Causes of a Heavy Snowfall Process in Eastern Yunnan in 2022

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Abstract Based on NCEP/NCAR reanalysis data, Micaps data and ground observation data, the physical characteristics of a heavy snowfall process in eastern Yunnan from January 31 to February 3, 2022 were analyzed. The results show that the circulation background of the heavy snowfall process was "north-ridge and south-trough" type, and the cold air accumulated in the deep East Asian transverse trough. The cold advection behind the trough moved southwards into eastern Yunnan under the movement of the transverse trough. The establishment of upper and lower air jet provided abundant water vapor, and the snowfall area coincided with the strong water vapor convergence area. The strong cold center near the ground was maintained, and the cold air moved southwards. As a result, the cold pad was lasting and deep, and the ground temperature was 0 ℃ or below, which was conducive to snow accumulation on the ground. Seen from the spatial distribution of pseudo-equivalent potential temperature, the low layer always had certain warm and wet conditions during the heavy snowfall, which was conducive to the establishment of unstable energy. The snowfall occurred near the θ_{se} steep area and the warm and wet unstable area. The vertical distribution of temperature had a good indication of precipitation form. The upper layer was controlled by strong cold advection, while the middle and lower troposphere was controlled by warm advection, and there was a warm inversion layer, which was conducive to the transformation of ice crystals into snowflakes, so that ice crystals fell to the ground in the form of snowflakes.

Key words Heavy snowfall; "North-ridge and south-trough" type; Torrent; Characteristics of physical quantities

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Qujing City, which is located in the east of Yunnan Province and the middle of Yunnan – Guizhou Plateau, is adjacent to Guizhou Province and Guangxi Zhuang Autonomous Region in the east, so it is known as the "throat of Yunnan". In terms of terrain, it is high in the northwest and low in the southeast. Because it is located in the low-latitude plateau, the topography and complex terrain of the plateau lead to complex and diverse types of climate, and the vertical difference is obvious. It has unique characteristics of the plateau three-dimensional climate.

In the winter half year, cold air frequently affects Qujing, and strong cold air will cause severe weather such as snowstorm and low-temperature freezing, which will have adverse effects on electricity, agriculture, transportation and people's daily life. Many domestic meteorologists have studied and analyzed the cold air[1 – 5], and the southbound cold air mainly invades the east of Yunnan from the northeast and east. For instance, Yao Yu *et al.*[6] analyzed cold air activities in the winter half year in Yunnan from 1961 to 2014, and found that the three types of cold air affecting Yunnan in the winter half year were general cold air, strong cold air and cold wave. The regions affected by cold air with different intensity also had obvious differences due to terrain and other factors. Hai Yunsha and Tao Yun *et al.*[7 – 8] studied the activity regularity of cold wave in Yunnan for many years, and found that cold wave mainly occurred in the winter half year, and had a significant correlation with temperature and precipitation; the frequency of cold wave tended to decrease. Domestic scholars[9 – 12] made certain studies on the high-low and low-space circulation situation, physical quantity characteristics, falling area and disaster of heavy snowfall, and pointed out that the occurrence of heavy snowfall required sufficient water vapor sources, strong vertical upward movement and long duration. Liu Yulian *et al.*[13] analyzed the climatic characteristics of heavy snowfall in China during 1961 – 2014, and found that there were obvious differences in the influence of geographical environment characteristics on the distribution of heavy snowfall in China, among which the heavy snowfall events in the eastern Tibetan Plateau mainly occurred in early winter and early spring. Zhang Tengfei *et al.*[14] analyzed a heavy snowfall process in 2004, and pointed out that the cooperation between strong cold air and the south trough during the heavy snowfall process in the low-latitude plateau was crucial. Tao Yun and Duan Changchun *et al.*[15 – 17] made a statistical analysis on the formation causes and changing characteristics of snowfall processes in Yunnan. It was found that the frequency of snowfall in Yunnan showed a significant decreasing trend, and the snowfall processes were mainly caused by three circulation patterns, including north ridge and south trough (50%), north transversal trough with south trough (30%), and north transversal trough without south trough (20%). The three types of cold air that caused snowfall all invaded from the northeast of Yunnan.

In this paper, based the actual data and reanalysis data of snowfall in eastern Yunnan (103° – 105°E, 24° – 27° N), the

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physical characteristics of a heavy snowfall process from January 31 to February 3, 2022 was analyzed to further understand the physical mechanism of the occurrence of heavy snowfall in eastern Yunnan and provide basis for future meteorological forecast.

