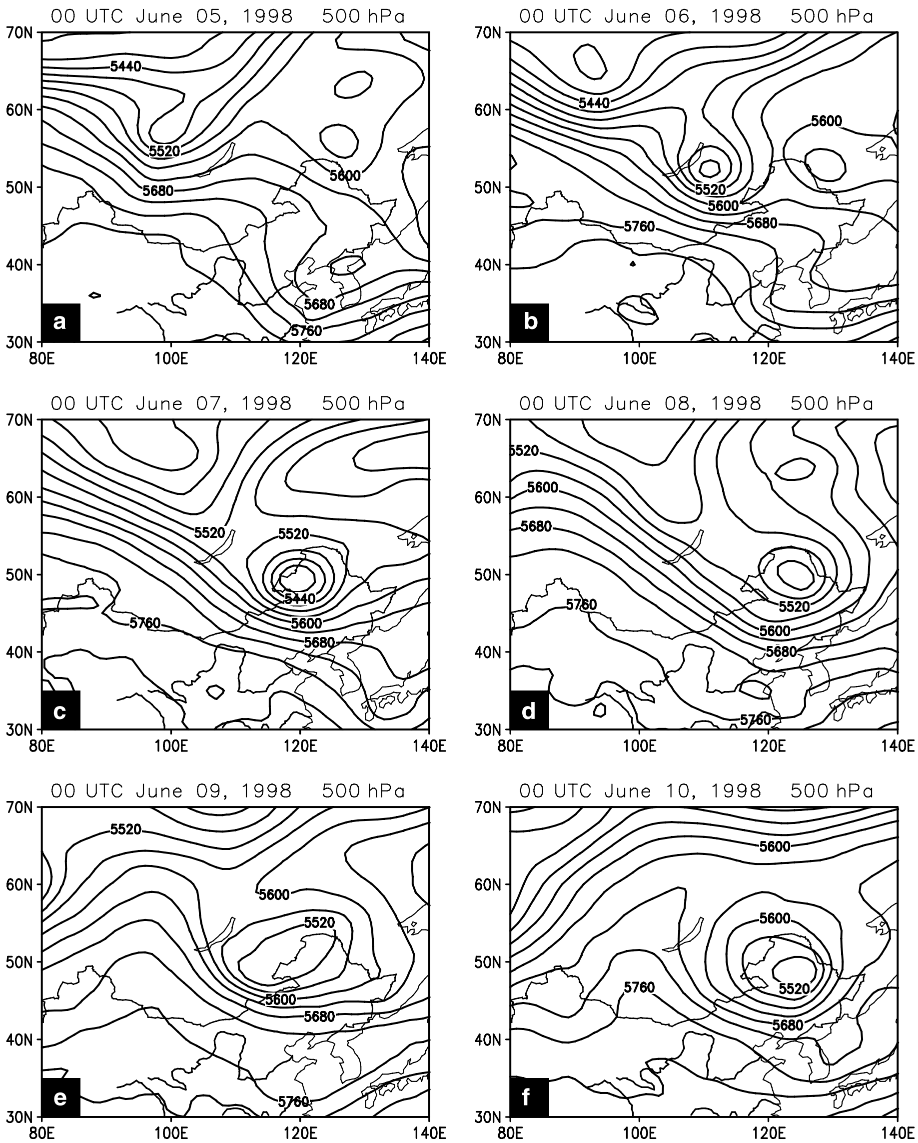

Fig. 6. Geopotential height in gpm at 500 hPa. (**a**) 0000 UTC 5 June 1998, (**b**) 0000 UTC 6 June 1998, (**c**) 0000 UTC 7 June 1998, (**d**) 0000 UTC 8 June 1998, (**e**) 0000 UTC 9 June 1998, (**f**) 0000 UTC 10 June 1998, (**g**) 0000 UTC 12 June 1998, (**h**) 0000 UTC 14 June 1998, (**i**) 0000 UTC 16 June 1998, (**j**) 0000 UTC 18 June 1998, (**k**) 0000 UTC 20 June 1998, (**l**) 0000 UTC 22 June 1998

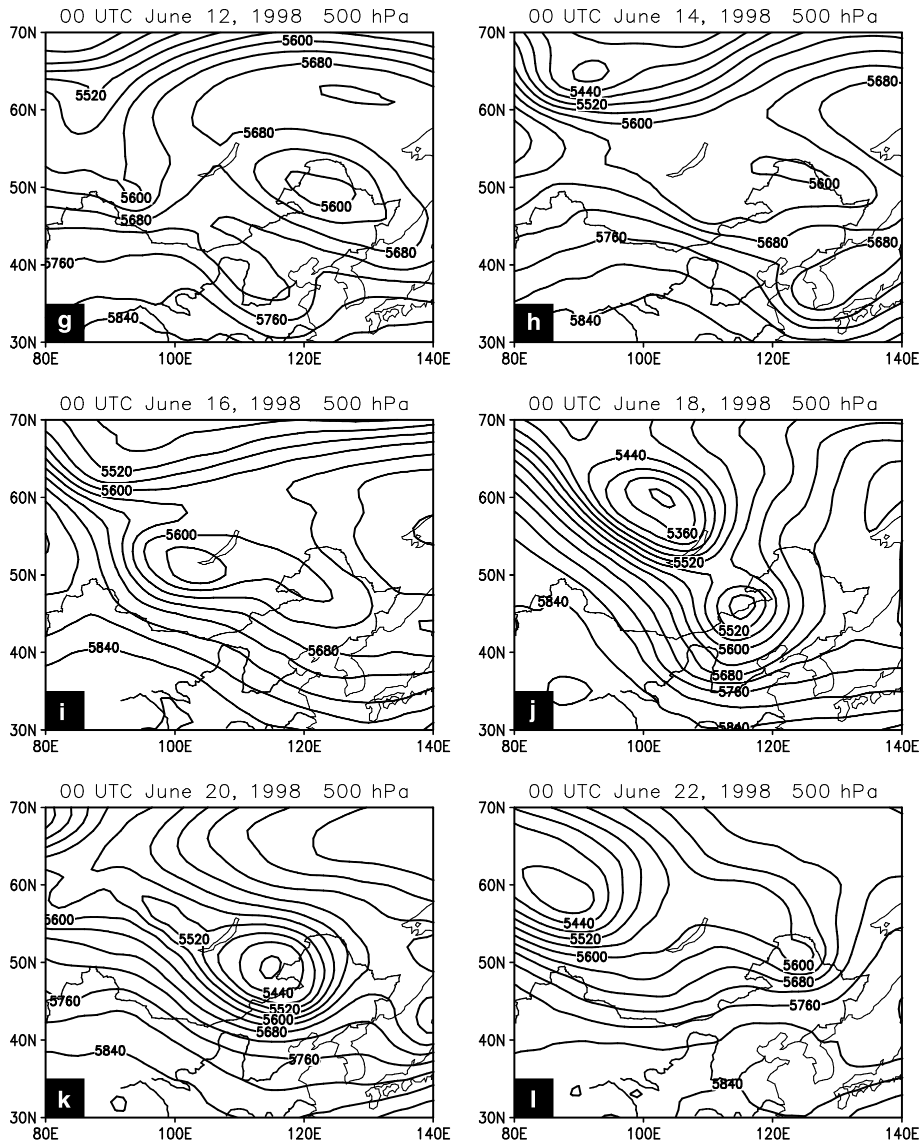

Fig. 6 (*continued*)

$$F_{g2} = -\frac{1}{2}\frac{1}{\nabla\theta}(\nabla\theta)^2 D_h, \tag{2}$$

$$F_{g3} = -\frac{1}{2}\frac{1}{|\nabla\theta|}\left\{\left[\left(\frac{\partial\theta}{\partial x}\right)^2 - \left(\frac{\partial\theta}{\partial y}\right)^2\right]A_f + 2\frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial y}B_f\right\},$$

$$F_{g4} = -\frac{1}{|\nabla\theta|}\frac{\partial\theta}{\partial p}\left(\frac{\partial\theta}{\partial x}\frac{\partial w}{\partial x} + \frac{\partial\theta}{\partial y}\frac{\partial\omega}{\partial y}\right),$$

$$A_f = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}, B_f = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}.$$

