Study on Happening and Extincting Mechanism of a Squall Line along the Eastern Helan Mountain

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Abstract. In the afternoon of June 17, 2020, a squall line occurred over the eastern region of Helan Mountain in Ningxia, accompanied by lightning, strong wind and short-term heavy precipitation, which affected north and middle part of Ningxia and Wuhai of Inner Mongolia. Basing on the Doppler radar data and conventional meteorological observation data, the weather process was analyzed. the results show that: (1) the cold air from the middle and high latitudes intersected with the near surface warming air in Alashan of Inner Mongolia, which promoted the development of convection and induced the formation of squall line; (2) the temperature and pressure field at high and low level were asymmetrical and the weather system presented a forward tilting structure, which was conducive to the occurrence of strong convective weathers such as squall line ;(3) the squall line strengthened when moving across Helan Mountain due to the topographic uplifting and the strong vertical wind shear;(4) After moving into north and middle part of Ningxia ,the convergence and divergence configuration of the squall line weakened, the circulation energy faded and the convective structure and circulation field became incomplete gradually, the inclined sinking airflow in the back of the squall line gradually weakened due to the precipitation.

Keywords: Eastern region of Helan mountain, squall line, forward tilting structure, topographic uplifting

1. Introduction
Squall lines are banded (line) mesoscale (MCS) convective systems, which are multi-monomer line storms capable of producing widespread regional gales. Squall lines are approximately tens to hundreds of kilometers long and tens to 200 kilometers wide on a horizontal scale and can last from a few hours to a dozen hours [1]. Squall lines can bring violent and extremely destructive weather. The occurrence of squall lines is usually accompanied by thunderstorms, high winds, hail, heavy precipitation, and other catastrophic weather [2]. Due to the small horizontal scale and short life span...
of squall lines, the gradient of meteorological elements changes, the weather is intense and difficult to forecast [3]. As the special geological landscape in the eastern part of Helan Mountains, short-term strong convective weather in summer often triggers flash floods, geological damage and other disasters. Zhang Fanghua et al analyzed the causes of squall lines in a diagnostic study and found that the intrusion of dry and cold air in the upper troposphere and the strong convergence of warm and humid airflow in the lower layers are the triggering mechanisms of squall line weather [4]. Wang Xiuming et al showed that the low-level humidity becomes a determinant of the storm structure under the vertical shear configuration of strong winds in the lower and middle troposphere, while highly organized squall lines are easily formed in the medium and high humidity environments [5]. Yang Shanshan et al pointed out that squall lines exist in 700 hPa and 850 hPa before the occurrence of squall lines, and 700 hPa and 850 hPa shear lines lag behind 500 hPa trough lines, and the system shows a processional structure, which is conducive to strengthening atmospheric vertical motion and promoting convective development [6].

Chen Yuying et al studied the catastrophic heavy precipitation weather at the eastern foot of the Helan Mountains and pointed out that the topography of the Helan Mountains blocked the movement of air currents resulting in bypass flow, frictional convergence and windward slope uplift, which favored the enhancement of heavy precipitation on its eastern side [7].

2. Data and methods
The sources used in this paper are conventional meteorological observations, Ningxia automatic weather station observations, satellite cloud maps and Doppler radar echoes from Yinchuan station on June 17, 2020. Diagnostic analysis and weather science methods were used to analyze this squall line weather process.

3. Result analysis
3.1 Weather analysis
3.1.1 Space-time distribution. In the late afternoon of June 17, 2020, a squall line process occurred in the eastern foothills of the Helan Mountains in Ningxia. The length of the squall line was about 420 km and the width ranged from 30 to 80 km. At the time of the squall line transit, three national meteorological stations experienced thunderstorm gusts of magnitude 8 or higher (Shahu 21.1 m/s, Pingluo 20.1 m/s, Shitanjing 17.7 m/s). The instantaneous wind speed at Yinchuan weather station was 16 m/s. The time span of thunderstorm cloud to ground flash (ground flash) was from 16:14:08 to 18:15:27, lasting for 2 hours, with a maximum intensity of 71.05 KA/μs in absolute value. The maximum 1-h rainfall was 16.8 mm (Shahu station, 17:18:00, Beijing time, same below).

