Analysis of a Rare Heavy Rain Weather Process in Autumn in Ulanqab City

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Abstract Based on the conventional observation data and NCEP/NCAR reanalysis data, the circulation situation, influencing systems and causes of the heavy rain during September 20 –21, 2010 in Ulanqab City were analyzed from the evolution process of weather circulation situation and the changes of various physical quantity fields. The results show that there was an obvious frontal zone between 45 –52° N, which brought strong cold air. The transport of warm and humid air outside the subtropical high and typhoon was the main water vapor source of the strong precipitation, and the southwest jet at 700 hPa transported abundant water vapor. There was a broad inverted trough to the south of 45° N, with a central value of 1 000.0 hPa. Ulanqab City was on the top of the inverted trough, stable and less moved, which was conducive to the occurrence of systematic heavy precipitation. The rainstorm was a strong precipitation process caused by the intersection of cold air brought by the southward movement of the upper frontal zone and warm and humid air outside the subtropical high. After the precipitation, the invasion of strong cold air brought frost and cold wave weather to Ulanqab City.

Key words Frontal zone; Subtropical high; Inverted trough; Frost; Ulanqab City

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Ulanqab City is located in the central and western part of Inner Mongolia, with complex topography. The Yinshan Mountains run across the center of the city, so that the city has ridge-shaped terrain (it is low in the south and north and high in the middle), and Ulanqab is divided into two distinct climate regions. The elevation rises from about 1 000 m in the north to more than 2 000 m in the middle, and drops to about 1 100 m in the south. In front of the Yinshan Mountains, there are mainly hills and mountains, with many ravines; behind the mountains, there are mainly hills and grasslands, with flat terrain[1 –2]. Ulanqab has a medium-temperate continental monsoon climate. Summer is short, and rain and heat are synchronized. Precipitation is concentrated, and 60% –70% of precipitation occurs in summer (June – August)[2].

Rainstorm is one of the main disasters in Inner Mongolia. The heavy rain appearing in September 20 –21, 2010 is a rare precipitation process in Ulanqab City, causing great losses to the national economy and people's lives and property. The rainstorm caused flooding in seven villages in Xinghe County, and 67.33 hm^2 of crops was affected. 271 houses collapsed, and the direct economic loss reached 4.2 million yuan. On the morning of September 22 after the precipitation, there was cold wave and frost weather in most parts of the city. The rainstorm weather systems affecting western and central Inner Mongolia mainly include cold shear, warm and humid shear, north trough and south vortex, Mongolia cold vortex, west trough, and low-level jet[3]. The timely and accurate forecast of the disastrous weather will play a decisive role in the reduction of agricultural production and people's economic losses. In this paper, the development mechanism and physical conditions of heavy precipitation during September 20 – 21, 2010 were analyzed to provide some reference for the future forecast of such process.

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1 Actual situation of precipitation, cold wave, and frost

The actual situation of precipitation, cold wave, and frost was shown in Table 1.

2 Circulation situation

2.1 High-altitude situation In the 500 hPa circulation field, there were two ridges and one trough in the EC forecast field three days before the precipitation, and the system was relatively stable. At 08:00 on the 19th, Ulanqab City was in the westerly flow of two ridges and one trough, and the subtropical high was northerly and easterly. The upper 588 line jumped to 37° N in the north, and extended to 102° E in the west. Meanwhile, a typhoon to the south of the subtropical high moved along the periphery of the subtropical high, and gradually moved to the north. On the south side of Lake Baikal, there was an obvious frontal zone between 45 – 52° N, and there were 5 isotherms within 10 latitudes. By 08:00 on the 20th, the frontal zone obviously moved southwards between 40 –45° N, and Ulanqab City was under the control of the frontal zone. At the same time, the typhoon continued to move northwestwards, and the subtropical high retreated to the east. At this time, the warm and humid air along the periphery of the subtropical high and the cold air brought by the northern frontal zone met over Ulanqab City, providing favorable conditions for precipitation.