Here, F_g is the frontogenesis function which is defined as the variation ratio with time of the horizontal gradient of the certain meteorological parameter, for example, potential temperature (Keysern and Shapiro, 1986). F_{g1}, F_{g2}, F_{g3}, F_{g4} are diabatic heating term, horizontal divergence term, horizontal deformation term and tilting term associating with vertical velocity, respectively. θ is potential temperature, and D_h is the horizontal divergence. The frontogenesis function at 850 hPa is shown in Fig. 9. The maximum of the frontogenesis function also extended southeastwards into Northeast China. This is consistent with the distribution of the temperature advection. That means again the cold air contributed significantly to initiate the COLs. It should also be emphasized (in Fig. 10) that the frontogenesis area was vertically deeper and concentrated mainly in middle troposphere. The

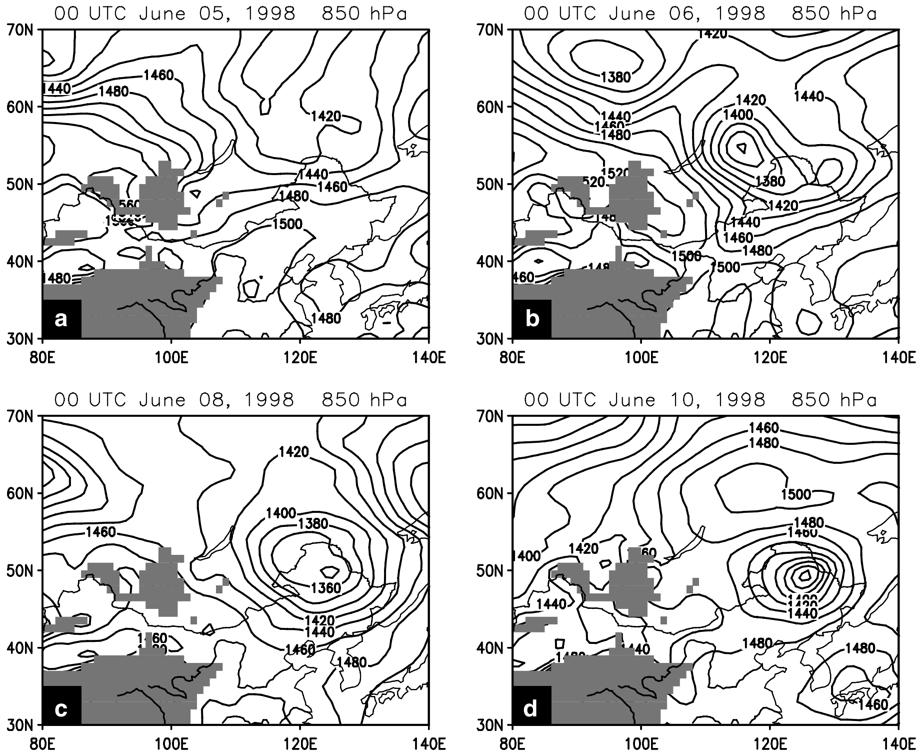

Fig. 7. Geopotential height in gpm at 850 hPa. (**a**) 0000 UTC 5 June 1998, (**b**) 0000 UTC 6 June 1998, (**c**) 0000 UTC 8 June 1998, and (**d**) 0000 UTC 10 June 1998, shaded area is the terrain higher than 1500 m

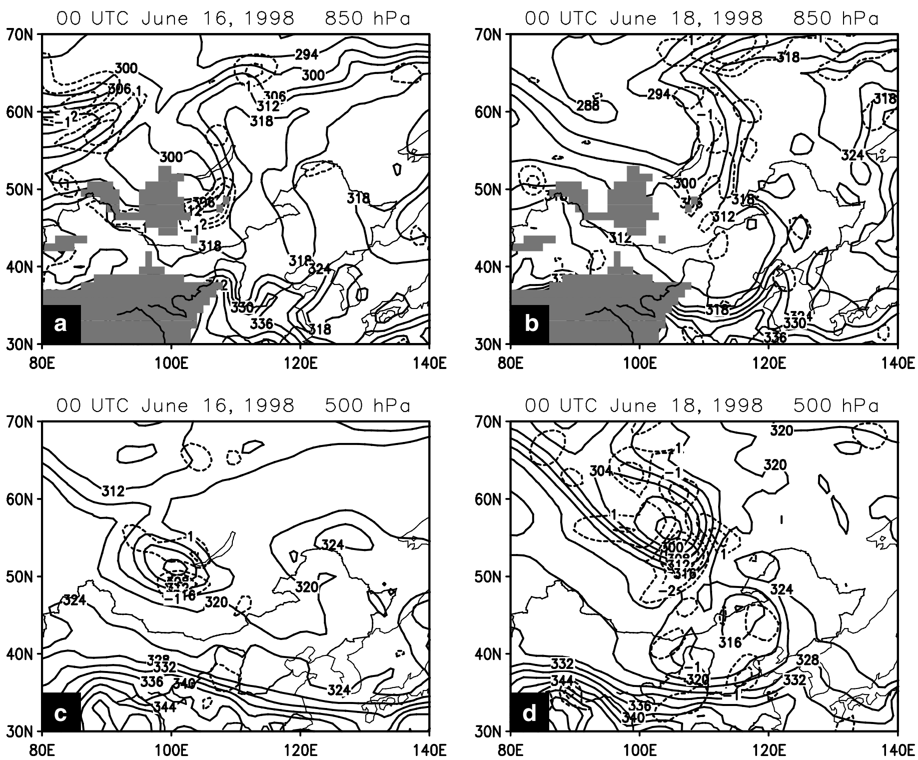

Fig. 8. Pseudo-equivalent potential temperature and temperature advection (units: K; $10^{-4}\,°C \cdot s^{-1}$). The thick solid lines are pseudo-equivalent potential temperature, and the short dashed line are temperature advection. (**a**) at 850 hPa, 0000 UTC 16 June 1998, (**b**) at 850 hPa, 0000 UTC 18 June 1998, (**c**) at 500 hPa, 0000 UTC 16 June 1998, (**d**) at 500 hPa, 0000 UTC 18 June 1998. The shaded area in (**a**) and (**b**) are the terrain higher than 1500 m

moving of the cold air, especially, the upward motion branch ahead the cold front can be a possible triggering mechanism.