1 Actual situation of weather

From January 31 to February 3, 2022, low temperature weather with rain and snow occurred in Qujing City from north to south, and severe snowstorm and local severe snowstorm happened in the central and northern regions, while light snow or sleet appeared in the other regions. This process was characterized by large cooling range, large amounts of rain and snow, long duration and wide range. The lowest temperature in the center and north of the city was 0 ℃ or below, among which the lowest temperature in Huize, Xuanwei, northern Zhanyi and northwestern Fuyuan was −2 ℃ or below. The lowest temperature in the stations appeared in Dahai Caoshan of Huize, only −7.4 ℃ (Fig. 1a), while the lowest temperature in the urban stations was −3.6 ℃, appearing in Huize (Table 1). The maximum daily precipitation (rain and snow) appeared in the urban area of Xuanwei on February 2, reaching 27.6 mm. The maximum hourly precipitation intensity appeared at 05:00 on the 2nd, up to 6.4 mm. The maximum accumulated precipitation was 30.2 mm, appearing in the urban area of Xuanwei (Table 1). The maximum snow depth was up to 14.0 cm in Xuanwei, 11.0 cm in Fuyuan, 10.3 cm in Huize, 7.0 cm in Qilin, 4.9 cm in Zhanyi, and 3.7 cm Malong (Table 1). At 08:00, the snow depth of the urban stations in the counties of Qujing was ordered as follows: February 3, February 2, and January 31.

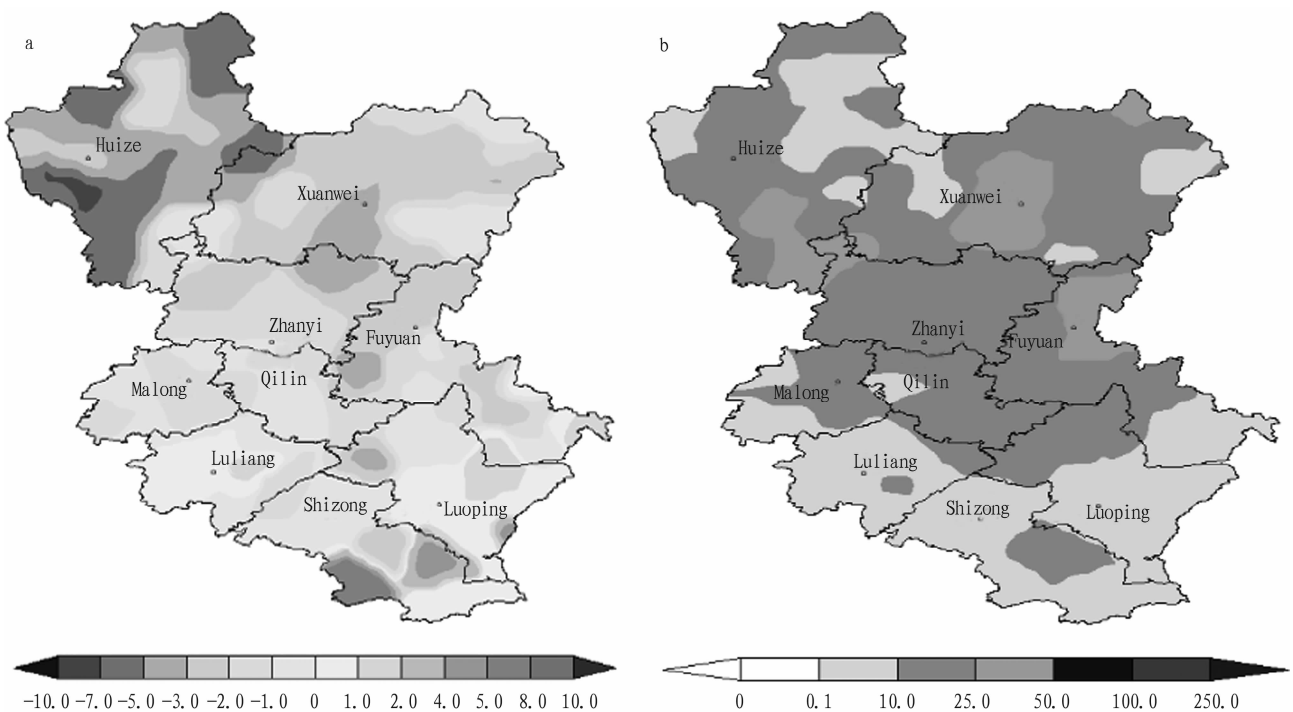

Fig. 1 Distribution of the minimum temperature (a, unit: ℃) and cumulative rainfall (b, unit: mm) from 20:00 on January 31 to 20:00 on February 3 in 2022

Table 1 Precipitation and minimum temperature in each county of Qujing from January 31 to February 3 in 2022

County	Precipitation mm	Minimum temperature//℃	Maximum snow depth//cm
Qilin	9.0	−0.5	7.0
Xuanwei	30.2	−2.8	14.0
Fuyuan	25.9	−1.5	11.0
Luoping	5.9	0.6	0
Shizong	0.3	−0.8	0
Huize	13.2	−3.6	10.3
Malong	10.7	−1.5	3.7
Luliang	2.3	0.8	0
Zhanyi	10.8	−0.8	4.9

Table 2 Snow depth in each county of Qujing at 08:00 from January 31 to February 3 in 2022 cm