The Helan Mountains are oriented north-south (Figure 1a), the mountains are asymmetrical from east to west, the western side has a gentle slope, the northwest and southwest are connected to the desert, the climate is dry and precipitation is scarce. The eastern side has interlocking cliffs and valleys with large slopes. The eastern foot is located between Helan Mountain and Yinchuan Plain, with relatively low altitude terrain and relatively good vegetation, and the average annual precipitation is 200mm. The weather system is easy to strengthen when it goes over the Helan Mountains into Ningxia due to the topographic uplift.

From 13 to 21 h on June 17, convective precipitation occurred successively in the Ningxia plain located at the eastern foothills of Helan Mountains under the influence of the eastward shift of the Biao line, with the accumulated precipitation amount ranging from 5 to 18 mm (Figure 1b). During this process, 42 ground flashes occurred in north-central Ningxia (Fig. 1c, LI is lightning intensity; LS is lightning steepness). 17:39:26, a maximum ground flash intensity (absolute value) of 71.05 kA/μs occurred in Pingluo County, and the simultaneous 1-h rainfall at the Shahu meteorological station in Pingluo County reached 16.8 mm, which is consistent with the study related to the fact that lightning was mainly concentrated in the area with the strongest precipitation.
3.1.2 Evolution of single station meteorological elements. The minute-by-minute observation data from the Shahu weather station was selected at 15:30-18:30 on June 17 to analyze the characteristics of the changes in air pressure, temperature, relative humidity, wind speed and other meteorological elements during the squall line transit (Figure 1d).

At 15:30, the pressure at this station dropped slowly and evenly from 883.0 hPa to 881.9 hPa at 16:41, a drop of 1.1 hPa. As the squall line approached, the pressure surged all the way up. 17:06, the pressure rose to a maximum of 885.1 hPa, an increase of 3.2 hPa, and then the pressure remained at about 885 (±0.1) hPa. The high pressure was maintained for 34 minutes until 17:40.

From 16:52 to 17:25, the temperature dropped steeply from above 27 ℃ to 16.8 ℃ in 33 minutes, and then maintained at 17-18 ℃. The surface temperature plummeted to 19.1 ℃ from 55.4 ℃ before the squall line transit, and the convective cold pool effect contributed to the rapid decrease in surface temperature.

From 15:30 to 16:54, the relative humidity was maintained between 30% and 36%. As the squall line approached, the relative humidity soared, reaching 84% at 17:44, an increase of more than a factor of 1. After the precipitation appeared, the relative humidity remained at around 70%.

Between 15:30 and 16:46, the average wind speed was between 2 and 4 m/s. As the squall line approached, the wind direction gradually changed from southeast to east, and the wind speed dropped briefly from 2.0 m/s to 1.3 m/s. Then the wind speed increased sharply, with a maximum peak of 15.2 m/s at 16:58, and the wind direction changed to northerly, with a transient great wind speed of 21.1 m/s.