Not all of COLs are associated with heavy rainfalls and a certain kind of the COLs can cause heavy rainfalls only when there are enough

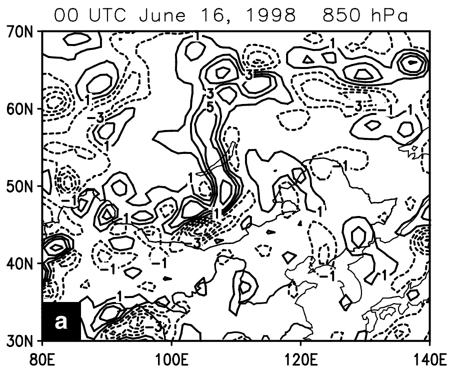

Fig. 9. Frontogenesis function at 850 hPa (unit: $10^{-10} \cdot K \cdot s^{-1} \cdot m^{-1}$). The solid lines and the dashed lines represent the positive and negative values of frontogenesis function, respectively. (**a**) 0000 UTC 16 June 1998, (**b**) 0000 UTC 19 June 1998

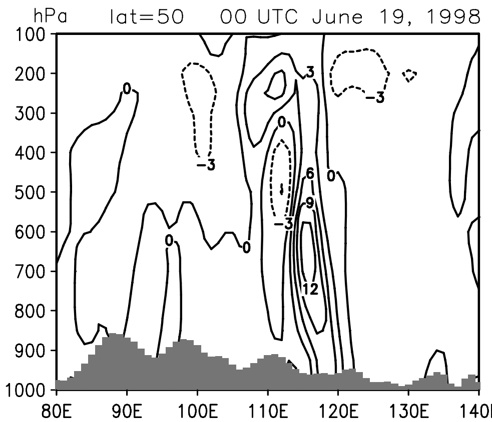

Fig. 10. Vertical cross section of frontogenesis function along 50° N at 0000 UTC 19 June 1998 (unit: $10^{-10}\,K \cdot s^{-10} \cdot m^{-10}$), shaded area represents the terrain

water vapor and strong upward motion existing in COLs. Undoubtedly, moisture is the very important factor for the occurrence of heavy rainfalls. It is well known that China is located in Asia monsoon area and in summer, the summer monsoon transports a large amount of moisture to East China, even to East Asia (Ramage, 1971; Tao and Chen, 1988; Zeng et al, 1994). The monsoon surge arrives at South China in May, approaches to the Yangtze River region in middle-June and then moves to North China around mid-July, even farther to North of 40° N. Sometimes, the monsoon current could approach to Northeast China when it is strong enough (Tao, 1980; Zhao et al, 2004). It is thought that the moisture flux (MF) represents the water vapor amount passing through the unit area, (for example, 1 cm × 1 hPa) in unit time. MF can demonstrate the quantity and direction of moisture transportation and divergence of moisture flux (DMF) can describe the concentrating ability of water vapor. The formula of moisture flux and divergence of moisture flux (Tao, 1980) are, respectively:

$$MF = \frac{1}{g} Vq, \tag{3}$$

$$\mathrm{DMF} = \frac{1}{g} \nabla \cdot Vq. \tag{4}$$

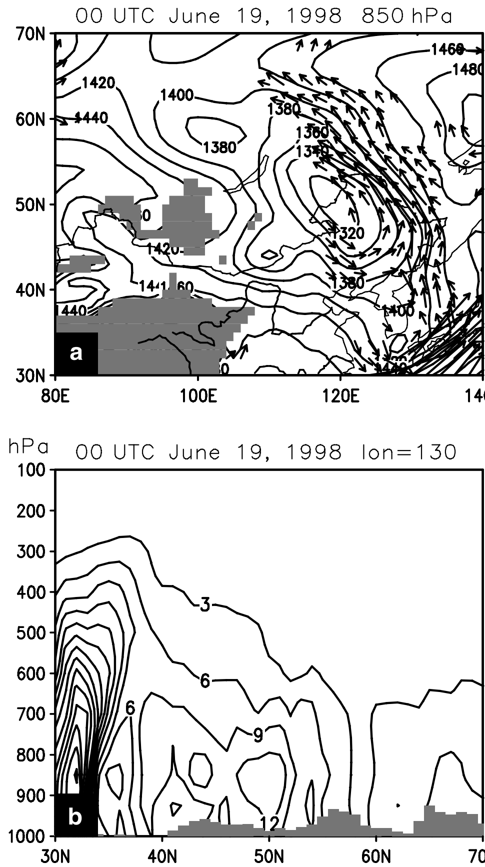

Fig. 11a. Geopotential height in gpm (solid) and moisture flux (vector) larger than $5 \times 10^{-3}\,g \cdot s^{-1} \cdot cm^{-1} \cdot hPa^{-1}$ at 850 hPa at 0000 UTC 19 June 1998, shaded area is the terrain higher than 1500 m; (**b**) The vertical cross section of moisture flux along 130° E at 0000 UTC 19 June 1998 (unit: $10^{-3}\,g \cdot s^{-1} \cdot cm^{-1} \cdot hPa^{-1}$), shaded area is terrain

Here, g is gravity acceleration, V is wind vector and q is specific humidity. Therefore, the unit of MF and DMF should be $g \cdot s^{-1} \cdot cm^{-1} \cdot hPa^{-1}$ and $g \cdot s^{-1} \cdot cm^{-2} \cdot hPa^{-1}$, respectively.

Figure 11a shows the geopotential height and moisture flux at 850 hPa at 0000 UTC 19 June 1998. It can be revealed that the moist southwest monsoon current from the lower latitude area influenced the Yangtze River first, arrived at East China Sea and then turned to be southeast current in East China Sea, finally moved into Northeast China. The current provided the enough moisture supply and benefited the precipitation in Northeast China.

It can be noticed there were two rainbands in East China, namely, one in the Yangtze River valley, and the other in Northeast China (see Fig. 3a and b). There was a less precipitation area between the two rain-bands mentioned-above. The phenomena can also be seen clearly from the vertical cross section of moisture flux along 130° E (Fig. 11b). There were two maxima of moisture flux in 40°–50° N and around 30° N, respectively. The former was located in Northeast China and the isoline of $9 \times 10^{-3}\, g \cdot s^{-1} \cdot cm^{-1} \cdot hPa^{-1}$ was up to 700 hPa between 40°–50° N.

From the distribution of Satellite TBB at 0000 UTC 18 June 1998 in Fig. 12, it can be

