Deformation field strength and Vertical vorticity to horizontal vorticity conversion term In the process of two shear line Rainstorms in Ningxia

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Abstract: This paper makes a comparative analysis of the two rainstorm weather processes ("7.1 rainstorm" and "7.22 rainstorm" for The rainfall data of automatic station, the routine data collected by The indicative effects of deformation field intensity change and horizontal vorticity The indicative effects of deformation field intensity change and horizontal vorticity conversion to vertical vorticity during two heavy rains are analyzed emphatically. The results showed that in two processes, the shear line of "7.1 rainstorm" is in the south and the shear line of the "7.22 rainstorm" process is in the north, which make the location of the two storms different. The location of the large value center of the 700 hPa deformation field and the occurrence of the rainstorm are synchronized When the deformation field large value center moves to the position of the When the deformation field large value center moves to the position of the shear line, a medium cyclone is generated on the shear line, which promotes the generation of heavy rain. The maximum value of the conversion from horizontal vorticity to vertical vorticity appears before the rainstorm, and the intensity of the rainstorm is the maximum value of the conversion from horizontal vorticity to vertical vorticity appears before the rainstorm, and the intensity of the rainstorm is strongest after 6h-8h, which can indicate the forecast of the rainstorm. The large value center of the vorticity conversion item in the "7.1 rainstorm" process is located in the west of Helan mountain and extends to the northeast of Ningxia. The large value center of the vorticity conversion item in the "7.22 rainstorm" process moves to the direction of Liupan mountain in Guyuan and Then stagnated and disappeared.

1. Introduction

Heavy rainfall is one of the main disasters in Ningxia in summer, which often causes flash floods, geological disasters and urban and rural flooding. Most of the rainstorms in Ningxia are seasonal, showing the characteristics of more south and less north, mostly occurring during the period of strong subtropical high pressure from July to August, and in most cases when there are offshore typhoons folding north. The eastward cold air and the southward warm and humid airflow are blocked or lifted by the Helan Mountains and Liupan Mountains, and the low vortex or shear line transit triggers strong convection, which triggers heavy rainfall. After the mesoscale system enters Ningxia, it often moves out in a northerly or southerly direction, with different paths, resulting in different locations of heavy precipitation centers. Most of the cases form short-lived, intense, sudden and localized rainstorms along the Helan Mountains or Liupan Mountains at the north and south ends of Ningxia. In the study of heavy rainfall in Ningxia, Ji et al. (2012), Xiao Yunqing et al. (2018, 2019, 2020), Chen Yuying (2018), et al. Hu Wendong (2015), et al. and Yang Kan (2020) have conducted a lot of analytical studies on the formation of heavy rainfall in Ningxia, and concluded that heavy rainfall weather processes in Ningxia mostly occur under the condition of strong paramount, high temperature and high humidity. Moreover, it is often influenced by mesoscale systems such as 500hPa cold trough, 700hPa low vortex or shear line, and the indicators of physical quantities in the formation of heavy rainfall in Ningxia have been statistically and summarized.

Many meteorologists in China have conducted a lot of research and achieved important results on the role of the intensity change of deformation field and the horizontal vorticity to vertical vorticity conversion term on the approval of heavy rainfall. Wang Fucun et al. (2014) found that in the rapid-onset phase of low vorticity, the majority of the growth of 500hPa vertical vorticity comes from the conversion of horizontal vorticity to vertical vorticity. Jiang Yongqiang (2010) et al. found that the deformation field can guide the convergence of dry and cold air and warm and humid air, and the mid-latitude mesoscale vorticity tends to occur within the saddle-type field and on the shear line where the wind field is very weak. Gu Jiajia et al. (2017) showed that low-level convergence and high-level dispersion, with a symmetric distribution of positive and negative temperature advection in the boundary layer, correspond to the development of enhanced upward motion of the mesoscale secondary circulation. Yabin Zhang et al. (2016) showed that the cold shear line of the rapid eastward southward pressure in the middle and low layers and the strength of the cold front on the ground have important effects on the heavy rainfall process. Yang et al. (2016) found that the vertical circulation structure between the upper-level anticyclonic circulation and the lower-level low vortex shear further enhances the development of convective instability systems, while the continuous transport and convergence of low-level water vapor provides favorable water vapor conditions for the development of persistent rainstorms. In addition, the occurrence of many heavy rainfall processes is influenced by shear lines (Nie Yun et al. 2019; Chen Xiaoqiu et al. 2016; Zhao Runhua et al. 2011). Ji et al. (2012) pointed out that the large precipitation fall zone is located in the convergence zone between the left side of the low-level rapid and the tail of the shear line, which can be a typical feature of the mesoscale heavy rainfall weather system in Ningxia.

The role of deformation field intensity changes and horizontal vorticity to vertical vorticity conversion terms on the approval of heavy rainfall is less studied by forecasters in Ningxia. In this paper, we focus on the conversion of horizontal vorticity to vertical vorticity during the rainstorm by comparing and analyzing two regional rainstorms in Ningxia from July 1 to 2 and July 22 to 23, 2018, as well as studying the role of deformation field intensity on the development of low vortex wet obliquity compressibility and vorticity. At the same time, the similarities and differences of the circulation situation and triggering mechanism between the southern and northern rainstorms in Ningxia are explored with a view to improving the forecast and warning level of heavy rainstorms and short-duration heavy precipitation. This provides valuable theoretical analysis and applications for future heavy rainfall forecasting.

2. Information and methods

This paper analyzes the changes of physical quantities during the "7.1 rainstorm" and "7.22 rainstorm" in Ningxia by using automatic station data, 0.125°×0.125°ECMWF reanalysis data, and conventional data accessed by MICAPS4. The analysis focuses on the changes of deformation field strength, horizontal vorticity to vertical vorticity conversion and the influence of the occurrence of rainstorm in Ningxia.

1.1 Deformation field strength

Wang Fucun et al. (2014) expressed the deformation field in terms of deformation coefficients and the total deformation E contains the expansion deformation F1 and shear deformation F2 i.e.

$$F_1 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \qquad \text{..} \quad (1)$$

$$F_2 = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \text{ ....} (2)$$

$$E = \sqrt{F_1^2} + \sqrt{F_2^2} \text{ ....} (3)$$

The later analysis utilizes E to denote the deformation intensity of the deformation field.

1.2 Horizontal vorticity to vertical vorticity conversion

The conversion rate relationship for converting horizontal vorticity to vertical vorticity is

$$(\frac{\partial \zeta}{\partial t})_{Twist} = \eta.\nabla\omega \text{ ....} (4)$$

where: ζ is the vertical component of the relative vorticity, ω is the vertical velocity, and $\eta = \xi i + \eta j$ is the horizontal vorticity vector. The scalar form of Eq. (4) can be written as

$$(\frac{\partial \zeta}{\partial t})_{Twist} = \frac{\partial \omega}{\partial y}\frac{\partial u}{\partial p} - \frac{\partial \omega}{\partial x}\frac{\partial v}{\partial p} \text{ ....} (5)$$

From equation (5), when there is a horizontal vorticity tube and the vertical velocity is not uniformly distributed horizontally, it $(\frac{\partial \zeta}{\partial t})_{Twist} > 0$ will produce a positive vertical vorticity component, which is conducive to the generation or development of cyclonic circulation. Conversely, a negative vertical vorticity component is generated, which is conducive to the generation or development of anticyclonic circulation.

3. Weather conditions and circulation background of the two rainstorm processes

The two precipitation processes of "7.1 rainstorm" and "7.22 rainstorm" were concentrated in the south-central area of Ningxia and the north-central area of Ningxia, which basically represent the basic characteristics of the rainstorm in the north and south of Ningxia.

Precipitation (warm area) began at 00:00 on July 1, 2018 (all times used in this article are Beijing time), and the rain intensity became heavy at 08:00, until the end of the heavy rain process at 08:00 on July 2. This process was affected by the combined influence of cold air and southerly air currents, and heavy to torrential rain occurred throughout Ningxia, with precipitation mainly concentrated in the south-central region of Ningxia. There were two centers of heavy precipitation (Figure 1a, Figure 2a), the maximum cumulative rainfall appeared in Zhongning Shikong Dukou for 132.4mm. the maximum hourly rain intensity reached 55.8mm h-1 in Xinhua Village, and the process precipitation exceeded 100mm at five sites (three sites in Zhongning to Concentric, two in Guiyuan area). The main precipitation is divided into two periods, July 1 14:00 to 20:00, heavy precipitation center in central Ningxia Zhongning to concentric area; July 1 20:00 to 2 05:00 heavy precipitation center in southern Ningxia, Guyuan area.

The heavy rainfall process occurred again from 08:00 on July 22 to 08:00 on July 24, 2018 (Figure 1b, Figure 2b), with precipitation mainly concentrated in the north-central area of Ningxia (the large precipitation area was along the northern section of the Helan Mountains). The maximum cumulative precipitation and maximum hourly precipitation were both in the Helan Mountain ski resort, 297.4mm and 74.1mm h-1 respectively. 4 automatic station sites with rainfall greater than 200mm, this process is stronger than the "7.1 rainstorm" rainstorm intensity. The process of heavy precipitation is also divided into two periods: the first period for the 22 19:00 to 23 08:00, the northern section of the Heilan Mountains along the rainstorm; the second period in the afternoon of July 23 of the same year in the north central region of Ningxia a slightly larger range of regional rainstorm weather.