Table 1 Precipitation, the minimum temperature and temperature drop in Ulanqab City during September 20 – 22, 2010

Region	Precipitation // mm	Minimum temperature // ℃			Temperature drop // ℃
		Morning of the 20th	Morning of the 21st	Morning of the 22nd	
Siziwang Banner	32.9	7.7	4.9	–0.2	7.9
Chahar Right Wing Middle Banner	47.2	7.7	1.8	–2.2	9.9
Chahar Right Wing Back Banner	40.5	10.9	5.5	–0.4	11.3
Shangdu County	39.4	10.6	5.1	–0.9	11.5
Huade County	41.2	9.0	3.0	–0.4	9.4
Zhuozi County	52.4	10.3	6.2	–1.2	11.5
Liangcheng County	58.3	11.5	6.9	–0.3	11.8
Jining District	53.9	9.3	5.0	–0.9	10.2
Chahar Right Wing Front Banner	67.5	9.3	6.1	–0.6	9.9
Xinghe County	56.8	9.4	5.3	–0.3	9.7
Fengzhen City	59.9	11.4	6.4	0.3	11.1

In the 700 hPa circulation field, the circulation situation was basically the same as that of 500 hPa at 08:00 on the 19th. Wulanqabu City was in the westerly air flow, and a 308 closed thermal low pressure moved eastwards along the periphery of 316 line to the west of Hetao. The southwest air flow guided it to the vicinity of 37° N, providing favorable water vapor conditions for precipitation. By 08:00 on the 20th, the subtropical high and the continental high pressure connected, and the typhoon moved further northwestwards. Ulanqab City was in a west-high and east-low circulation situation, which was very favorable to precipitation. At the same time, the frontal zone near Lake Baikal moved further to the south, so that the cold air brought by the northern frontal zone and the southwest warm and humid air along the periphery of the subtropical high converged over Ulanqab City, forming favorable precipitation conditions. Meanwhile, there was a northwest and southwest transverse shear near 42° N, 107 – 110° E, and the maintenance time was longer. By 20:00 on the 20th, the low pressure on the west side of the 308 line and Hetao area connected to form a northwest southeast cold trough in Wulanqab City, which was more favorable to precipitation.

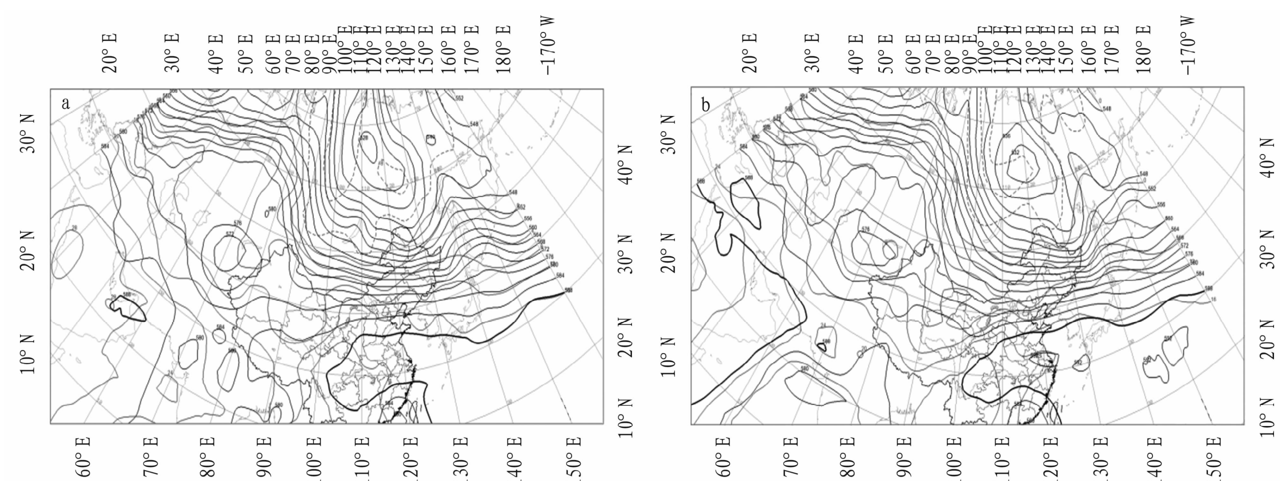


Fig. 1 500 hPa height field and 850 hPa temperature field at 08:00 (a) and 20:00 (b) on September 20, 2010