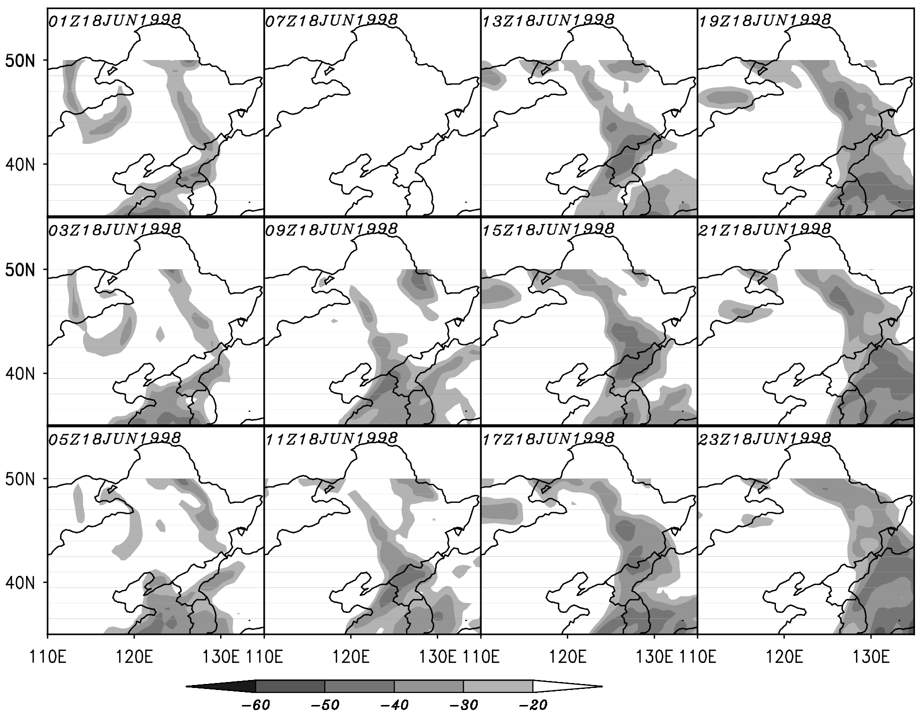

Fig. 12. TBB (unit: °C) from GMS-5 satellite at 18 June 1998

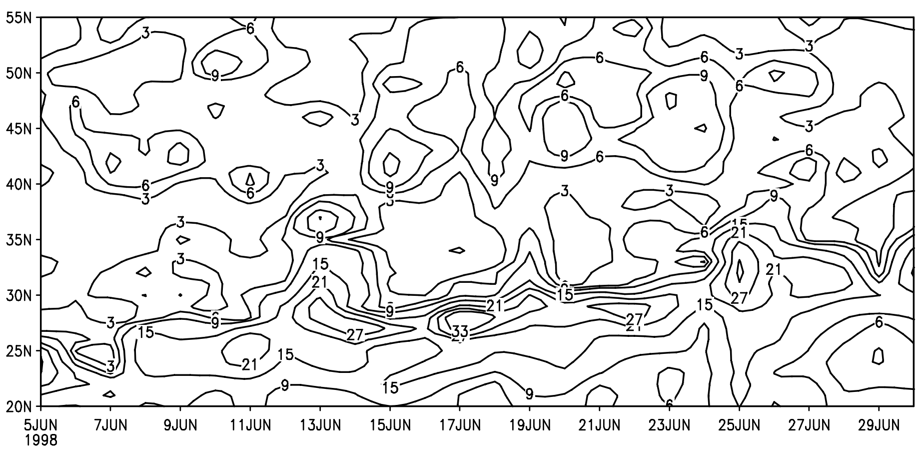

Fig. 13. The time-latitude cross section of moisture flux at 850 hPa along 130° E from 5 June to 30 June 1998 (unit: $10^{-3}\, g \cdot s^{-1} \cdot cm^{-1} \cdot hPa^{-1}$)

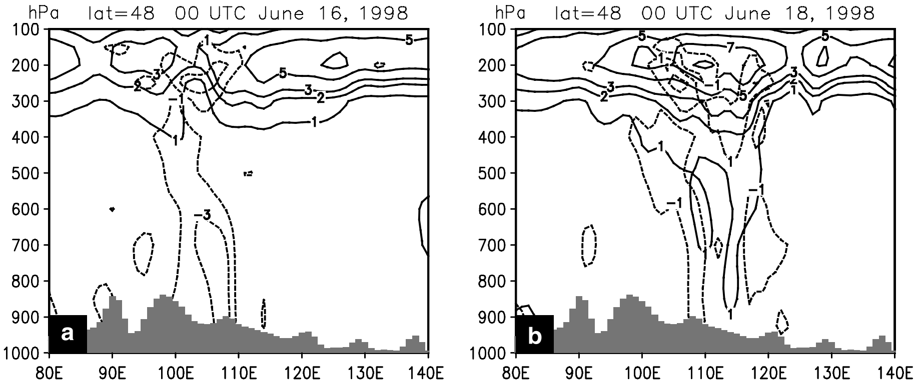

Fig. 14. Vertical cross section of potential vorticity (solid) and temperature advection (dashed) along 48° N (units: $10^{-6}\,m^2 \cdot s^{-1} \cdot K \cdot kg^{-1}$; $10^{-4}\,°C \cdot s^{-1}$), at (**a**) 0000 UTC 16 June 1998, and (**b**) 0000 UTC 18 June 1998, shaded area represents the terrain

clearly seen that there were the cloud bands extending from South China to Northeast China at 0100 UTC 18 June 1998, and then weakened, after that the other cloud band approached to Northeast China again. The cloud band mentioned-above could confirmed clearly that the moisture come from the lower latitude area related with summer monsoon. It would be better if the satellite TBB data at 0000 UTC 19 June, the same time as in Fig. 11, could be employed. Unfortunately, the satellite TBB at that time was not available. Nevertheless, form Fig. 12, the extension of the cloud band from south to north can still be obviously revealed. Moreover, to understand more details of the distribution of moisture flux, the time-latitude cross section at 850 hPa along 130° E during 5–30 June is shown in Fig. 13. It can be seen that one band-shaped maxima of moisture flux between 40°–50° N existed during 5–12 June and 14–24 June besides the other band-shaped maxima of moisture flux in the Yangtze River during 12–26 June. The results support those in Figs. 11 and 12.

For a better understanding of the vertical structure of COLs, the vertical cross sections of the potential vorticity PV (Hoskins and Pedder, 1980; Hoskins et al, 1985) and temperature advection (see formula 1) have been drawn. The definition of the potential vorticity is as follows:

$$PV = -g(\zeta_p + f)\frac{\partial \theta}{\partial p}, \tag{5}$$

where, ζ_p is relative vorticity on pressure surface.

It can be noticed that the maximum of the potential vorticity (1 PV unit (1 PVU) = $10^{-6}\,m^2 \cdot s^{-1} \cdot K \cdot kg^{-1}$) concentrated on the upper troposphere above 300 hPa (Fig. 14a). Two days later (Fig. 14b) the maximum of potential vorticity-isoline of 1 PVU extended downward to 900 hPa west of 120° E. It shows that the anomaly of PV was located firstly in upper troposphere and then the anomaly extended downwards to the middle-lower troposphere. It has been seen that the maximum of PV around 200 hPa in Fig. 14b was 9 PVU, whereas the maximum in European case was 4 PVU (Hill and Browning, 1987). The PV maximum in this case seemed to be stronger than that in the case in Europe. On the other hand, strong cold advection (dashed lines in Fig. 14a, b) was in middle troposphere from 700 to 400 hPa and it was not pronounced in the lower troposphere.

To clarify the vertical structure of temperature field, vertical cross section of the temperature deviation from the mean values along 50° N were analyzed. The vertical cross sections were taken across the center at the COLs. Because the COLs

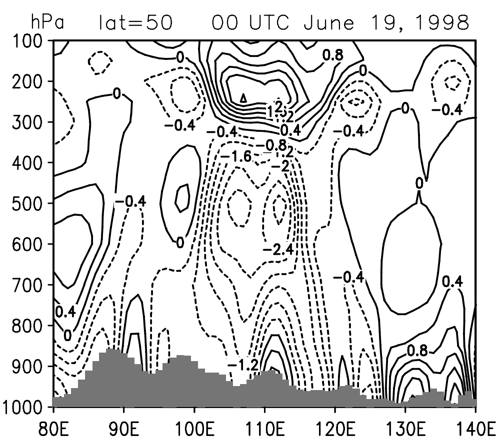

Fig. 15. Vertical cross section of temperature deviation along 50°N at 0000 UTC 19 June 1998 (unit: °C). (solid-positive; dashed-negative), shaded area represents the terrain

did not stay exactly in the same latitude and the same longitude each day, some vertical cross sections were along 48.0° N, whereas the others were along 50.0° N. Figure 15 shows the temperature deviation distribution at 0000 UTC 19 June 1998. It can be found that the negative deviation dominated in middle–lower troposphere below 300 hPa between 100°–125° N which was almost in the same region as the cold dome. It can be deduced that the structure of COLs was the cold core that was different not only from the warm core in middle–upper troposphere of the tropical cyclone (Zhao and Mills, 1991; Qi and Zhao, 2003), but also from the weak warm core in middle-upper troposphere of Meiyu (Baiu) front lows in subtropical zone (Matsumoto et al, 1971; Zhao, 1988; Bei et al, 2002; Zhang and Zhao, 2004). Obviously, the COLs seemed to be the extratropical systems. However, it was quite different from the typical extratropical cyclone (Petterssen and Sembye, 1971) because the COLs were not so clear in wind and geopotential height fields in lower troposphere sometimes. In fact, the cold dome of the COL could be identified again from Fig. 16 that there was the minimum of less 300 K below 800 hPa between 112°–117° E, and basically, a cold dome can be revealed in troposphere in the figure.