From Figure 1a,b and Figure 2a,b, we can see that the "7.1 rainstorm" process and the "7.22 rainstorm" process are divided into two periods of heavy precipitation. The center of heavy precipitation in both periods was distributed in a north-south pattern, and moved from west to east, and after reaching the territory of Ningxia, the rain area of the "7.1 rainstorm" process moved out to the south of east. The "7.22 rainstorm" process rain area to the east north direction moved out of Ningxia.

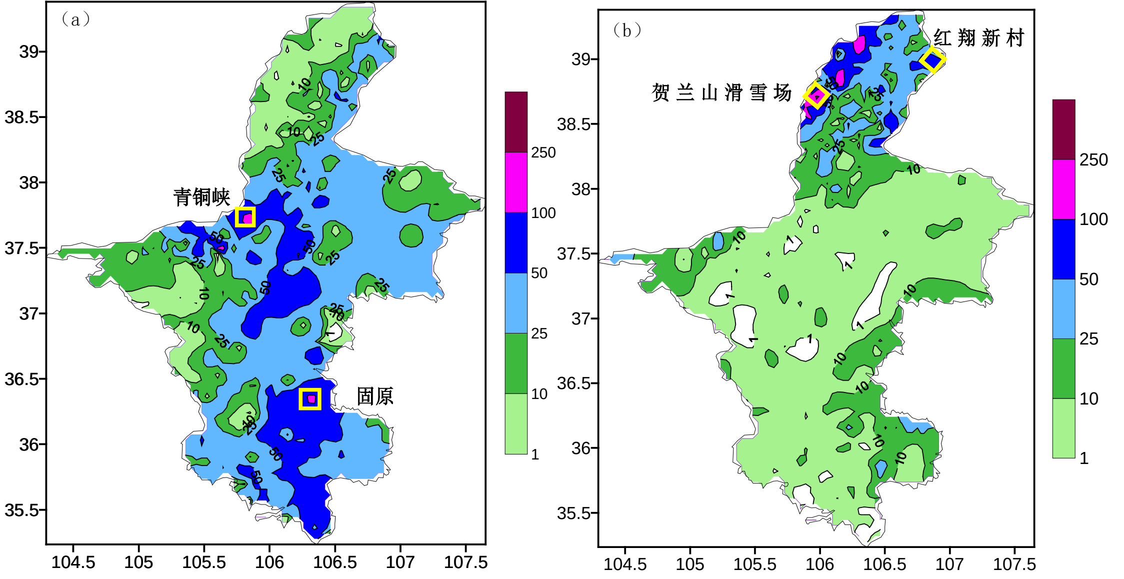
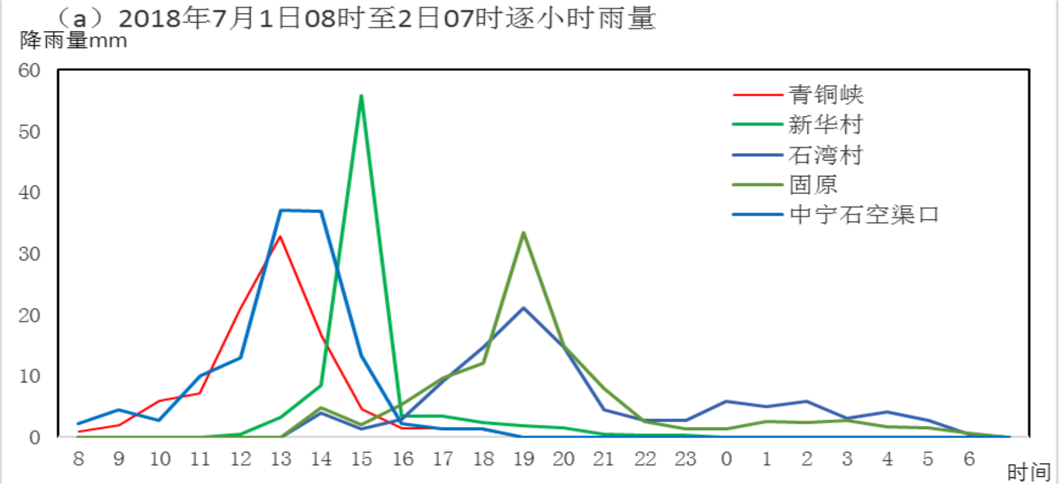


Fig. 1 The cumulative rainfall (unit: mm) of Ningxia from 00:00 BT 1 to 08:00 BT 2 July 2018(a) and 08:00 BT 22 to 08:00 BT 24 July 2018(b)


（a）2018年7月1日08时至2日07时逐小时雨量

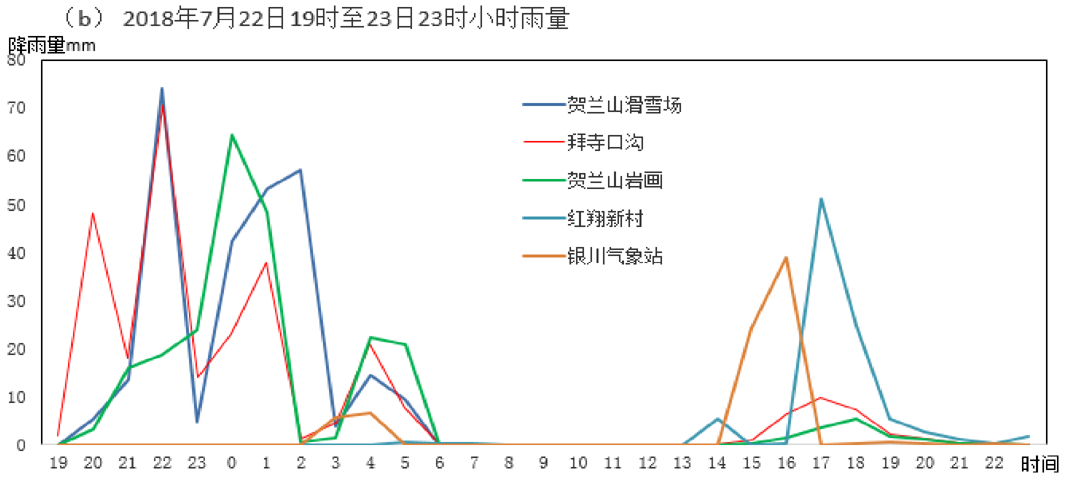

（b）2018年7月22日19时至23日23时小时雨量

Fig.2 Hourly rainfall (unit: mm) at stations of Ningxia from 08:00 BT 1 to 07:00 BT 2 July 2018(a) and 19:00 BT 22 to 08:00 BT 23 July 2018(b)

To analyze the circulation of the two rainstorm processes, the high and low altitude situation at 08:00 on July 1 before the start of heavy precipitation was selected for analysis. Ningxia 200hPa (Figure 3a) is influenced by anticyclonic circulation at high altitude, and Ningxia is a dispersion zone. The mid-level 500hPa (Fig. 3b) maintains two troughs and one ridge in Eurasia. The high-pressure ridge is located west of Lake Baikal to the west of the river, and the two low-pressure troughs are located from Central Siberia to Lake Balkhash and east of Lake Baikal. Ningxia is located at the bottom of the cold trough of Lake Baikal, and the cold air is constantly moving eastward and southward under the influence of the northwest airflow, while the southward airflow develops on the Qinghai-Tibet Plateau, which transports the water vapor from the Bay of Bengal to Ningxia. 700hPa (Figure 3c) Mongolian low pressure trough develops eastward, and the southward airflow in front of the trough overlaps with the southward airflow on the west side of the subalpine, which transports the warm and humid air to Ningxia, and intersects with the cold air behind the Mongolian low pressure trough, and a shear line appears in the northwest of Helan Mountain. 850hPa (Fig. 3d), a high northeastern airflow and a southerly airflow form a wind direction and wind speed shear in northwestern Ningxia, with a cold shear line moving eastward along the Hexi Corridor in western Ningxia, while a warm shear line exists in central Ningxia.