County	January 31	February 2	February 3
Qilin	0	2.0	7.0
Xuanwei	1.0	11.0	13.0
Fuyuan	0.5	9.0	11.0
Luoping	0	0	0
Shizong	0	0	0
Huize	0	0	10.3
Malong	0	0	3.7
Luliang	0	0	0
Zhanyi	0	0.5	4.9

2 Analysis of weather situation

2.1 Analysis of upper air circulation

2.1.1 Circulation characteristics at 500 hPa. Fig. 2 shows the average circulation situation at 500 hPa during the cold wave snowfall process. In the middle and high latitudes, the key area of the main system affecting winter weather in Yunnan had "north-ridge and south-trough" circulation. The ridge area was at 80° – 110° E. The East Asian transverse trough was on the east side, and the deeper East Asian transverse trough was conducive to the accumulation of cold air. The slow movement of the transverse trough was conducive to guiding the cold advection move southwards into eastern Yunnan. Meanwhile, a small trough fluctuated over the Tibetan Plateau in low latitudes, and there was an obvious southern trough over the Bay of Bengal. In middle and high latitudes, the continuous flow of cold air to the south and the confluence of strong southwest warm and wet air in front of the south branch trough was one of the necessary conditions for the strong rain and snow weather in Qujing.

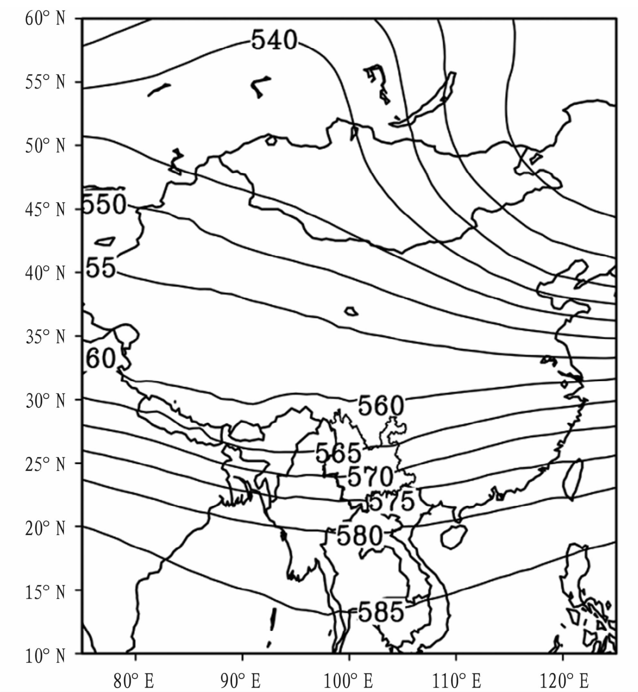

Fig. 2 Average geopotential height (unit: dagpm) at 500 hPa from January 31, 2022 to February 3 in 2022

Seen from the high-altitude circulation at 500 hPa at 20:00 on January 30 before the beginning of this process (the figure is omitted), the deep East Asia trough was accompanied by a closed cold center of –44 ℃, and there was a closed cold low-pressure circulation of 528 dagpm in Inner Mongolia, with a cold center intensity of –44 ℃. There was a closed cold center of –40 ℃ in the Lake Baikal – Siberian Plateau in front of the high-pressure ridge, a strong high-pressure ridge behind the trough, a strong cold center in front and bottom of the trough. At the beginning of the process, the northwest air in front of the trough led the cold advection move southwards. During the development of the process (Fig. 3a and Fig. 3b), the high-pressure ridge moved slowly eastwards. The northerly air guided the low vortex in front of the high-pressure ridge to move southeastwards and merge with the East Asian Great Trough, and moved slowly southwards. Cyclones formed in the south of the Qinghai – Tibet Plateau, which was conducive to the accumulation of a large number of cold air, and it gradually moved eastwards. The south branch trough near 90° E moved eastwards with the strengthening of the northwest airflow, and further affected Qujing. During the outbreak of the process (Fig. 3a and Fig. 3b), the East Asia Great Trough deepened and continued to move southwards, guiding the cold air to the south. The upper air jet in front of the south branch trough moved eastwards, and the warm and wet jet in the southwest exceeded 30 m/s. At 20:00 on February 2, the south branch trough was located in the center of Yunnan, and the warm and cold advection at 500 hPa intersected from Sichuan to Hubei.

2.1.2 Circulation characteristics at 700 hPa. As shown in Fig. 4, the circulation pattern at 700 hPa was similar to that of 500 hPa. During the process, the cold center intensity remained at –28 ℃. At 08:00 on the 1st, the isotherm of –4 ℃ was located in the south of Zhaotong. On the 2nd, the isotherm of –10 ℃ was located in the north of Zhaotong, and the isotherm of –4 ℃ was maintained in the middle of Qujing. The temperature of Qujing was maintained between –6 and –2 ℃, which was conducive to the occurrence of snowfall. In winter, cold air gathered in the Qinghai – Tibet Plateau, and the maintenance of cold sources was conducive to the strengthening of southwest air flow in the south side of the plateau. The southwest low-level jet formed in the Bay of Bengal, with an intensity of 25 m/s. The strong southwest jet continuously transported water vapor from the Bay of Bengal to Qujing. As the cold air after the East Asian great trough moved southwards and converged with the southwest jet stream in the Yangtze River basin to form an obvious convergence area, Qujing was located on the south side of the convergence extension line and the left side of the low-level jet stream. On the 3rd, the low level jet weakened significantly, and the process came to an end. To sum up, the maintenance of the low-level jet stream provided not only abundant water vapor but also better thermal and dynamic conditions for the rain and snow weather.