It is well known that the two important factors associated closely with the precipitation are the lifting of upward motion, and the moisture supply. The upward motion can be detected above 700 hPa between 98°–125° E in Fig. 16. In this

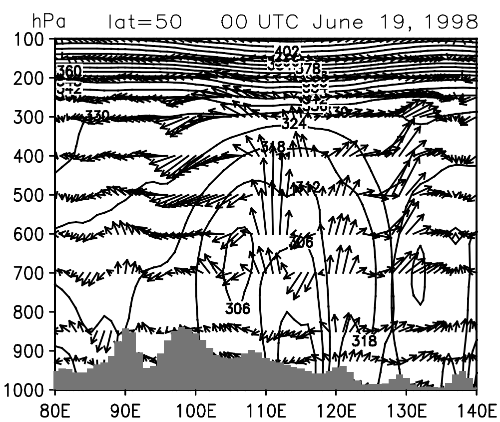

Fig. 16. Vertical cross section of pseudo-equivalent potential temperature (solid) in K and vertical circulation (vector) along 50° N at 0000 UTC 19 June 1998, shaded area represents the terrain

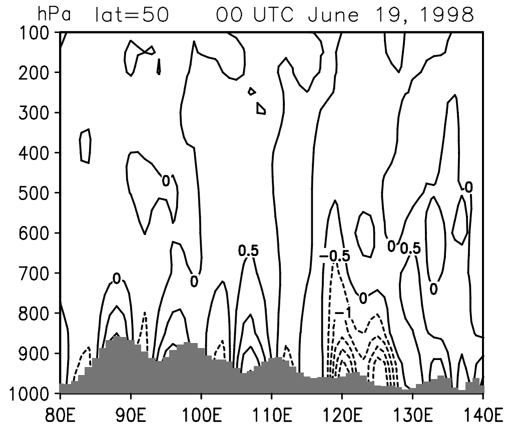

Fig. 17. Vertical cross section of divergence of moisture flux (solid-positive; dashed-negative) along 50°N at 0000 UTC 19 June 1998 (unit: $10^{-8}\,g\cdot s^{-2}\cdot cm^{-1}\cdot hPa^{-1}$), shaded area represents the terrain

case, the ascending current was very favorable to the occurrence of precipitation. It could be the result of the large scale dynamic forcing rather than thermal effect because of lack of the pronounced warm core in COLs.

In addition, the influence of moisture flux has been given in Figs. 11 and 13, respectively. As mentioned before, divergence of moisture flux (DMF) represents, in a more exact sense, the concentrating ability of water vapor in the heavy rainfall area. Here, DMF was calculated and shown in Fig. 17. The moisture "duct" concentrated mainly below 700 hPa between 117°–128° E, and that means water vapor entered the COLs along the south–north direction in lower troposphere.

For a better understanding of maintenance and intensification of the COLs, vorticity budget is calculated by following equation (Daggpaty and Sikka, 1977):

$$\frac{\partial \zeta}{\partial t} = A_\zeta + B_\zeta + C_\zeta + D_\zeta + E_\zeta$$
$$A_\zeta = -\left[u\frac{\partial \zeta}{\partial x} + v\left(\beta + \frac{\partial \zeta}{\partial y}\right)\right],$$
$$B_\zeta = -\omega\frac{\partial \zeta}{\partial p}, \qquad (6)$$
$$C_\zeta = -(f+\zeta)\nabla\cdot V,$$
$$D_\zeta = -\left(\frac{\partial \omega}{\partial x}\frac{\partial v}{\partial p} - \frac{\partial \omega}{\partial y}\frac{\partial u}{\partial p}\right),$$

$A_\zeta, B_\zeta, C_\zeta, D_\zeta$ are the horizontal advection term, the vertical advection term, the horizon-

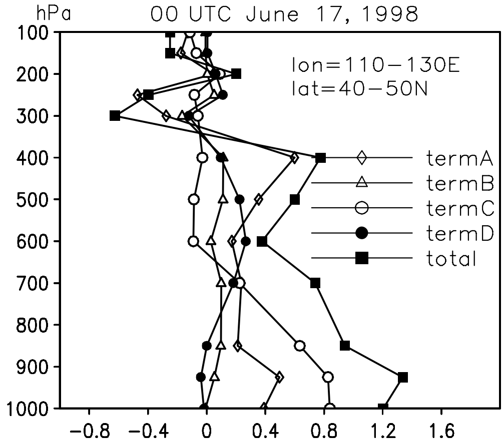

Fig. 18. Vertical profile of area mean of term A, B, C, and D of vorticity equation at 0000 UTC 17 June 1998 (unit: $10^{-9}\,s^{-2}$)

tal divergence term, and retortion term, respectively. In Fig. 18, the positive relative vorticity increased below 350 hPa and the negative relative vorticity decreased above 350 hPa. It provided the favorable conditions for the development of COLs. It has been noticed that both the horizontal advection term and the horizontal divergence term contributed significantly to the maintenance of positive relative vorticity, whereas the vertical advection term was smaller than the other terms. Nevertheless, the total sum of the four terms mentioned-above was a positive contribution to the relative vorticity of COLs. This may be one of the reasons why the COLs can maintain in Northeast China persistently.