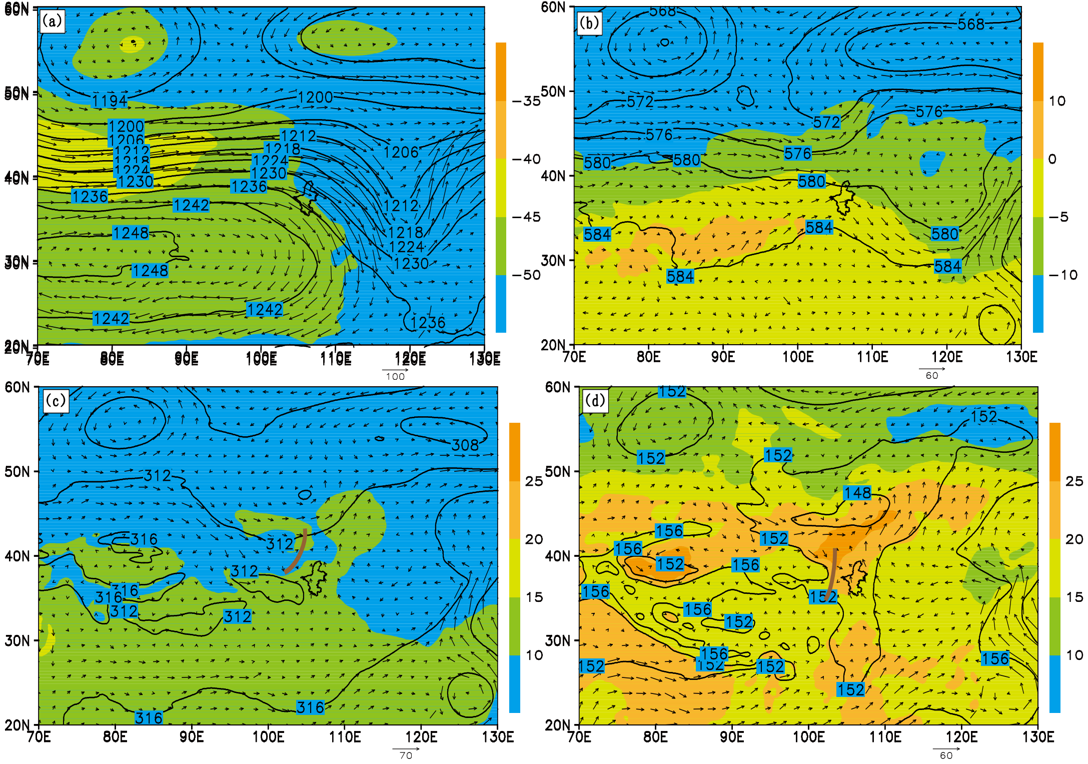


Fig. 3 Circulation at 200hPa(a), 500hPa(b), 700hPa(c) and 850hPa(d) at 08:00BT 1 July (solid line is potential altitude, unit: dagpm; shadow is temperature, unit: °C; brown line is shear line)

During the "7.22 rainstorm", at 20:00 on July 22, 200hPa (Fig. 4a) was located in the divergence zone in northern Ningxia, corresponding to the high altitude dispersion. 500hPa (Fig. 4b) was in the circulation background of "east high and west low", and there was a low trough in central Gansu. The trough moves eastward. Ningxia is located at the edge of the subtropical high pressure, and the sub high has retreated eastward significantly during the night of 22nd. 700hPa and 850hPa (Fig. 4c,d) have low vortex and shear line approaching in the west of Ningxia, and warm shear line is maintained in the north of Ningxia. 500hPa southwest airflow, 700hPa southward airflow, 850hPa eastward airflow "four streams "convergence in the eastern foothills of Helan Mountains, conducive to water vapor uplift.

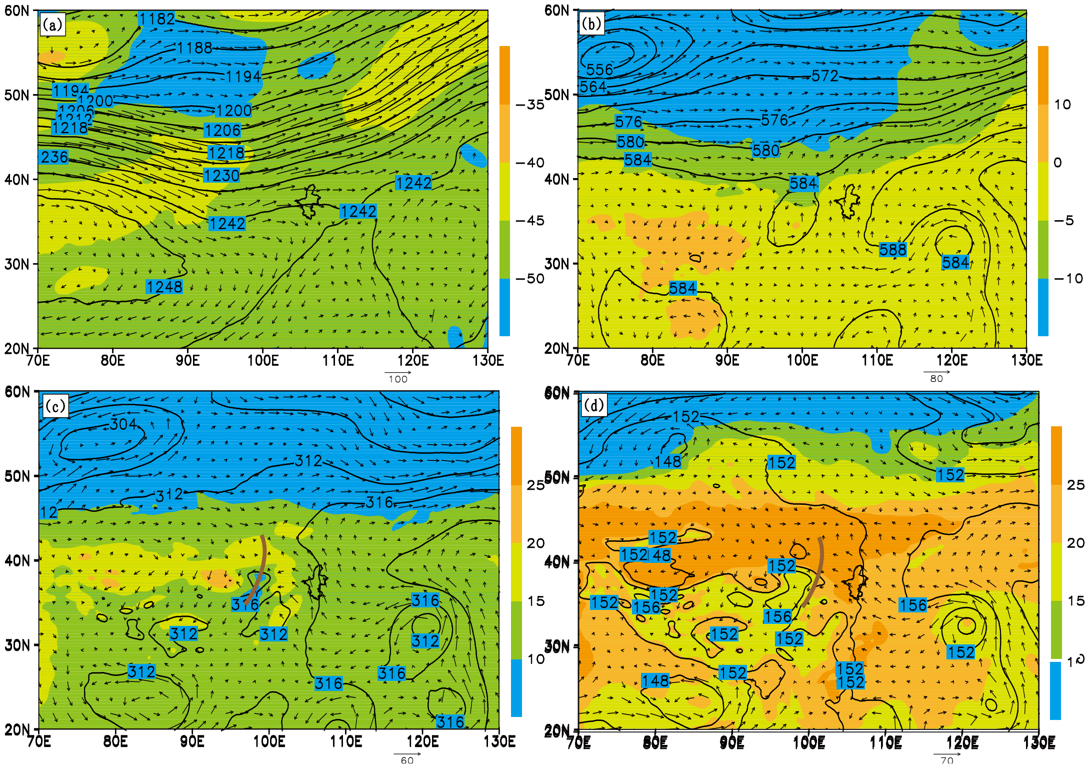


Fig. 4 Circulation at 200hPa(a), 500hPa(b), 700hPa(c) and 850hPa(d) at 20:00 22 July (solid line is potential altitude, unit: dagpm; shadow is temperature, unit: °C; brown line is shear line)

Comprehensive analysis, the two rainstorm process are in 700hPa, 850 hPa continental high pressure and the western Pacific subtropical high pressure between the formation of a similar saddle field, Ningxia is in the center of the nearby, and the low-level airflow in Ningxia convergence to form an upward movement. The difference between the two regional rainstorms is that the position of the shear line during the "7.1 rainstorm" was to the south, and the shear line moved in the southeast direction after entering Ningxia; the shear line during the "7.22 rainstorm" was to the north, and the shear line moved in the northeast direction after entering Ningxia, and the rainstorm area and The position and direction of the tangent line coincide.

4. Comparative analysis of precipitation conditions between the two processes

4.1 Comparative analysis of water vapor conditions

Ningxia forecasters (Feng, 2012) concluded that the occurrence of heavy rainfall in Ningxia, especially regional rainstorms of slightly larger extent, generally requires water vapor transport for more than 24 hours in the early stage. The corresponding water vapor sources generally have three directions: first, water vapor from the Bay of Bengal, second, southward airflow in the middle and low altitudes, which transports water vapor from the South China Sea to the north, and third, eastward airflow in the near-surface layer, which brings water vapor from the East China Sea. By analyzing the 700hPa water vapor flux maps at 14:00 on July 1 and 20:00 on July 22, we can find that the water vapor during the "7.1 rainstorm" (Fig. 5a) was mainly transported northward to Ningxia by the southerly low-level jet stream from the Bay of Bengal and the western part of the South China Sea, and there was obvious water vapor flux convergence in most of Ningxia. In contrast, the "7.22 rainstorm" process was mainly influenced by the southeastern airflow (Figure 5b), which transported water vapor from the South China Sea and the East China Sea to Ningxia, and the intensity of water vapor flux in Ningxia was stronger than that of the "7.1 rainstorm" process.

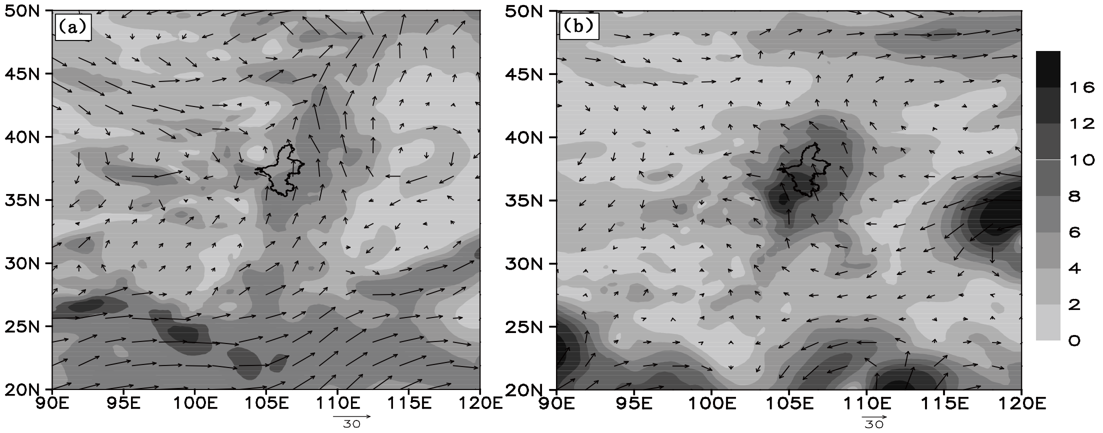


Fig. 5 Water vapor flux field (shaded area, Unit:g.cm-1.hPa-1.s-1) and wind field (arrowhead, Unit:m.s-1) of 700hPa at 14:00BT 1 July (a) and 20:00BT 22 July (b)

4.2 Comparative analysis of unstable conditions

4.2.1 Pseudocomparable bit temperature

On the spatial and temporal profiles of pseudo-equivalent temperature and water vapor flux dispersion (Figure 6a,b), the process of "7.1 rainstorm" started to show an obvious enhancement of unstable energy from the night of 30th, and the energy front area was dense and deep. At the same time, the water vapor convergence was strengthened and maintained, and at 08:00 on July 1, the convective unstable laminar junction was cold at the top and warm at the bottom over Xinhua Village, Dingtang Town, Ningxia (Figure 6a), with an unstable energy of 234.9 J/kg, and a revised CAPE of 1531.9 J/kg at 14:00, which was favorable to the occurrence of convective weather. and the start of heavy precipitation.