2.2 Sea level pressure field On the 19th, a strong high pressure existed near Lake Baikal in the sea level pressure field. The center of the high pressure was at 94 – 102° E, 52 – 56° N, with the central value of 1 027.5 hPa. There was a broad inverted trough to the south of 45° N, and the center of the inverted trough was at 35 – 37° N, 101 – 104° E. There were two closed isobaric lines, and the central value was 1 000.0 hPa. Ulanqab City was in the inverted trough, while the weather was mainly cloudy to the south of 40° N. At 20:00, the latitudinal scale of the inverted trough gradually increased, and the system was obviously lifted to the north under its influence. By 02:00 on the 20th, the center closure line was 997.5 hPa, and the system increased and was stable with little movement at this time. It was still maintained at 08:00. However, the cold high pressure located near Lake Baikal moved southwards, which increased the pressure gradient in the north and west of Ulanqab City. At this time, Ulanqab City was in front of the inverted trough, and precipitation gradually appeared from the west. At 14:00, the inverted trough further moved to the north, and Ulanqab City was on the top of the inverted trough. Precipitation occurred in the whole city. At 20:00, the inverted trough was still stable and less moved, and Ulanqab City was in the interior of the cold and warm frontal zone. The precipitation was the strongest. By 02:00 on the 21st, the inverted trough moved eastwards, and the precipitation nearly ended.

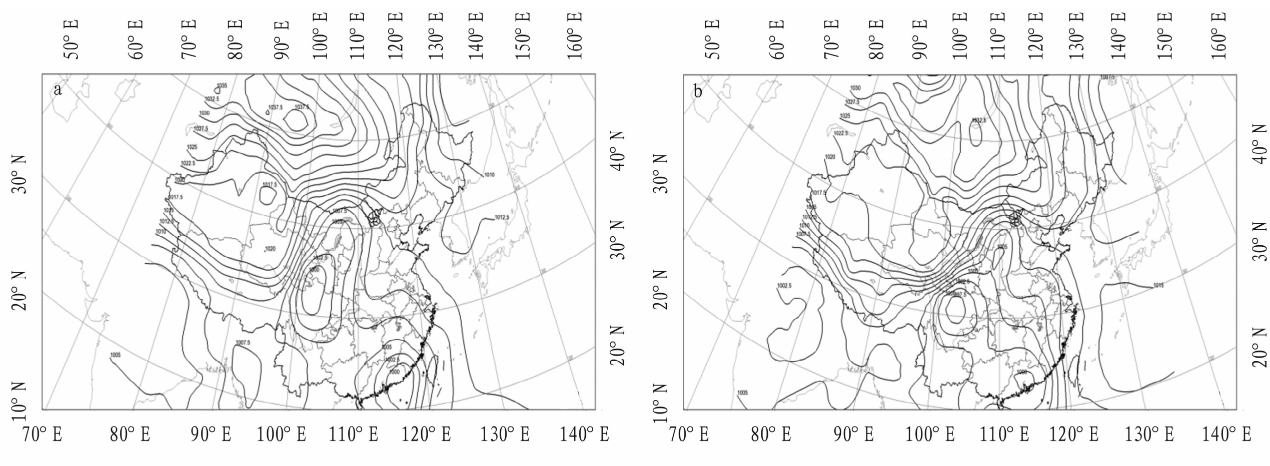


Fig. 2 Sea level pressure field at 08:00 (a) and 20:00 (b) on September 20, 2010

2.3 Satellite cloud images Seen from the satellite cloud image at 15:00 on the 19th, there was a typhoon at 20 – 30° N, 115 – 125° E, and it played a very important role in the precipitation process. In the early morning of the 20th, it can be seen from the cloud image that the cloud system on the periphery of the typhoon continued to move into the southwest, and then the convective cloud system in the southwest moved from the west to the north, providing favorable water vapor conditions for this precipitation.