2.1.3 Surface circulation pattern. Before the arrival of strong cold air, Qujing was affected by warm advection, and the weather situation was good. As can be seen from the surface map (Fig. 1), the sub-surface cold high-pressure center 1 065 hPa was located near the Lake Baikal, and the sub-cold high-pressure center 1 040 hPa was located in Qinghai. At 20:00 on the 31st, cold air moved southwards from Inner Mongolia to affect Guizhou. Limited by topographic factors, the easterly backflow affected Qujing. The warm and humid air and easterly backflow at the lower level formed a north – south stationary front over eastern Yunnan, which had obvious diurnal variation characteristics. The position of the stationary front was stable from the 31st to 1st, and the sea level pressure in the east of the city was 1 020 hPa. Under the joint action of continuous cold air moving southwards and strong warm and humid air flow, the frontal surface swung from east to west, and the temperature changed with it. The maximum daily variation of temperature appeared in Zhanyi on the 2nd, up to –7 ℃. The sea level pressure during the strongest period 1 020 hPa was located in Kunming, and the maximum reached 1 025 – 1 027.5 hPa in the east of Qujing.

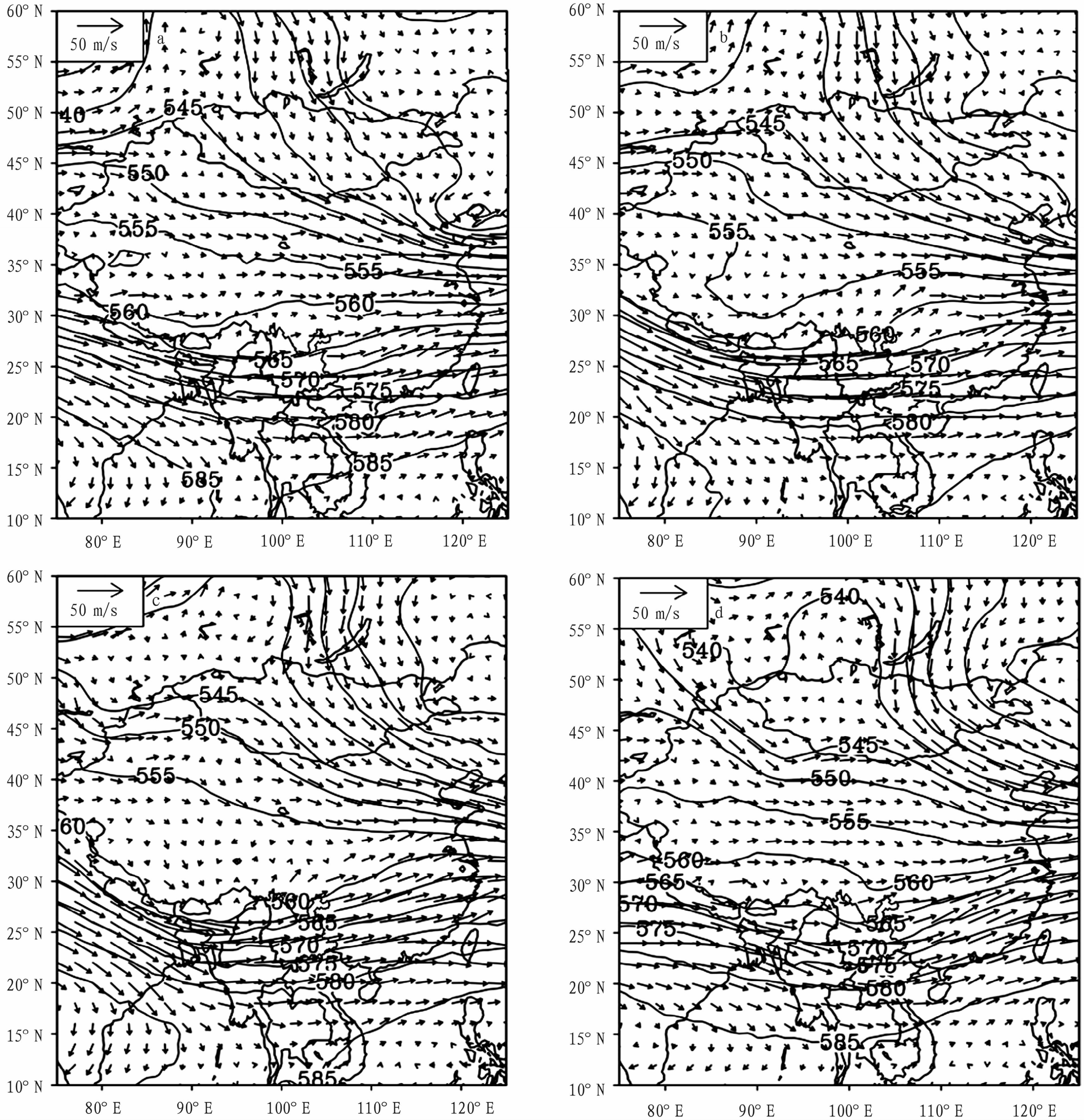

Fig. 3 Height field (unit: gpm) and wind field (unit: m/s) at 500 hPa at 20:00 (a) on January 31, 08:00 (b) and 20:00 (c) on February 1, and 20:00 (d) on February 2, 2022

Qujing was located on the east side of the frontal surface, with obvious rain and snow weather. Cold air continued to move southwards, so that the cold pad was lasting and deep. Meanwhile, the ground temperature was low, below 0℃, which was conducive to snow accumulation on the ground.

3 Analysis of water vapor conditions

Through the analysis of water vapor flux in the whole layer during the cold wave snowfall weather (Fig. 5a), it is found that the low-level jet established a water vapor channel to continuously transport water vapor from the Bay of Bengal and the South China Sea to Qujing. With the eastward movement of the low-level jet, water vapor transport was always strong during the process, which was most obvious from the night of the 1st to the day of the 2nd. The analysis of the divergence of water vapor flux (Fig. 5b and Fig. 5c) shows that the intersection of low-level jet and cold air intrusion also significantly strengthened the divergence convergence zone of water vapor flux, always showing a north – south trend, and the central intensity reached -2×10^{-7} g · (cm^2 · hPa · s). The divergence convergence zone of water vapor flux was consistent with the rainfall and snow region. It can be seen that the cold wave snowfall process had abundant water vapor conditions.