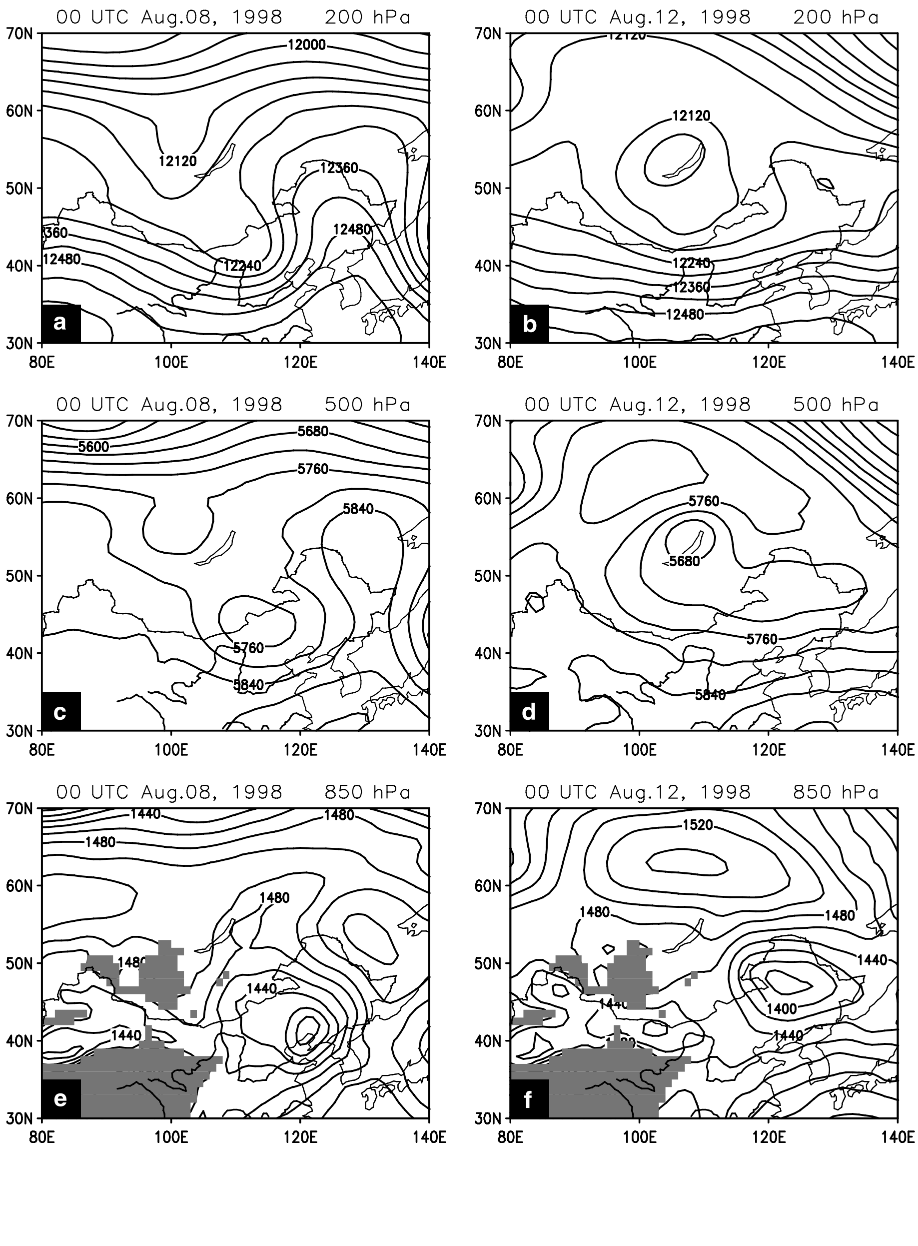

Fig. 19. Geopotential height in gpm. (**a**) at 200 hPa, 0000 UTC 08 August 1998, (**b**) at 200 hPa, 0000 UTC 12 August 1998, (**c**) at 500 hPa, 0000 UTC 08 August 1998, (**d**) at 500 hPa, 0000 UTC 12 August 1998, (**e**) at 850 hPa, 0000 UTC 08 August 1998, (**f**) at 850 hPa, 0000 UTC 12 August 1998. The shaded area in (**e**) and (**f**) are the terrain higher than 1500 m

4.2 Case in August (type C)

As mentioned before, another type of COLs influenced Northeast China significantly during August 1998. The case in August is analyzed in this section. The similar diagnosis as those in previous section has been conducted here, and the detailed descriptions regarding the related method and formulas can be found in the previous section. The results were discussed briefly in this section. From the geopotential height field at 200 hPa at 0000 UTC 8 August 1998 (Fig. 19a), it can be noticed there was a small trough in west of Lake Baikal near the national boundary between Russia and Mongolia without a closed circulation. At 0000 UTC 12 August (Fig. 19b), a closed circulation within a wide trough was located over Mongolia and west part of Northeast China. Also, at 0000 UTC 8 August (Fig. 19c), a closed COL at 500 hPa appeared in eastern Mongolia and west part of Northeast China. At the same time, the ridge over coast area of East Asia moved eastwards and the other ridge in west of Siberia amplified. At 0000 UTC 12 August (Fig. 19d), the ridge in west Siberia strengthened and the COL covered the Mongolia and north part of Northeast China. In addition, the COL was located in Northeast China at 850 hPa at 0000 UTC 8 August (Fig. 19e) and also the southeast current, related with the summer monsoon system, transported rich moisture to Northeast China. At 0000 UTC 12 August (Fig. 19f), the COL deepened and the closed isoline with 1400 gpm appeared. The common characteristics of the cases in June and August were that the closed circulations in the middle troposphere formed slightly earlier than those in the upper troposphere.

From the distribution of pseudo-equivalent potential temperature and cold air advection fields at 850 and 500 hPa at 0000 UTC 8 and 0000 UTC 11 August (Fig. 20), the eastward moving of cold air can be found. Especially, isoline of 332 K at 500 hPa moved from central Mongolia to Northeast China.

In the vertical cross section of frontogenesis function along 118° E at 0000 UTC 08 August 1998, the frontogenesis zone concentrated mainly over the region between 40°–50° N, with two maxima around 700 and 300 hPa, respectively (not shown). From Fig. 21, it can be noticed the moisture come also from the lower latitude area, and the strong moisture flux from Southeast China to Northeast China which was related with the summer monsoon.

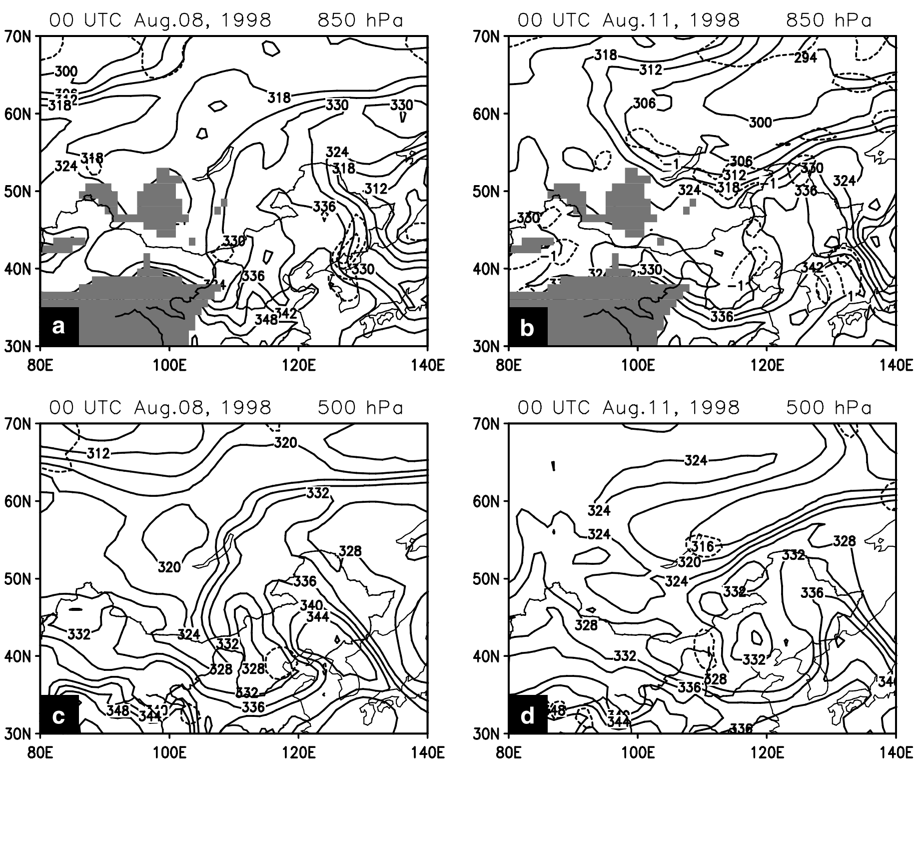

Fig. 20. Pseudo-equivalent potential temperature (solid) and temperature advection (dashed) (units: K; $10^{-4}\,°C \cdot s^{-1}$). (**a**) at 850 hPa, 0000 UTC 08 August 1998, (**b**) at 850 hPa, 0000 UTC 11 August 1998, (**c**) at 500 hPa, 0000 UTC 08 August 1998, (**d**) at 500 hPa, 0000 UTC 11 August 1998. The shaded area in (**a**) and (**b**) are the terrain higher than 1500 m