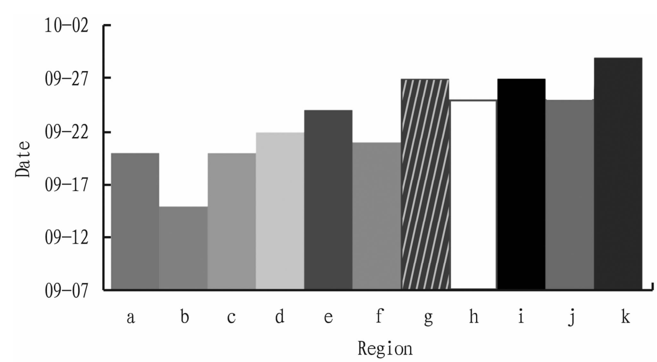
3 Diagnosis of physical quantity fields

3.1 Water vapor conditions From 20:00 on the 19th to 08:00 on the 20th, the relative humidity in Ulanqab City was above 70% – 90% at 700 hPa. From 14:00 to 20:00, it exceeded 90% at both 500 and 700 hPa, and was above 70% at 850 hPa, indicating that the water vapor conditions in the whole layer were very good. At 02:00 on the 21st, relative humidity was above 70% at only 500 hPa, and reduced to 40% – 50% at 700 and 850 hPa. The precipitation declined until the end.

3.2 Dynamic conditions Seen from the vorticity fields at 700 and 850 hPa, a positive vorticity center moved southeastwards in the upper reaches of Hetao area at 20:00 on the 19th. The wind direction convergence at 700 hPa was strong, which provided favorable conditions for the dynamic uplift. As time went by, it moved to Hetao area at 08:00 on the 20th and to Ulanqab City at 14:00. At that time, precipitation began to occur in Ulanqab City from the west to the east, and the vorticity center was stable and less moved until 20:00. During the movement of the vorticity center, precipitation was stronger in the south. By 08:00 on the 21st, the lower and middle vorticity reduced, and atmospheric convergence intensity decreased, so precipitation stopped. In the divergence field, there was strong convergence in the middle and lower layers from the 19th to the 20th, which was conducive to the continuation of the ascending motion in the lower layers. Seen from the combination of vorticity field and divergence field, the good convergence and lifting movement in the middle and low layers provided favorable dynamic conditions for the rainstorm weather.

4 Frost

The average occurrence time of frost in 11 Qixian stations of Ulanqab City from 1980 to 2010 was analyzed. 30 years of historical data shows that there was no temperature of 0 ℃ or below in the 11 stations in August. As shown in Fig. 3, the earliest frost in the city appeared in Chahar Right Wing Middle Banner. In the past 30 years, there were 14 times of frost appearing in early September for the first time, accounting for 40% of the total frequency. The earliest frost appeared both on September 2 in 1997 and 2005, with a temperature of – 0.8 and – 1.5 ℃, respectively. The first frost appeared the latest in Fengzhen, and in the past 30 years only two times of forest appeared in middle September, with a temperature of – 0.4 on September 19, 1989 and – 0.7 ℃ on September 18, 2011. There were 11 times of frost appearing in late September for the first time, accounting for 31.5%, and most of the rest appeared in October.



Note: a. Siziwang Banner; b. Chahar Right Wing Middle Banner; c. Chahar Right Wing Back Banner; d. Shangdu County; e. Huade County; f. Zhuozi County; g. Liangcheng County; h. Jining District; i. Chahar Right Wing Front Banner; j. Xinghe County; k. Fengzhen City.