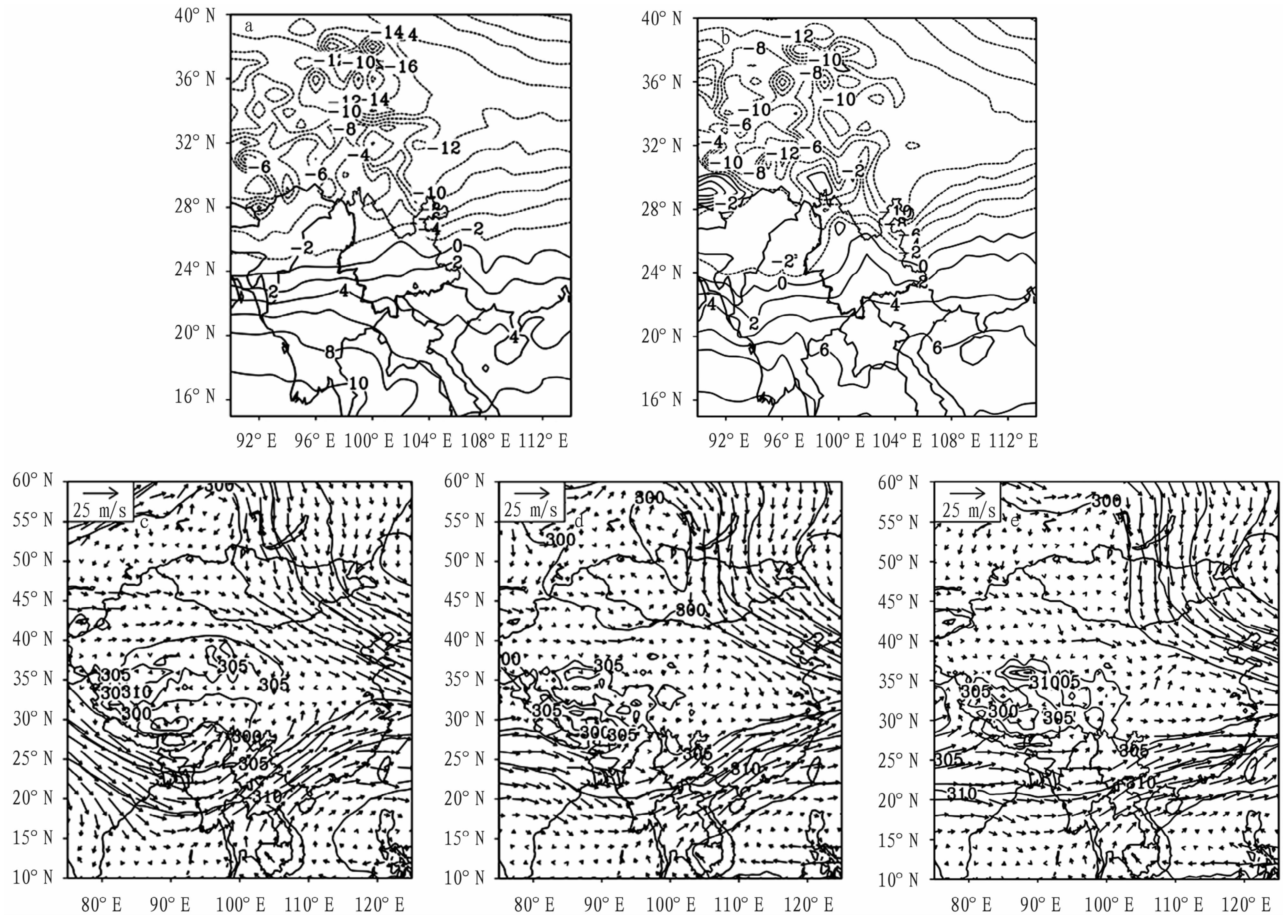

Fig.4 Temperature field (unit: ℃) at 700 hPa at 08:00 on February 1 (a) and 20:00 on the 2nd (b) as well as height field (unit: gpm) and wind field (unit: m/s) at 500 hPa at 20:00 on the 1st (c), 20:00 on the 2nd (d), and 08:00 on the 3rd (e) in 2022

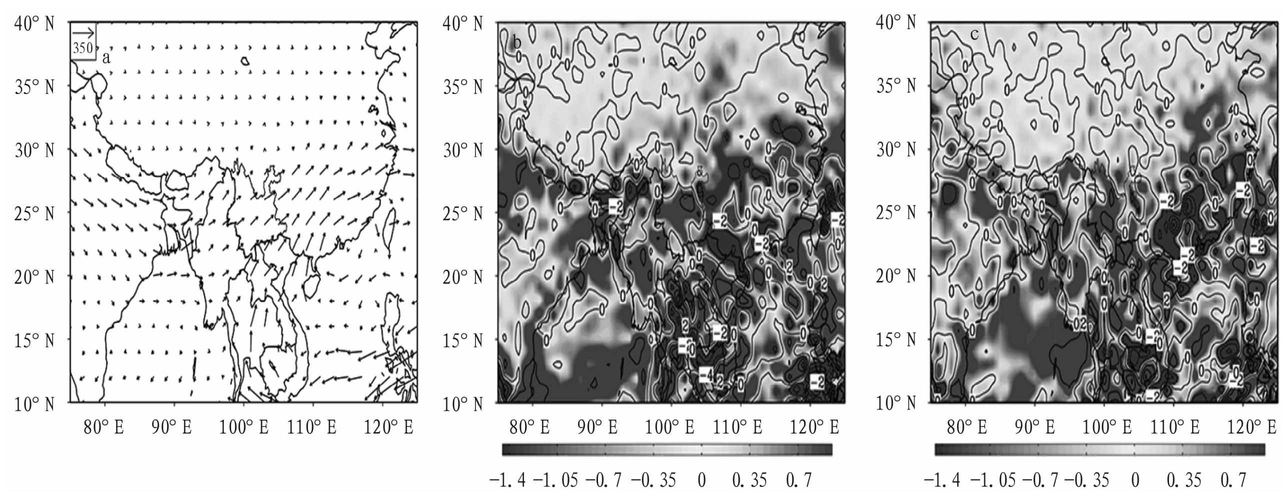

Fig.5 Water vapor transport direction (unit: m/s) at 700 hPa at 20:00 on February 1 (a) and water vapor flux divergence (unit: 10^{-8} g/(cm² · hPa · s)) at 700 hPa at 20:00 on February 1 (b) and 20:00 on February 2 (c) in 2022

4 Analysis of dynamic conditions

Under the influence of cold air, the cooperation of warm and wet air and dynamic lifting was conducive to the occurrence of rain and snow. From the analysis of vertical flow field and pseudo-equivalent potential temperature θ_{se} at 08:00 on January 30, 2022 (Fig.5), it is found that warm and wet updrafts and dry and cold downdrafts converged near the ground at 25° N, and there were obvious updrafts at 600 – 200 hPa between 24° and 25.5° N, and they were relatively deep, while there were obvious downdrafts between 26° and 27° N. It can be seen from the distribution of θ_{se} that at 08:00 on the 30th, there was an obvious steep area in the lower layer between 26.5° and 30° N, indicating that this area was in the development area of vertical vorticity[17]. On the night of the 30th, as the cold air strengthened and moved southwards, the steep area also moved southwards, and tended to be gentle. At 20:00 on the 31st, the steep area was located at 23° N and its northern area. From the night of the 31st to 20:00 of the 1st, with the strengthening of warm and humid updrafts at the lower level, the position of the steep area was raised to the north at 26° – 30° N and less moved. With the supplement of cold air, athe dynamic lifting conditions were good from the daytime of 2nd to the 3rd, and θ_{se} had an unusually steep area, affecting 23° N and its northern area at the strongest time. The warm and wet air in the south was always maintained during this period. In the early stage of the snowfall and during the snowfall process, θ_{se} decreased with the increase of the height in the area from the ground to 650 hPa in the south of Qujing, indicating that the lower layer always had certain warm and humid conditions. It can be seen that the rising and sinking movements coexisted during the snowfall process, and the strong and weak relationship led to the southward shift or less movement of the steep area, thereby providing enough dynamic lifting and condensation conditions for snowfall. The snowfall occurred near the steep area and in the warm and humid unstable area.