3.2 Circulation background and influence system
On the 500 hPa high altitude map at 08:00 on June 17, there were two troughs and one ridge in the middle and high latitudes of the Eurasian range, with a trough to the northwest of Lake Balkhash (Bahu), a cold vortex to the east of Heilongjiang, and a weak high-pressure ridge maintained to the west of Ningxia to Xinjiang, with Ningxia in the northwest airflow in front of the high-pressure ridge
(Figure 2a). At the time, cold air from the bottom of the cold trough of Bahu continuously spreads eastward, and cold air along the northwest airflow in front of the high-pressure ridge rapidly slides down to affect Ningxia. On the 500 hPa temperature field, the temperature difference from north to south in Ningxia reaches -8 °C, the temperature field upstream of Ningxia lags behind the height field, and there is obvious cold advection, which is favorable to the development of convection. On the 700 hPa altitude map (figure omitted), the eastern part of the northwest region is controlled by a temperature ridge with a central temperature maximum of 13 °C. There is a shear line in the north-central Inner Mongolia-North Alashan-Menggu-North-central Gansu line, and there is obvious warm advection. A warm ridge with a central intensity of 27 °C exists in the upper reaches of Ningxia on the 850 hPa high altitude map (figure omitted). There is a shear line in the northwest direction of Inner Mongolia - northwest direction of Gansu, the wind speed dispersion area in Ningxia, the relative humidity is low. The squall line formed at 16:00 and started to affect the northern part of Ningxia. The low and mid-level weather system showed an obvious forward structure (Figure 2b), and the position of the squall line was basically consistent with the direction of the 700 hPa shear line in combination with the radar echo combination reflectivity analysis.

![Weather chart at 500hPa of at 08:00 (a), weather systems at 08:00 and radar composite reflectivity at 16:57 (b) on 17 June 2020](image)

The analysis shows that the 850 hPa and 700 hPa shear lines are significantly behind the 500 hPa cold trough, and the horizontal distance of the 850 hPa warm shear line is about 140 km behind the 700 hPa warm shear line, while the 700 hPa warm shear line is about 170 km behind the 500 hPa cold trough. The cold advection exists in the upper level and the warm advection exists in the middle and low level, and the atmospheric stratification is unstable, which is favorable to the development of convection and the formation of squall lines.

3.3 Physical field diagnostic analysis
From the sounding chart of Yinchuan Meteorological Station at 08:00 on June 17 (Picture omitted), It can be seen there are obvious convective instability energy and convective suppression energy in the middle and low layers. The CAPE value is 140.1 J/Kg, and the convective suppression CIN value is 155.5 J/Kg. The disturbance of cold air can easily trigger the occurrence of convective weather. The temperature dew point difference of 850 hPa is 3 °C, the temperature dew point difference of 700 hPa is 6 °C, and the temperature dew point difference in the gas layer is maintained between 6-12.5 °C at the height of 2-3 km from the ground. The 0-6 km vertical wind shear vector difference is 14 m/s, and the vertical wind shear vector difference between 850-700 hPa is 12 m/s, indicating that there is a strong vertical wind shear in the atmospheric stratification, which is beneficial to Strong convective weather occurred. The temperature difference between 850 hPa and 500 hPa is 26 °C, indicating that the atmospheric stratification over Yinchuan Meteorological Station is unstable.

Calculate the convective weather in Ningxia and compare the convective index of the different heavy precipitation index in the 08h Yinchuan meteorological sounding data. the K index, the Showalter index SI and other related parameters all reflect the existence of convective unstable stratification over Yinchuan. Both the severe weather threat index and the storm intensity index exceeded the severe convective weather threshold. The height of free convection shows that the LFC is about 2800 m, while the altitude of Helan Mountain is 2000-3000 m, and the main peak is 3556 m.
Therefore, when the system moves eastward over the Helan Mountain, the entire convective cloud cluster will be lifted above the free convection height LFC, and the uplift of the terrain will trigger thunderstorms.

3.4 Evolution characteristics of squall line radar echo

Based on the Yinchuan Doppler weather radar data from 14:00 to 17:00 on June 17 (Figure 4), the evolution characteristics of the squall line echo were analyzed. Generally speaking, it can be divided into three stages: initial, development and maturity.