During the "7.22 rainstorm", the CAPE reached 2100 J/kg in the afternoon of the 22nd day after the real-world revision, and the unstable energy was significantly enhanced. At 20:00, Δθse(850-500) =20K at Helan Mountain ski area (Figure 6b), the temperature difference is large, and the unstable lamination is obviously cold at the top and warm at the bottom. At this time, due to the conditions triggered after the energy release, but it can be seen that the energy is not completely released, 23 is still at a certain instability. With the cold front system and the transit of low and medium altitude shear lines, the energy released by 20:00 on the 23rd turned into a stable structure.

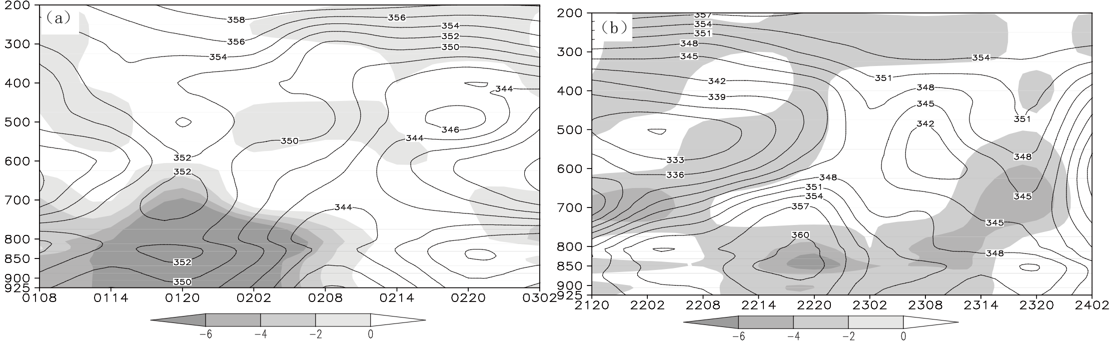


Fig. 6 Space-time profile of θse (black contour line, Unit:K) and water vapor flux divergence (shadow, Unit:g.cm-2.hPa-1.s-1) from 08:00BT 1 July to 02:00BT 3 July 3 (a), and from 20:00BT 21 July to 02:00BT 24 July (b)

The comparative analysis of the water vapor conditions and instability conditions of the two processes of "7.1 rainstorm" and "7.22 rainstorm" shows that the warm and humid airflow in the early stage of the precipitation of the two processes for more than 24 hours was transported northward, which made the high humidity and high energy zone established in Ningxia. The strong precipitation occurred near the center of the high-energy zone, and the precipitation process is the process of energy release, and there is an obvious correspondence between the location and movement direction of the shear line and the occurrence area of the rainstorm.

4.2.2 Comparison analysis of instability index and empirical index

Analyzing the sounding data of Yinchuan (the only sounding station in Ningxia that launched sounding balloons at 0800 and 2000 hours) (Figure omitted): Convective unstable stratification existed over Yinchuan station at 0800 hours on July 1. CAPE value was 234.9 J/kg, K index was 39 and Sha index was -1.95. The humidity of the whole layer was high and water vapor conditions were good. 1531.9 J/kg, which is favorable for the occurrence of convective weather.

At 08:00 on July 22, the low-level water vapor conditions were good and belonged to the lower wet and upper dry structure. There is a certain thickness of wet layer in the lower layer, meanwhile the suppression energy is greater than the wet convective effective potential energy at 08:00, meanwhile the height of zero degree layer is higher, indicating a thicker warm cloud layer. The CAPE reached 2100 J/kg through the afternoon live revision, and the CAPE of Yinchuan sounding at 20:00 on the 22nd increased significantly compared with that at 08:00, reaching about 1500 J/kg. The wind direction changed clockwise from low to high and was warm advection, and the vertical wind shear at 20:00 was significantly enhanced compared with that at 08:00.

Table 1 lists some physical quantities for the two storms. By comparing with the empirical indicators of the rainstorm of Ningxia forecasters (Feng, 2012), it is found that the specific humidity from 700 hpa to 850 hpa is greater than the empirical indicators. 850 hpa K-index and pseudo-equivalent potential temperature are also greater than the empirical statistical indicators. The two processes further validate the significance of the empirical indicators for each physical quantity of the Ningxia rainstorm.

Table 1. Comparison between "7.1 rainstorm" and "7.22 rainstorm" processes

	Date and time	1, 20:00	20:00 on 22nd	23rd 14:00	Empirical indicators
Specific humidity (g/kg)	700hpa	11	12	12	>8
Specific humidity (g/kg)	850hpa	13	15	16	>12
K-index (°C)	850hpa	38	46.9	37	>38
Pseudo equivalent potential temperature (K)	850hpa	350	360	356	>340

The comparative analysis of the water vapor conditions and unstable conditions of the two processes of "7.1 rainstorm" and "7.22 rainstorm" shows that the warm and humid airflow in the early stage of the two processes of precipitation for more than 24 hours was transported northward, and the establishment and development of high humidity and high energy areas were used for the The accumulation of energy for the occurrence of heavy rainfall. Strong precipitation occurs near the center of the high-energy zone, and the precipitation process is a process of energy release. At the end of the rainstorm, the high-energy zone disappears. There is a clear correspondence between the area where the rainstorm occurs and the location of the high-moisture and high-energy zone.

4.3 Vorticity, dispersion, vertical velocity analysis

From the spatial and temporal profiles of vorticity, scatter and vertical velocity at Xinhua Village, Concentric, Ningxia, from 0800 hours on June 30 to 0200 hours on July 3, 2018 (Fig. 7a) and at Helan Mountain Ski Resort, Ningxia, from 0800 hours on July 21 to 0200 hours on July 24 (Fig. 7b), we can see that: after 14:00 hours on July 1, 500hPa and below Ningxia are in the positive vorticity region, and the center of positive vorticity is near 800hPa, and with Below 600hPa, the negative scatter is also near 800hPa, with a central value of $^{-10\times10^{-5}\ s^{-1}}$, showing a typical configuration of the scatter field which is conducive to the generation of heavy rainfall, with "upper level dispersion and lower level convergence". The updraft over the storm area is very deep, stretching from the ground to 200hPa.

The process of "7.22 rainstorm" started from 08:00 on the 22nd to 08:00 on the 23rd, and the strongest upward motion occurred at 20:00 on the 22nd and 08:00 to 20:00 on the 23rd. At the same time, with the low-level convergence and high-level dispersion, compared with the "7.11 rainstorm", the vertical upward velocity was smaller and the duration was longer.

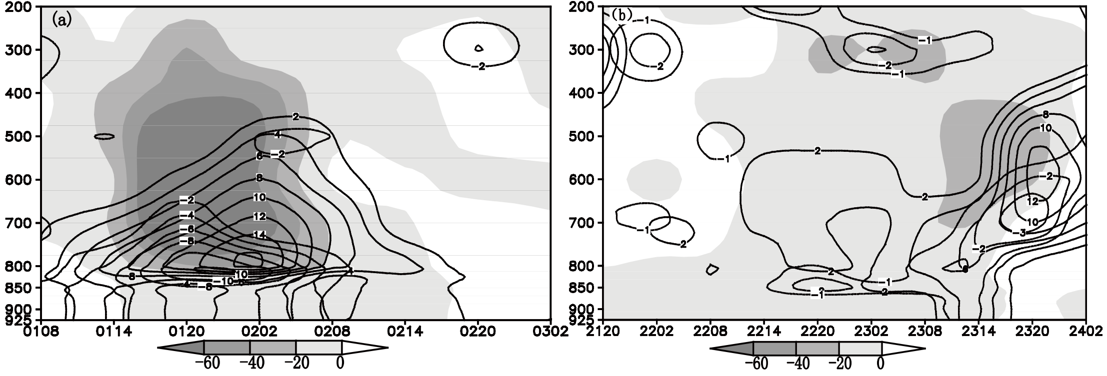


Fig. 7 Space-time profiles of vorticity (black contour line, unit: 10-5 s-1), divergence (green contour line, unit: 10-5 s-1) and vertical velocity (shadow, unit: pa s-1) from 08:00BT 1 July to 02:00BT 3 July (a), and from 20:00BT 21 July to 02:00 24 July (b)

5. Analysis of the role of overhead deformation field in the process of heavy rainfall

Wang Fucun et al. (2014) pointed out that near the expansion axis of the saddle-type field, the total deformation is the largest, and its location and orientation are consistent with the rainband, which is favorable to the formation of fronts and mesoscale cyclones. Ningxia is located in the eastern part of northwest China, and the altitude of sea level is above 1000 m, which is close to 850 hPa. Therefore, analyzing the ground pressure field or analyzing the position of 850 hPa saddle field expansion axis and the position and direction of total deformation field, and analyzing its relationship with the rainstorm band, can provide reference for future rainstorm forecasting.