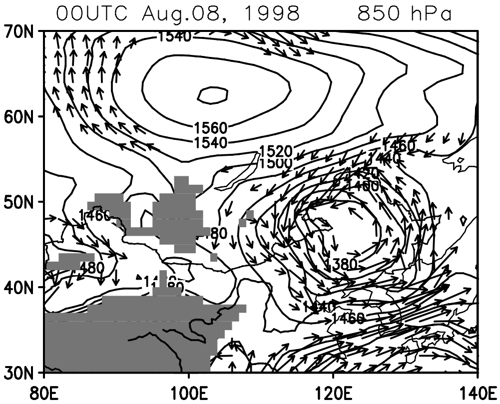

Fig. 21. Geopotential height in gpm (solid) and moisture flux (vector, larger than $5 \times 10^{-3}\,\mathrm{g \cdot s^{-1} \cdot cm^{-1} \cdot hPa^{-1}}$) at 850 hPa, at 0000 UTC 11 August 1998, shaded area is the terrain higher than 1500 m

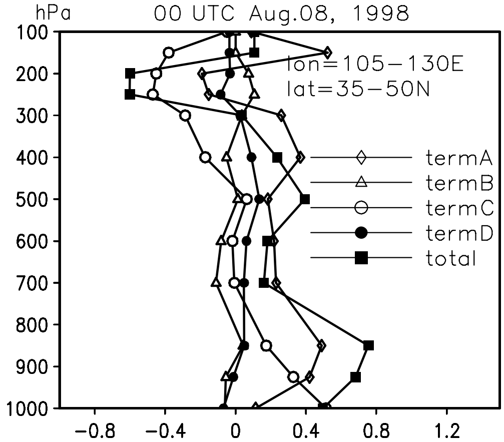

Fig. 23. Vertical profile of area mean (105°–130° E, 35°–50° N) of term A, B, C, and D of vorticity equation at 0000 UTC 08 August 1998 (unit: $10^{-9}\,\mathrm{s^{-2}}$)

For the case in August, the vertical cross section of the divergence of moisture flux along 45° N at 0000 UTC 9 August 1998 has been analyzed and the strong convergence zone of moisture flux (negative value) was below 600 hPa, between 120°–130° E (not shown). The main moisture concentrated also at the low levels of the troposphere.

Moreover, the maxima of potential vorticity were in upper troposphere at 0000 UTC 9 August in Fig. 22. And then, the potential vorticity isoline of $1 \times 10^{-6}\,\mathrm{m^{-2} \cdot s^{-1} \cdot K \cdot kg^{-1}}$ extended downward to 700 hPa. It indicated the disturbances of temperature field and wind field were more obvious in middle–upper troposphere, in comparison with those in lower troposphere.

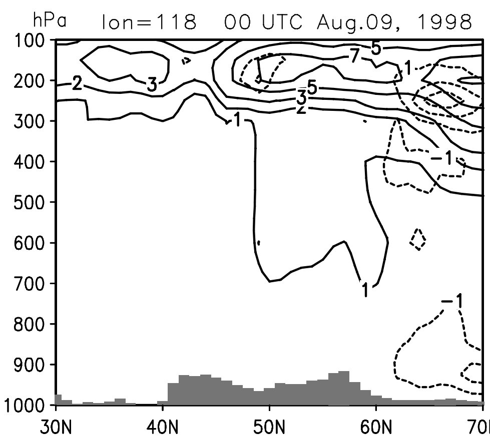

Fig. 22. Vertical cross section of potential vorticity (solid, unit: $\mathrm{m^{-2} \cdot s^{-1} \cdot K \cdot kg^{-1}}$) and temperature advection (dashed, Units: $10^{-4}\,\mathrm{°C \cdot s^{-1}}$) along 118° E at 0000 UTC 09 August 1998

From Fig. 23, the total vorticity budget was calculated in area of 105°–130° E, 35°–50° N at 0000 UTC 8 August and that benefited the development of COLs; also, both the horizontal advection term and the horizontal divergence term were larger than other terms, which is, to a certain extent, similar to the type A.

Here, similarities and differences between case in June and case in August were discussed. Both the Okhotsk high in June and West Siberia high in August were favorable to the formation and maintenance of COLs in Northeast China, and in addition, COLs appeared in middle troposphere earlier than those in upper troposphere. However, the difference was, in 1998, Okhotsk high seemed to maintain more stably than west Siberia high, so that the COLs in June can last for longer period. It will need further investigations to explain this phenomenon in the future.

4.3 Case in July (type B)

It is very necessary to introduce and discuss briefly the COL case in July, which belongs to type B, even though it did not cause the strong precipitation. Here, a case from 17–22 July was chosen for the discussion.

The feature differences between type B and the two other types mentioned-above can be seen from Fig. 24. First, the upper level jet (ULJ) at 200 hPa was stronger and the streak of ULJ approached to more than $60\,\mathrm{m \cdot s^{-1}}$ at 0000 UTC 21 July. There were westerlies with the small amplitude ridge rather than the blocking high. In addi-

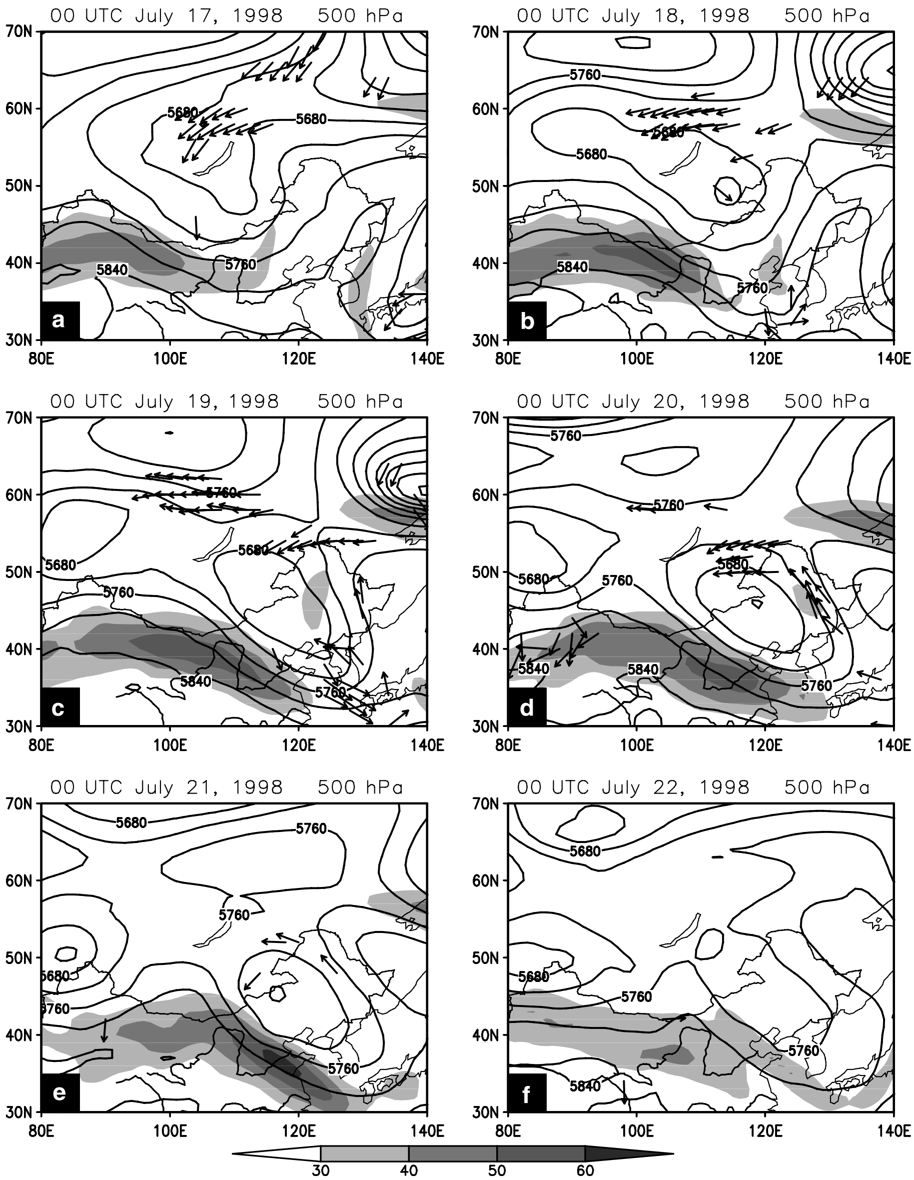

Fig. 24. Geopotential height at 500 hPa (solid line, gpm), wind speed at 200 hPa (shaded area, $m \cdot s^{-1}$), wind field at 850 hPa (vector, larger than $12\,m \cdot s^{-1}$). (**a**) 0000 UTC July 17 1998, (**b**) 0000 UTC July 18, 1998, (**c**) 0000 UTC July 19, 1998, (**d**) 0000 UTC July 20, 1998, (**e**) 0000 UTC July 21, 1998, (**f**) 0000 UTC July 22, 1998