3.4.1 Initial stage. At 14:03, there was a strong convective echo about 70 km long and 25 km wide at about 138 km from Shizuishan City, Ningxia, northwest of Wuhai City, Inner Mongolia (Figure 3a). The convective echelons consisted of three small monoliths with echo strengths greater than 45-50 dBz combined, and the radar echoes at this time showed a cluster-like distribution of multi-monolithic convective storm characteristics. At 14:31, the convective echelons developed and strengthened during the movement (Figure 3b), reaching a length of about 100 km, a width of about 40 km, and an echo intensity of more than 50 dBz. Two new convective monomers with an intensity of 15-20 dBz were generated at 70 km to the southwest and 50 km to the west. This forms a backward developmental pattern of the squall line, i.e., new monomers are formed behind the direction of movement of the already generated isolated thunderstorm monomers, and the new monomers grow and merge with the old ones in front of them.

3.4.2 Development stage. At 15:05, the convective echoes located in the convective echelons continued to move eastward and press southward (Figure 3c), and the northwest-oriented convective monoliths in Alashan Meng merged to form a band of echoes about 210 km long and centered by three echoes with intensity greater than 45-50 dBz. Its influence extends eastward to the Yellow River section at the northern end of Wuhai City, Inner Mongolia. The convective monomer located 50 km to the west of Alashan Meng merges with its newborn monomer in the Tengger Desert area to the southwest to form a new band echo. 15:33, the two echo bands merge into a narrow band squall line in the northeast-southwest direction during the movement to the southeast (Figure 3d), with a dense echo structure and well-defined contours. The shape presents a north-south asymmetric structure with a broad northern part and a slender southern comma-head pattern.

3.4.3 Maturity stage. At 16:01, the squall line crossed the Helan Mountains in northern Ningxia and continued to develop to a mature stage, forming a central intensity of 35-40 dBz and a multi-unit quasi-linked echo band of 300 km in length (Figure 3e). The local radar echo reflectivity from Wuhai City to Shizuishan City is greater than 50 dBz. The squall line started to affect Wuhai City, Inner
Mongolia and its surrounding area. 16:35, the northern end of the squall line had invaded Shizuishan City, Ningxia (Figure 3f), with a central intensity of 68 dBz and dramatic changes in meteorological elements. Three national meteorological stations experienced thunderstorm gusts of 8 or higher. At 16:41, as seen on the vertical profile of radar echoes (Figure 3g), the echo top height maximum was at 16 km, showing a multi-monomer pattern with an echo intensity at 65 dBz. At 16:53, the strong center in the radar echo vertical profile (Figure 3h) narrowed, and the echo top height dropped to 14 km, but the strong center echo intensity reached 68 dBz, at this time, the Shahu weather station was in the strong thunderstorm impact area. At 17:03, a strong echo appeared in Pingluo County, Shizuishan City, with a central maximum close to 70 dBz. The Shahu weather station is located in Pingluo County, which coincides with the time period of the intense weather phenomenon generated locally at the Shahu weather station. The overall direction of movement of the squall line was northwest-southeast, sweeping across the north-central region of Ningxia. The squall line affected northern Ningxia for up to 2 hours, and the system moved out of Ningxia around 20:00.

4. Conclusions

(1) The strong convective weather has typical squall line characteristics: squall line transit, sudden changes in wind direction, wind speed increased sharply, the pressure surged, the temperature dropped steeply, that is, the meteorological elements occurred more obvious changes. In particular, the squall line system in moving to the northern Ningxia Pingluo County Shahu weather station near the location of large lakes and wetlands, the afternoon near-surface moisture conditions are better, resulting in short-term heavy precipitation, thunderstorms and high winds and other strong convective weather, which is the most important reason for the process to become the center of the strongest.

(2) The squall line process is the cold air diffused from the bottom of the cold low pressure near Lake Balkhash in northern Xinjiang, guided by high altitude northwest airflow, moving south eastward in north central Ningxia triggered the formation of a mesoscale convective system squall line is formed in the form of backward development type.

(3) 850 hPa, 700 hPa shear line position is significantly behind the 500 hPa cold trough, high altitude influence system showing a forward structure, and the upper levels of cold advection, the middle and lower levels of warm advection, the atmospheric stratification is not stable, these are the squall line formation, the development of dynamic conditions.

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