5.1 Location of low-level saddle fields during the two rainstorms

The ground pressure field during the "7.1 rainstorm" and "7.22 rainstorm" is analyzed. During the "7.1 rainstorm" (Figure 8a), there was a low pressure center in the southwest of Ningxia, and the northern part of the Loop was controlled by a hot low pressure zone, while the western part of the Loop - the western corridor - the eastern part of the Loop was a horizontal strip of high pressure, and the eastern part of the Loop was a high pressure periphery. From the analysis of the saddle field changes and time evolution, Ningxia is located near the center of the long axis of the saddle field to the east, and the midpoint of the connecting line between the two low centers in the north and south. On the Qinghai-Tibet Plateau, the thermal low pressure (central pressure 990hPa) extends the inverted trough to the south-central part of Ningxia. The distribution of the pressure field during the "7.22 rainstorm" (Figure 8b) is also similar to the saddle field structure, but the difference is that there are two high-pressure centers controlling the southern part of the Tibetan Plateau to the Loop. The low pressure inversion trough controlling the Loop was distributed in a north-south strip, and Ningxia was in the middle of the line connecting the two low pressure centers before the rainstorm occurred. From the time evolution, it is also the location of this ground saddle field expansion axis. The cold front is located in the Qinghai region, indicating that the process is also mainly convective heavy precipitation in the warm area before the front, "7.1 rainstorm" cold air from the northern invasion of Ningxia, in the north central region of Ningxia rainfall, "7.22 rainstorm" process cold air from the western invasion of Ningxia The "7.22 rainstorm" process of cold air invasion from the western part of Ningxia, in the south-central area of Ningxia rainfall.

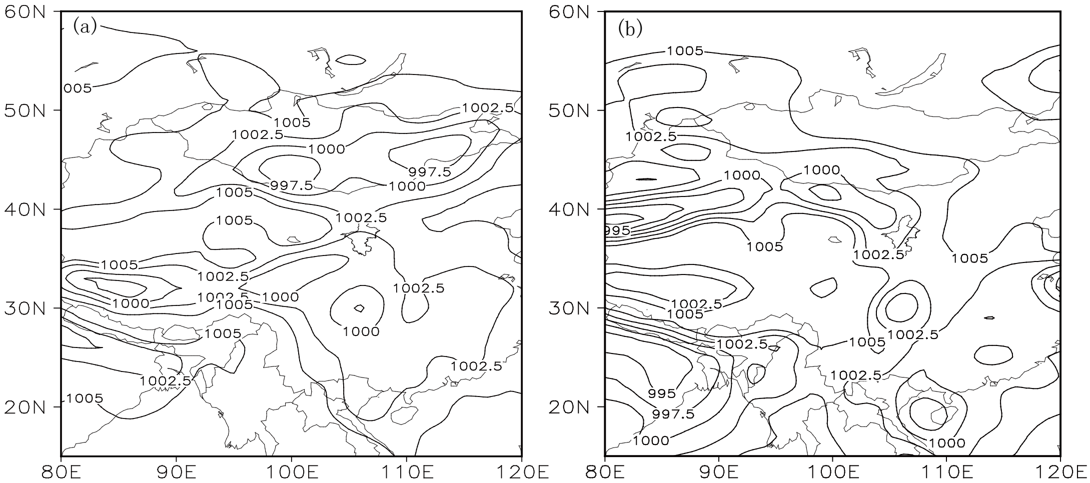


Fig. 8 Surface pressure field at 14:00on 1 July 2018 (a) and 20:00on 22 July 2018 (b)

5.2 Analysis of the intensity effect of high-altitude deformation field during two rainstorms

Wang Fucun et al. (2014) pointed out that in the saddle field and its expansion axis, the wind field is weak and the deformation coefficient is large, which is favorable to the formation of fronts and mesoscale cyclones. Based on the calculation results of Equation (3), this paper analyzes the distribution of 500 hPa and 700 hPa flow fields and total deformation during the "7.1 rainstorm" and "7.22 rainstorm" and the changes of different moments.

The "7.1 rainstorm" process is in the south-central region of Ningxia, 500 hPa height, July 1, 14:00 (Figure 9a), 20:00 (Figure 9b) to 2:02 (Figure 9c), the flow field is dominated by southwest airflow. The center of the large value of the intensity of the deformation field moved closer to the Loop along the Hexi Corridor, and the range of the center was small at the beginning, with a maximum value of 4× $^{10\text{-}5s\text{-}1.}$ $^{\text{At 20:00 on}}$ the 1st after the precipitation began, the large value center moved slowly eastward into Ningxia from the central to south-central part of Ningxia, and the maximum value of the center was still 4 × $^{10\text{-}5s\text{-}1}$. With the expansion of the precipitation large value center to the east and south, a large range of deformation field large value area was formed in central Ningxia from concentric and south of Zhongning to Guyuan (Figure 9c), corresponding to the rainstorm central zone also moved from concentric and Zhongning in central Ningxia to Guyuan (Figure 1a, Figure 2a). 700 hPa height, at 14:00 on July 1 (Figure 9d), the flow field was dominated by southerly airflow, with a shear line in the line from Zhongwei to $^{4\times10\text{-}5s\text{-}1}$ center, shear line and deformation field large value area close to overlap. Around 15:00 hours in the area of Zhongning Shikong maximum hourly rain intensity (Figure 2b), July 1, 20:00 hours (Figure 9e) flow field turned to southeast dominated, wind speed increased, deformation field intensity of large values of the center also to the east slowly moving at the same time to the direction of Guyuan, the central value increased to 8 × $^{10\text{-}5s\text{-}1}$. At this time Guyuan precipitation for the strongest time. Analysis of the role of the deformation field in the rainstorm process, the relationship between the total deformation large value area and the location of the center of heavy precipitation, corresponding to the area of maximum precipitation by time (Figure 2). 2018 July 1 night low and medium altitude shear lines and deformation field large value area superimposed, strengthening the low and medium altitude convergence rise, thus strengthening the convection. This can also be found in the vorticity and vertical velocity of Fig. 7a. By 02:00 on the 2nd, the intensity of the deformation field gradually became smaller (Fig. 9f) and the precipitation weakened, and the heavy precipitation area moved eastward. the direction of the 500hPa total deformation large value area coincided with the moving direction of the largest area of the rainstorm, and the low-level 700hPa deformation field large value central area and the rainstorm area had a good correspondence. During the eastward movement of the shear line in the south-central region of Ningxia, we can pay attention to the moving direction of the large value area of the deformation field, and analyze whether the eastward movement of the shear line and the large value center of the deformation field intensity overlap, and the overlapping part is prone to short-time heavy precipitation, which is indicative of the movement of the heavy rainfall area and the heavy rainfall center.

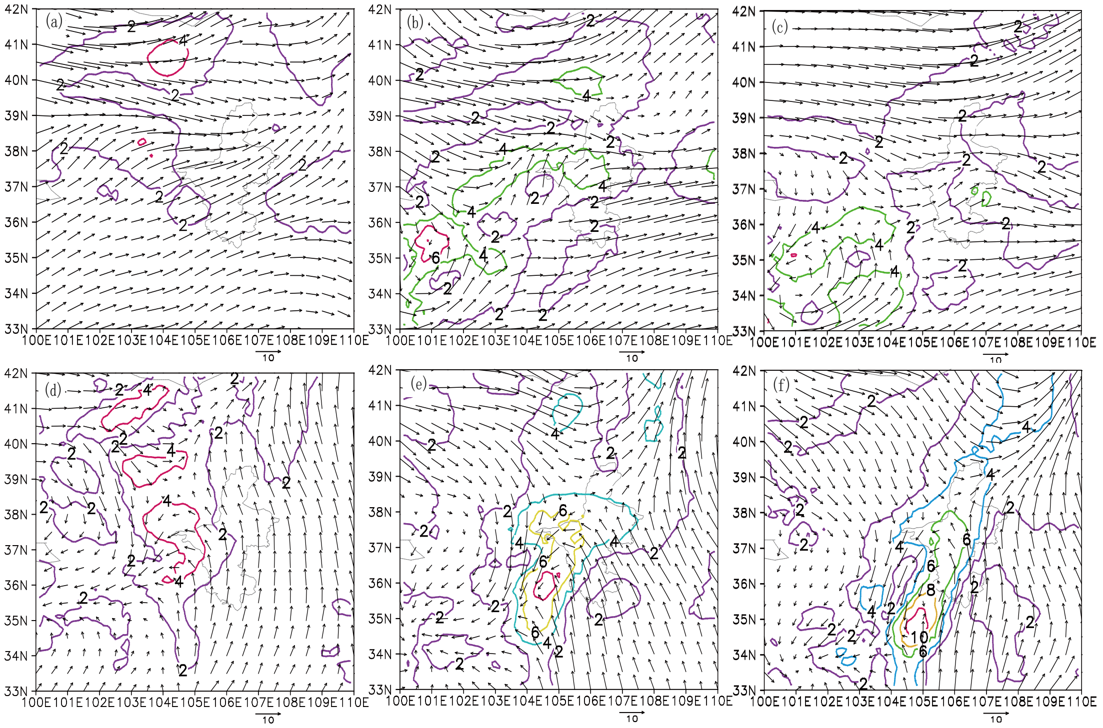


Fig. 9 Distribution of flow field and total deformation (solid line unit: 10-5s-1) at 500hPa (a-c) and 700hPa (d-f) at 14:00, 20: 00 on July 1 and 02:00 on July 2, 2018