tion, the COLs at 500 hPa moved and weakened fast (Fig. 24). Particularly, the southern current at 850 hPa from the lower latitude area was not obvious (Fig. 24) and it implied the summer monsoon in type B was weaker than that in type A and C. In a word, both the middle latitude system and the lower latitude system in type B are quite different from those in type A or C, which makes type B not favorable to the occurrence of heavy rainfall in Northeast China.

5. Conclusions and discussions

East Asia is one of the three most preferred areas of COLs occurrence in the world. Only few researches regarding the COLs in this area have been conducted, moreover, the most of them are the results of climatologic statistics. In this paper, the record sustained heavy rainfall in Northeast China during the period from 1 June to 31 August 1998 and the related COLs have been investigated. The results demonstrated Northeast Asia, including Northeast China is, indeed, one of the preferred areas, especially in summer of 1998. The main characteristics of COLs relating with the sustained heavy rainfall in Northeast China have been revealed in this paper. The main conclusions are as follows:

(1) Two kinds of blocking high pressure systems: the COLs in Northeast China from June 1 to August 31, 1998 resulted from the sustained

maintenance of the Okhotsk high and Siberia high, respectively. It was revealed that in June and August 1998, the ridges and trough in the westerlies were very stationary. In the most cases, the Okhotsk high was located over the coast area in East China in June and the Siberia High was situated over the west of Lake Baikal in August, both of them were very favorable to formation and maintenance of COLs in Northeast China and Northeast Asia, and it was one of important features in Asia during summer in 1998. However, the Okhotsk high seemed to maintain more stably than West Siberia High at least in 1998. It seems to be the reason why the COLs in Northeast China lasted for a longer period than normal.

(2) Three main types of COLs in Northeast China: according to the different tracks, namely type A, B and C were cataloged, which were the COLs moving from Lake Baikal (type A), moving eastward from Mongolia and Inner Mongolian Autonomous region, China (type B) and moving northeastward from Yangtze River and Yellow River (type C), respectively.

It has been noticed that type A and C were, in the most cases, associated with the blocking high and therefore the COLs moved slowly so that the precipitation was accumulated in almost the same region, whereas the type B was related to the westerlies with the small amplitude wave, the COLs shifted fast, therefore the less precipitation was detected. It can explain why the strong heavy rainfalls appeared mainly in June and August rather than in July 1998.

(3) Contribution of baroclinity to formation and maintenance of COLs: the computational results of temperature advection showed that the obvious cold advection origining from the west of Lake Baikal and Mongolia advanced into Northeast China, particularly in middle and upper troposphere, where the potential instability become pronounced and it was very favorable to the occurrence of the precipitation. Moreover, the maximum of the frontogenesis function can also be found in Northeast China. That means the baroclinity associated with the frontal zone, especially the upward motion ahead the front could still play an important role in initiating and developing of COLs, even though it was weaker than that in Mongolian cyclone with the severe dust storm in North China during spring (Zhao and Zhao, 2004).

(4) Evolution of potential vorticity (PV) anomaly: the analysis of potential vorticity has been conducted. There were the maxima of PV anomaly in upper troposphere and the maxima extended usually downwards to middle troposphere. Potential vorticity is a function of the absolute vorticity and the static stability, therefore, its maxima could benefit the intensification and the development of the COLs. It has been revealed that the PV maxima from upper troposphere were more obvious than that in the lower troposphere and the structures are similar to those in Europe (Hill and Browning, 1987), however, PV anomaly in Northeast China in this case was stronger than case in Europe. For clarifying the mechanism of the maintenance of vorticity, the vorticity budget was calculated and the results showed that the horizontal advection term and the horizontal divergence term contributed significantly to the maintenance of positive relative vorticity. It can explain, to a certain extent, why the COLs can last in Northeast China for long periods in summer, 1998.

(5) Summer monsoon activity and moisture source places: the moisture supply as one of the important influencing factors contributed very significantly to the occurrence of the sustained heavy rainfall. In this case, the moisture came from East China Sea, and from the South China Sea in lower latitude area. Very rich water vapor was transported by the summer monsoon current to Northeast China. The maximum of moisture flux concentrated mainly in low troposphere below 850 hPa, along the east edge of the COLs. It has been noticed that COLs in June and August were associated with the sustained precipitation but the COLs in July were not. One of the important factors is whether enough moisture supply is available or not. The impact of summer monsoon on the precipitation of COLs was one of main characteristics in Northeast Asia. It implies that the interaction between lower and middle latitude area exists.

(6) Structure of the COLs in Northeast China: From the distribution of pseudo-equivalent potential temperature, it can be revealed that the cold air dome existed in the COL, which was similar to the cold pool in Europe (Hill and browning, 1987), however, the PV anomaly related with the cold dome of the COLs in this paper was more pronounced than that in Europe. The structure of the COLs was not only different from the warm core in middle–upper troposphere of tropical cyclone, but also different from the weaker warm core in middle–upper troposphere of Meiyu (Changma, Baiu) front low in subtropical zone. Obviously, it may imply the COLs in this study seemed to be the extratropical systems. However, they were not exactly same to extratropical cyclones because it is not necessary for them to have a closed low pressure system in lower troposphere or the front at surface, and the COL in middle–upper troposphere were clearer. Meanwhile the computational results of the temperature deviation indicated the cold air was below 300 hPa and the release of the latent heating was not pronounced. The upward motion could be caused by the lifting of dynamic forcing.

(7) Discussion: similarities and differences between the COLs Northeast China and the COLs systems in the other area are discussed here. In the summer 1998, the COLs in Northeast China lasted for the longer period than those in other areas, for example, the mean period in Europe (Nieto et al, 2005). What is the possible reason? It may result from sustained maintenance of the Okhotsk high or Siberia high in summer in 1998. In addition, the COLs in Northeast China concentrated mainly in middle and upper troposphere, and the COLs in southern Australia were more pronounced in lower troposphere.

It should also be pointed out that there are many different types of COLs in the world and it is impossible to discuss all kinds of COLs in this paper, even only in Northeast China. It has noticed that a number of COLs were related with light rainfall or only with the temperature drop, even with squall lines in North China (Zhao et al, 1980). Moreover, a series of complicated dynamical problems are related with the initiation and development of COLs, including the formation and the breakdown of the blocking high, the short range variation of summer monsoon and the contribution of mesoscale convective systems in COLs (Zeng, 1983). These questions have not been clarified in depth. However, they are beyond the scope of this paper. These topics will be discussed in our other papers in future.

Acknowledgements

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