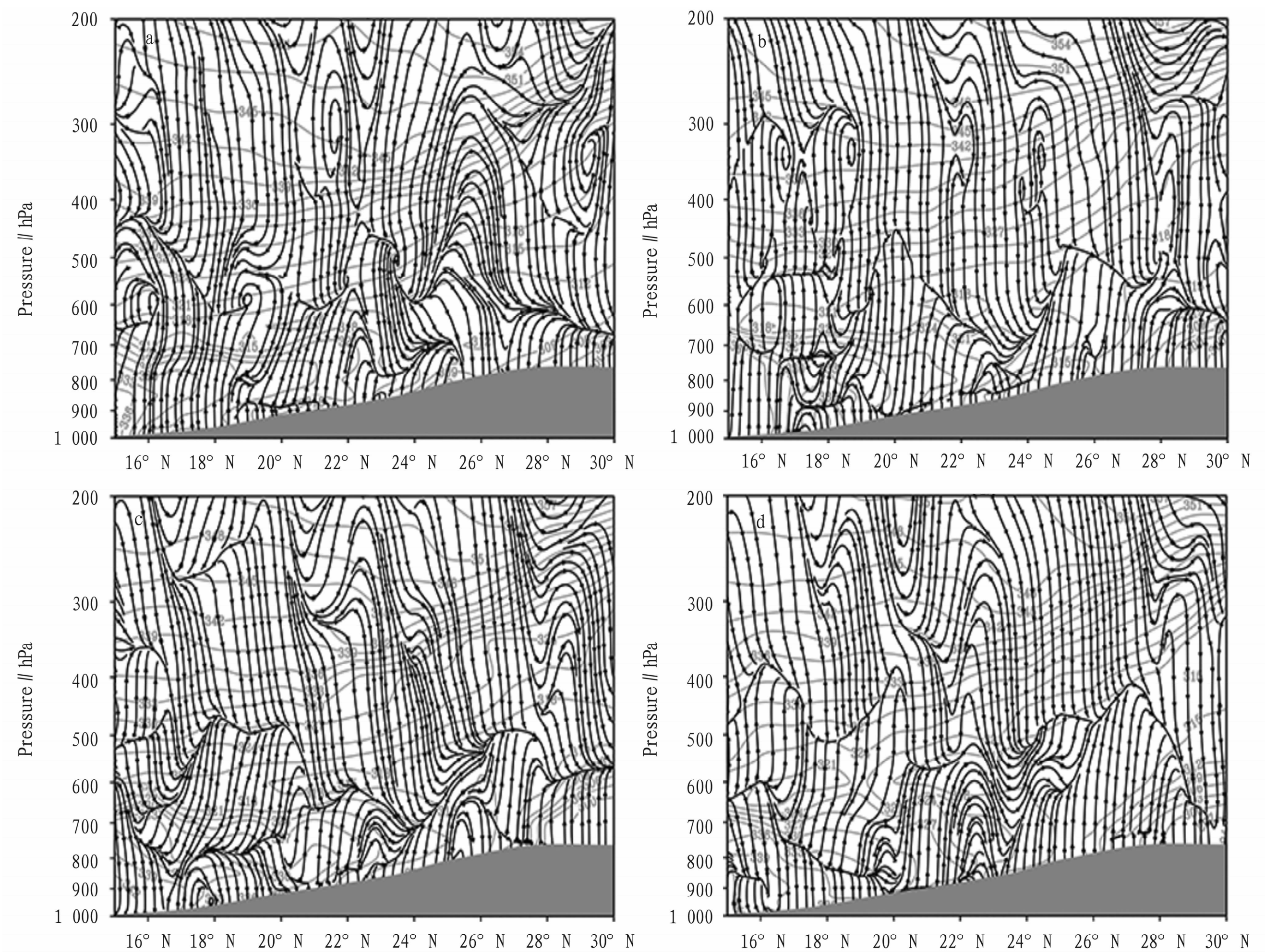

Fig. 6 Vertical flow field (flow line, unit: m/s) and θ_{se} vertical profile (dashed line, unit: K) along 103° E at 08:00 on January 30 (a), 20:00 on January 31 (b), 20:00 on February 1 (c), 20:00 on February 2 (d) in 2022