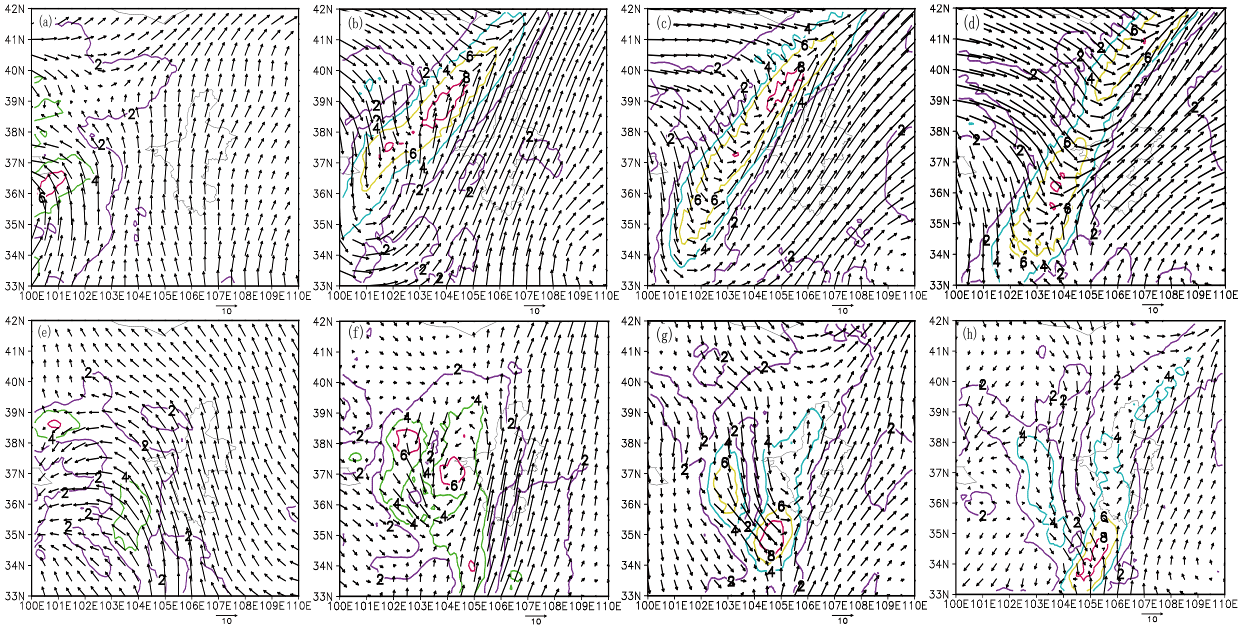


Fig. 10 Distribution of flow field (streamline) and total deformation (solid line unit: 10-5s-1) at 500hPa (a-c) and 700hPa (d-f) at 20:00 on July 22 and 08:00, 14:00 on July 23, 2018

The relationship between the intensity of the total deformation field and the area of large values during the "7.22 rainstorm" was analyzed. 500 hPa and 700 hPa flow fields were consistent southward flow at 20 July 2018 (Figure 10a-h), and the total deformation at both levels was distributed in a band along the northeast-southwest shear line, with a central value of 2 × 10-5s-1 at 700 hPa at 20 July 2018 (Figure 10e). With the onset of precipitation, the intensity center of the 500 hPa (Fig. 9a-d) deformation field, which is distributed along the northeast-southwest tangent line, is divided into two centers, the northern center moving northeastward along the Helan Mountains and the southern center moving southeastward along the Pingliang in the process of eastward movement· south to southeast. The northern center of 500 hPa reached 8×10-5s-1 and the southern center was $^{4\times10\text{-}5\text{s-}1}$ by 14:00 on the 22nd. 700 hPa (Fig. 10g) was also distributed along the shear line in a northeast-southwest direction, and the center was located in the southwest direction from Heilan Mountain to Ningxia. 10h). Comparing Fig. 9d, Fig. 9h and Fig. 2b, it can be seen that when the heavy precipitation appeared in the Helan Mountains ski area after 20:00 on the 22nd, it coincided with the time when the large value of the center of the northern part of the 700 hPa deformation field intensity appeared. (Figure 10c,d,g,h), the location of the large value center and the shear line nearly coincided, and the shear line and the large value area of the deformation field were superimposed to strengthen the convection. The superimposed area is basically the same as the north-central Ningxia rainstorm area, and the front is also strengthened on the ground map when the shear line and the large value area of the deformation field are superimposed, and moves to the northeast (figure omitted).

Overall, it is located in the total deformation large value area, which is favorable to the strengthening of the surface front. During the two rainstorms, the direction of the 500hPa total deformation large value area coincides with the direction of the maximum area of the rainstorm movement. There is a good correspondence between the central area of the low-level 700hPa deformation field large value and the storm area. We can pay attention to the moving direction of the deformation field large value area, analyze whether there is a shear line moving eastward, and whether the shear line or low vortex overlaps with the deformation field intensity large value center. The overlapping part is prone to short-time heavy precipitation, which is indicative of the movement of the storm area and the storm center.

The different positions of the shear lines lead to the two rainstorm fallout areas located in the north and south of Ningxia, respectively. In the two processes, near the saddle field expansion axis, the total deformation is the largest, and its position and direction are basically consistent with the rainband. Near the saddle point of the saddle field and its eastern expansion axis is the area formed by the center of the large value of the deformation field, and it is also the main area where the rainstorm occurs. The location and direction of deformation field intensity movement in the two processes are also the location and direction of the precipitation major value area. 700 hPa deformation field major value center position and the location and time of rainstorm occurrence are synchronized, and the location and movement direction of deformation field major value center indicate the area of rainstorm occurrence. The analysis of the movement of the large value center of the deformation field is indicative for the forecast of the strong center of the rainstorm in Ningxia in the future.

5.3 Analysis of the role of the conversion effect of horizontal vorticity to vertical vorticity

The analysis of Wang Fucun et al. (2014) shows that the vast majority of the increase in vertical vorticity is from the contribution of the torsional term, i.e., the horizontal to vertical vorticity conversion plays a major role in the rapid development of the low vortex circulation. The maximum value of the twist term appears 6 h ahead of the vertical vorticity, and the intensity of the storm suddenly increases after 8-10 h, which is a good indicator for storm forecasting. Based on the above equations (4) and (5), the 0.125°×0.125°ECMWF reanalysis data were used to analyze and calculate the conversion terms from horizontal to vertical vorticity for the two processes of "7.1 rainstorm" and "7.22 rainstorm" (Figs. The flow fields (streamlines) and the horizontal vorticity to vertical vorticity conversion distribution at 500hPa (Fig. 11a-c) and 700hPa (Fig. 11d-f) at 1400 and 2000 hours on July 1 and 0200 hours on July 2, 2018 are shown in Figs. 11a-f and 12a-h. It can also be seen from the figure that, corresponding to the 500hPa horizontal vorticity to vertical vorticity transition distribution map, three positive centers appeared in the area of Zhongning, Concentration and Guyuan respectively 6 hours before the appearance of the storm. And it is also in 4 to 6 hours after the development of shear lines in Zhongning to concentric and and Guyuan area. Corresponding to the radar map of Wuzhong, Ningxia, there are thunderstorm monoliths and low-level fronts generated and developed near the three positive centers (Figure 12a). Figure 11(d-f) shows the 700 hPa horizontal vorticity to vertical vorticity conversion distribution, also three positive centers of $^{1\times10\text{-}9\text{s-}2}$ appear around Zhongning to Concentric and Guyuan, only the center value is slightly smaller than 500 hPa, and the shape of the large value center value is closer to the shape of the storm. After the start of the storm, the vorticity change generated by the twist term at 20:00 on the 1st expanded in the positive area near the center of the low vortex and moved eastward to the south (Figure 11e) to expand the range. At the same time, the gradient of the west measurement in the positive center increased significantly, and the negative center also became $^{-10\times10\text{-}9s\text{-}2}$ and became larger from the low level to the high level. 20:00 on the 1st the vorticity change generated by the twist term in the low vortex shear line from Zhongning to concentric area and Guyuan area twist term increased to $^{3\times10\text{-}9s\text{-}2}$, at this time the shear line was gradually strengthened at about 19.30 minutes at the same time. Velocity field on the northwest of the Guyuan radar began to appear more obvious frontal structure (Figure 12b), 6 hours after the south of Ningxia Guyuan area appeared hourly rain intensity maximum.