Fig. 3 Average occurrence time of frost in 11 Qixian stations of Ulanqab City from 1980 to 2010

5 Conclusions

(1) This heavy precipitation process was caused by the cold

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In the radial velocity field (1.5° elevation angle), from 08:00 on the 17th to 08:00 on the 18th, Ulanqap City was mostly controlled by southwest and westerly wind, and the zero velocity line was positively "S"-shaped; the wind turned along with the height, indicating warm advection. At 08:00 on the 18th, the wind first turned along with the height and then reversed in the northerly area (Fig. 7a), indicating that the warm and cold advection intersected. After 08:00, the zero velocity line gradually extended from northwest to southeast, that is, there was southwest wind at both high and low altitudes. As the cold front gradually moved eastwards and southwards, the velocity field showed a typical cold front shape. Around 10:00, the velocity was negative in the northwest and southwest at the rear of Jining station and positive in the northeast of Jining station, indicating that Jining station was located in front of the cold front (Fig. 7b). At around 10:26, the cold front passed through the city (Fig. 7c). Jining station was controlled by the northwest air flow, and negative speed changed into positive speed from southwest to northeast in the lower reaches (Fig. 7d). Then Ulanqab City was gradually controlled by northwesterly wind, and the snowfall tended to end.

5 Conclusions

Based on the observation data of meteorological stations, Doppler radar observation data, and ERA-5 reanalysis data of Ulanqab City, a snowstorm process in Ulanqab City in the early spring of 2022 was analyzed.

(1) This process involved a wide range, and had a long duration and large snowfall. It was accompanied by the transformation of rain, sleet, and snow, belonging to type II snowstorm. The main precipitation period can be divided into two stages: in the first stage, snowfall was small, lasted for a long time, and was distributed evenly in space; in the second stage, rainfall was heavy, lasted for a short time, and was dispersed in space. The snowfall in the process increased from north to south, and was larger in some areas.

(2) The snowfall process was formed under the combined influence of short-wave trough at 500 hPa, transverse trough 700 hPa, closed low-pressure system at 850 hPa, surface low-pressure inverted trough, frontal cyclone and other systems. The barrier of the downstream ridge of the trough on the 17th made the trough last longer, and the ground low-pressure inverted trough provided sufficient water vapor transport, so the duration was longer. On the 18th, there was a transverse trough at 700 hPa and a frontal cyclone on the ground. Overall, the system was stronger than that on the 17th, and the upward movement was strong, so the precipitation intensity was greater.

(3) During the process, the water vapor at 700 hPa was more in the south and less in the north, which tended to be consistent with the spatial variation of snowfall. At 08:00 on the 18th, a wet tongue in the southwest of Ulanqab extended to the west of central Ulanqab, and the negative large-value area of water vapor flux divergence corresponded to it. At the same time, the specific humidity field in the west of the region was perpendicular to the wind field, showing that sufficient water vapor and water vapor transport were compatible with strong water vapor convergence.

(4) The strong upward motion was one of the reasons for the high intensity of hourly precipitation on the 18th. In Siziwang Banner, when the hourly snowfall was strong, the ascending movement appeared from 850 to 300 hPa, and the large-value center of the ascending movement was near 700 hPa. There was a divergence field at 500 hPa and a convergence field from 700 hPa to the ground. A strong upward motion was formed under the cooperation of suction.

(5) During the process, the top height of echoes was 3 – 5 km in most areas and more than 5 km in local areas. The composite reflectivity ranged from 15 to 25 dBZ in most areas and from 30 to 35 dBZ in local areas. The echoes were mainly flaky and accompanied by scattered cotton echoes. The zero velocity line of radial velocity was "S"-shaped, indicating that it was controlled by southwest and westerly winds in most of the time, and there was obvious warm advection. There was cold advection in the northern area at about 08:00 on the 18th. Meanwhile, the cold front passed through the city on the morning of the 18th, and after the transit, Ulanqab City was gradually controlled by northwest wind, and the snowfall tended to end.

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air brought by the southward movement of the upper frontal zone and the warm and humid air outside the subtropical high.

(2) At 500 and 700 hPa, there were two troughs and one ridge, and the southwest jet existed at the lower level, which provided very favorable water vapor conditions and unstable energy conditions for the rainstorm process, and promoted the occurrence of upward movement.

(3) In terms of temperature conditions, the intrusion of strong cold air at the rear of the frontal zone after the precipitation was the main feature of the frost and cold wave weather process.

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