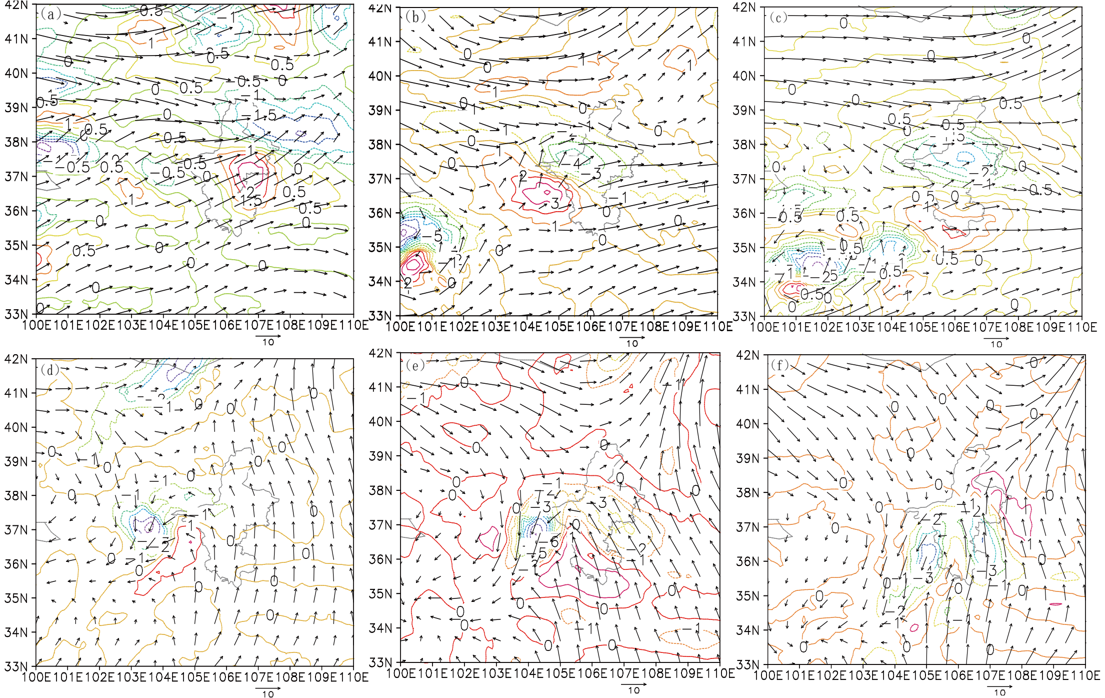


Fig. 11 The distribution of vorticity twisting term (isoline, unit: 10-9s-2) and wind field (vector, unit: m-s-1) in 500hPa(a-c) and 700hPa(d-f) at 14:00, 20:00 on July 1 and 02:00 on July 2, 2018

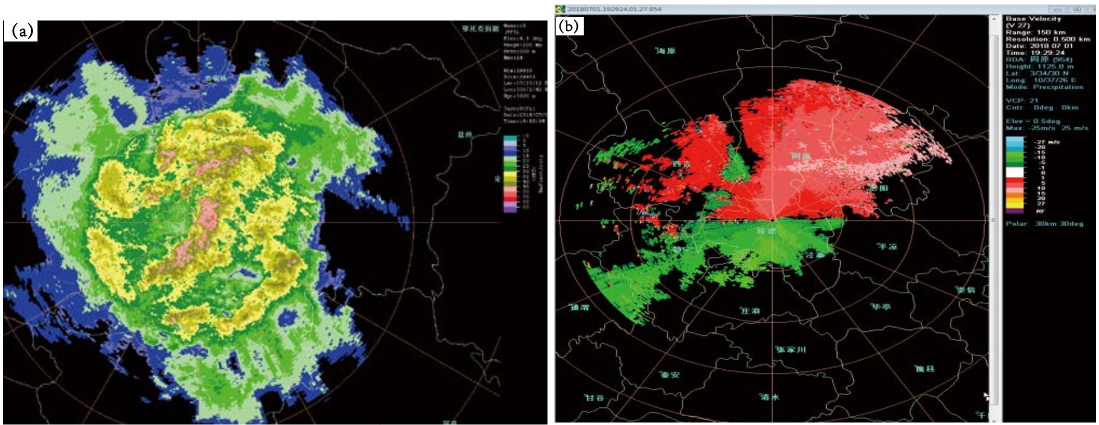


Fig.12 (a)Basic reflectivity of Wuzhong radar at 15:59 on July 1, 2018 (b) wind speed of Guyuan radar at 19:29 on July 1

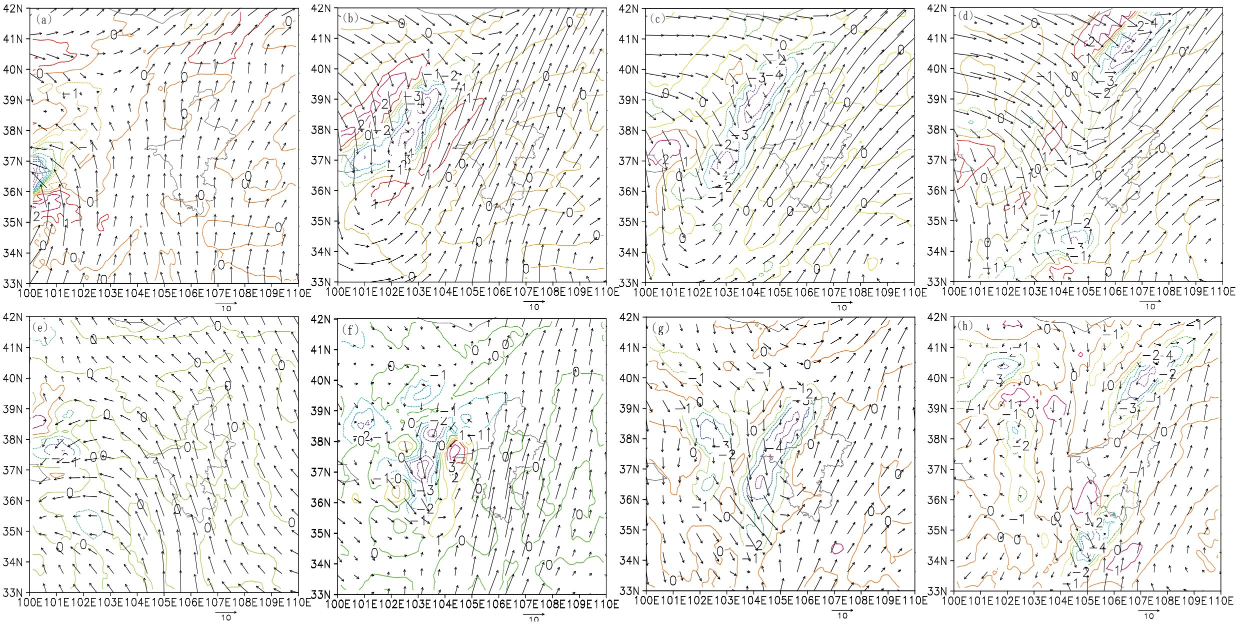


Fig. 13 The distribution of vorticity twisting term (isoline, unit: 10-9s-2) and wind field (vector, unit: m-s-1) in 500hPa(a-c) and 700hPa(d-f) at 20:00 on July 22 and 08:00, 14:00, 20:00 on July 23, 2018

Similarly, for the "7.22 rainstorm" 500hPa and 700hPa vorticity reversal term (Figure 13a-h), it can be seen from the figure that at 20:00 on July 22, the positive center of the northwest vortex at 500hPa and the negative center to its west, and the positive and negative gradients are obvious. During the whole process of rainfall in Helan Mountain ski resort on the night of 22nd, the negative center does not move in place, but the positive and negative gradients increase. This phenomenon can explain the continuous appearance of thunderstorm monomers at Helan Mountain ski resort, which were generated in situ and disappeared in situ (Figure omitted), while the short-time heavy precipitation was only held at the same location. 23rd 08:00 the positive center moved to the northeast, and the positive center value was $^{1\times10\text{-}9s\text{-}2}$, and the positive and negative gradients increased significantly, and the negative center value to the northwest of the positive center reached $^{\text{-}5\times10\text{-}9s\text{-}2}$. As seen from the flow field, the Low-altitude rapids are obviously strengthened, corresponding to the 700hPa flow field to see the cold and warm wind speed shear are obviously strengthened. By 14:00 on the 23rd, the positive center continued to move northeastward to expand the range, and the positive center decreased, while the negative center moved less and strengthened in situ, and the center value reached $^{\text{-}5\times10\text{-}9s\text{-}2}$. By 20:00 on the 23rd, it reached the northern part of Ningxia, and the negative center value was $^{\text{-}6\times10\text{-}9s\text{-}2.}$ The analysis shows that the time of the appearance of heavy precipitation at the Helan Mountain ski resort on the night of the 22nd, multiple thunderstorms generated under the effect of topographic uplift The heavy precipitation from 14:00 to 16:00 on the afternoon of the 23rd was generated and developed on the radar map of Yinchuan, Ningxia, about 6 hours after the vorticity reversal term reached its maximum in the positive and negative gradients in the area west of Ningxia at 08:00 (Figure 13b). The 700hPa horizontal vorticity to vertical vorticity transition also started from 08:00 on the 23rd to produce a positive center west of Zhongwei, Ningxia, with a central intensity of $^{4\times10\text{-}9s\text{-}2,\text{ and the}}$ positive center disappeared from 14:00. A low vortex was generated to the west of Zhongwei at 08:00 on the 23rd (figure omitted), and because of the slow movement of the low vortex, a strong negative center appeared at the back of the storm. And the rainstorm zone corresponds exactly to the area with the largest gradient in front of the negative center.

In a comprehensive analysis, the horizontal vorticity to vertical vorticity conversion term is clearly indicated at both 500 hPa and 700 hPa during the occurrence of deep systematic rainstorms, and the storm center occurs in the area with the largest gradient of the positive and negative horizontal vorticity to vertical vorticity conversion term at 500 hPa. Corresponding to the location of the positive center of the horizontal to vertical vorticity transition term at 700 hPa, fronts are generated near the positive center of both processes (Fig. 12a b) or multiple thunderstorm singletons are generated and developed (Fig. 14). When the gradient of the horizontal vorticity to vertical vorticity conversion term positive and negative center is the largest, the intensity of the storm is the strongest after 6h. The location of the large value center and the largest gradient of the vorticity transition term during the "7.1 rainstorm" was located on the west side of Helan Mountain extending toward northeast Ningxia. "7.22 rainstorm" process vorticity conversion term large value center and the location of the largest gradient to Guyuan Liupan Mountain direction to move slightly stagnant and then disappear, and heavy precipitation center moving in the same direction.

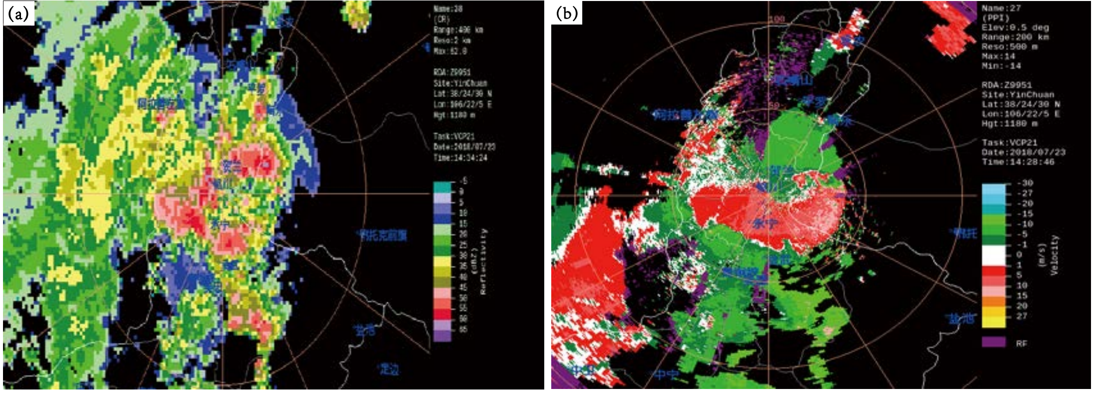


Fig.14 (a)Basic reflectivity of Yinchuan radar at 14:34 on July 23, and (b) wind speed of Yinchuan radar at 14:28 on July 23

6. Summary

This paper analyzes two local heavy rainfall weather processes in Ningxia from July 1 to 2 and July 22 to 23, 2018, using automatic station data, 0.125°×0.125°ECMWF reanalysis data, and conventional data retrieved by MICAPS4, etc. The analysis focuses on the role played by the deformation field and the horizontal to vertical vorticity conversion in the two rainstorm processes, and the following conclusions are obtained.

(1) The "7.1 rainstorm" and "7.22 rainstorm" process are triggered by the eastward movement of the shear line. Among them, the "7.1 rainstorm" process shear line position is southward, after entering Ningxia to the southeast, corresponding to the storm position is southward. The "7.22 rainstorm" process shear line to the north, the shear line into Ningxia after moving in the northeast direction, corresponding to the location of the rainstorm to the north.

(2) The two processes of "7.1 rainstorm" and "7.22 rainstorm" were characterized by low-level convergence and high-level dispersion. Both processes were preceded by more than 24 hours of warm and humid airflow to the north, making the high humidity and high energy zone established in Ningxia. The heavy precipitation occurred near the center of the high-energy zone, and the location and direction of the shear line corresponded to the high-moisture, high-energy zone and the area where the rainstorm occurred.

(3) Near the saddle field expansion axis of the two processes, the total deformation is the largest, and its location and direction are basically the same as the storm area. Near the saddle point of the saddle field and its eastern expansion axis is the area where the large value center of the deformation field is formed, and it is also the main area where the heavy rainfall occurs. The direction of movement of deformation field intensity in the two processes is also the direction of appearance of precipitation major value area, when the deformation field major value center is formed or moved to the position of the shear line, it coincides with it, the shear line strengthens and moves slowly, so that the rain intensity strengthens. 700 hPa deformation field major value center position and storm occurrence position and appearance time are synchronized, the position and movement direction of deformation field major value center indicates the occurrence area of storm. The analysis of the movement of the large-value center of the deformation field is indicative for the forecast of the strong center of rainstorm in Ningxia in the future.

(4) When deep systematic storms occur, the horizontal to vertical vorticity conversion term is clearly indicated at both 500hPa and 700hPa, and the storm center appears in the area with the largest

gradient before the negative center of the horizontal to vertical vorticity conversion term at 500hPa, which corresponds to the location of the positive center of the horizontal to vertical vorticity conversion term at 700hPa. There are often thunderstorm monomers generated and developed near the positive center, corresponding to the strongest rainstorm intensity after 6h. The large value center of the vorticity conversion term of the "7.1 rainstorm" process is located on the west side of Helan Mountain extending to the northeast of Ningxia. The "7.22 rainstorm" process vorticity conversion term large value center moved slightly stagnant towards Guyuan Liupan Mountain and then disappeared. This is consistent with the direction of the heavy precipitation center, which is a good indication of the rainstorm occurrence area.

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References

[1] X Q. Chen ,Y.Q. Wang ."Structural characteristics analysis of the JH cyclone based on NCEP data of an eastward-triggered rainstorm"[J]. Heavy rainfall disaster,2016. vol. 35, no.1, pp.53-60.
[2] Y. Chen. ,N. Chen , X.F. Ren,et al." Forecast bias and predictability analysis of rare very heavy rainstorms in the eastern part of Helan Mountains"[J]. Meteorology,2018.vol.44,no.1, pp.159-169.
[3] Feng. "Ningxia Forecaster's Handbook" [M]. Beijing: Meteorological Publishing House,2012. pp.74-101.
[4] J.J. Gu ,W Wu ." Mesoscale characteristics analysis of the 2016 "7.9" extraordinarily heavy rainstorm process in northern Henan "[J]. Heavy rainfall disaster, 2017.vol.36, no.5, pp.440-452.
[5] W. D. Hu , K. A. N. Yang., S. Y. Huang.,et al. " Characterization of radar data during a gust front triggered strong convection "[J]. Highland Meteorology,2015. vol.34, no.5, pp.1452-1464.
[6] X. L. Ji. ,X. L Chen. ,Jian Shao ,et al. "Mesoscale system analysis of a frontal transit short duration rainstorm in an arid region "[J]. China Desert, 2012. vol.32, no.6, pp.1731-1737.
[7] Y. Q. Jiang ,Y. Y. Wang ." Influence of topography on the saddle field of the July 1998 Erdong megathrust rainstorm "[J]. Highland Meteorology, 2010. vol.29, no.2, pp. 297-308.
[8] Y. Nie , J. X. Zhou , F. Yang ,et al. "Mesoscale system evolution and environmental field characteristics of rainstorms in a warm summer area on the southeast side of Fanjing Mountain "[J]. Stormwater Hazards,2021.vol.40, no.2,pp. 125-135.
[9] F. C. Wang ,D. B. Xu ,S. Y. Xiu ,et al. "Analysis of physical mechanisms of a large rainstorm in eastern Northwest China "[J]. Highland Meteorology,2014. vol.33, no.6,pp.1501-1513.
[10]Y. Q. Xiao ,W. D . Hu ,L. B. Zhao ,et al."A comprehensive comparative analysis of two heavy rainfall processes in north-central Ningxia"[J]. Highland Meteorology,2008. vol.27, no.3, pp.576-583.
[11]Y. Q. Xiao ,Y. Y. Yang ,H. B. Zhu ,et al. "Diagnostic analysis of physical mechanisms of the July 22-23, 2018 heavy rainfall weather process in Ningxia"[J]. Ningxia Engineering and Technology, 2019. vol.18, no.3, pp.193-201.
[12]Y.Q. Xiao ,X.Y. Shen ,X.L. Zhang ,et al. "Diagnostic analysis of wet level eddies during two local rainstorms in the eastern part of Helan Mountains"[J]. Storm water hazard,2020. vol.39, no.2,pp. 148-157.
[13]K. Yang ,X.L. Ji ,L.Mao ,et al. "Analysis of the influence of Heilan Mountain topography on the 8.21 mega flood storm in the context of anomalous circulation"[J]. Journal of Natural Hazards,2020. vol.29, no.1, pp.132-142.
[14]Y. B. Zhang ,J. Qiao ,L.W. Qu ,et al."Analysis of environmental conditions and mesoscale characteristics of the "8.3" heavy rainstorm in Xi'an"[J]. Storm hazards,2016. vol.35, no.5, pp.427-436.
[15]Q. Yang ,G. Q. Chen ,H. X. Mao ,et al."Analysis of the physical mechanism of a persistent

rainstorm process in Tongren, Guizhou, July 2014"[J]. Storm water hazard, 2016. vol.35, no.3, pp.261-270.

[16]R. H. Zhao ,H. B. Shen ,Y. C. Li ." Analysis of the "7.9" low-level wind-shear weather process at Chengdu Shuangliu Airport"[J]. Highland and Mountain Meteorological Research, 2011. vol.31, no.2, pp. 35-38.