5 Analysis of thermal conditions

Fig. 7 shows the latitudinal profiles of temperature advection, vertical velocity, and full wind velocity along 103.8° E during the heavy snowfall. It is found that during the process, Qujing area was in the strong ascending movement area. In the first stage, the warm advection rose strongly at 550 – 200 hPa between 26.5° and 27° N at 20:00 on the 30th, and there was cold advection near the ground to the north of 27° N. The cold advection gradually moved southwards to affect counties (cities and districts) of Qujing. On the 31st, there was always warm advection disturbance near the ground, and the existence of low-level warm tongue provided better thermal conditions for the formation of the heavy snowfall. From 08:00 to 14:00 on February 1, the temperature over Qujing rose with the increase of height. The middle and lower troposphere was under the control of warm advection. Between 500 and 300 hPa, there was a warm inversion layer with an intensity of 3 – 6 ℃ and a thickness of about 3 500 m. The upper layer was under the control of strong cold advection, with a central intensity of 12 ℃. The temperature near 700 hPa was – 3 ℃. Ice crystals melted in the warm inversion layer during the process of falling, and continued to fall to the ground in the form of snowflakes. In other periods, the temperature from the ground to the upper level declined with the increase of height, and it was basically controlled by strong cold advection. In the afternoon of the 3^{rd}, the cold air weakened significantly, and the whole layer was basically controlled by warm advection, so that the snow tended to end.

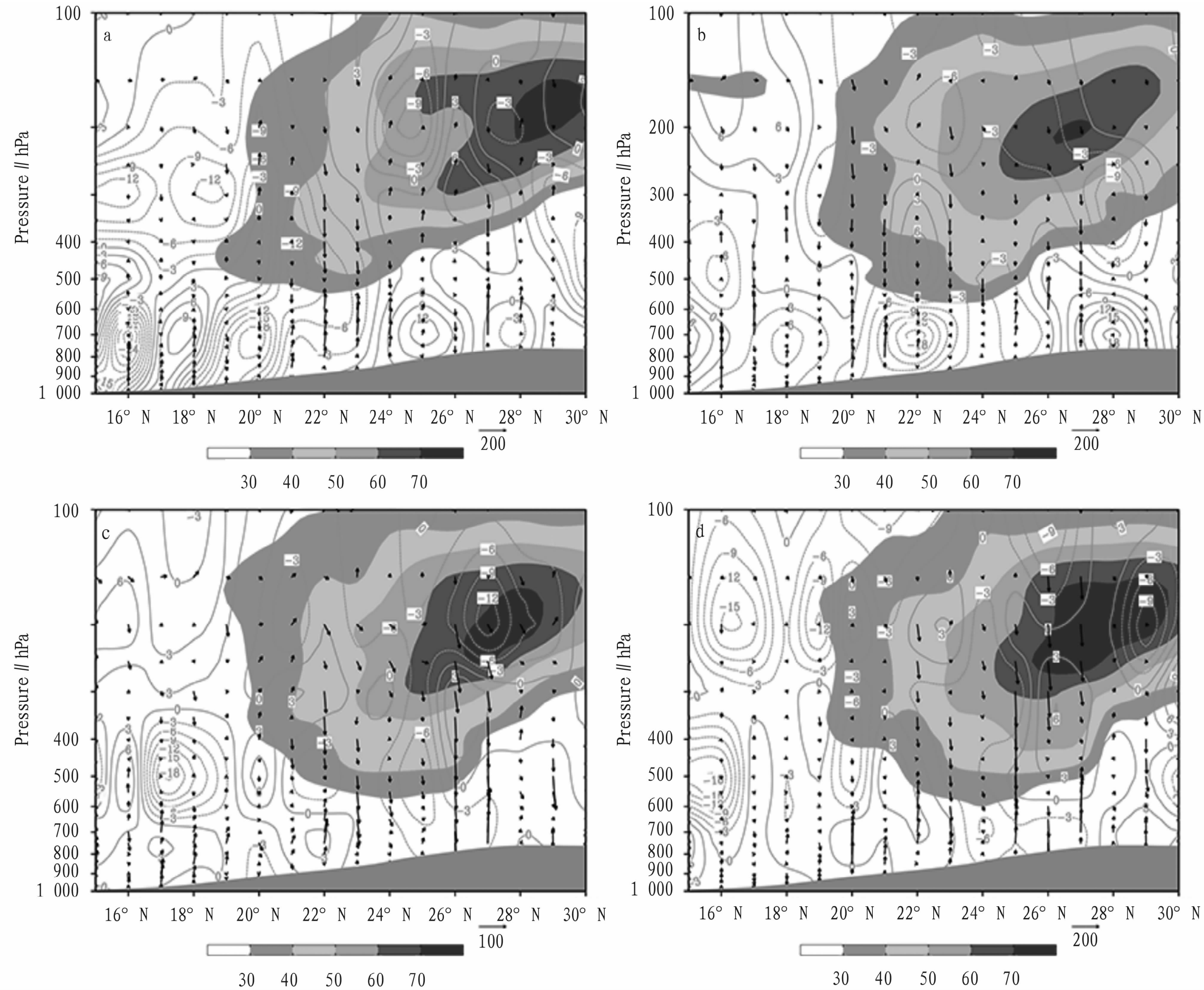

Fig. 7 Superposition charts of vertical profiles of temperature advection (black contour line, unit: K/s), vertical velocity (vector arrow, unit: m/s), and total wind velocity (color spot, unit: m/s) along 103° E at 20:00 on 30 January (a), 20:00 on February 31 (b), 08:00 (c) and 20:00 (d) on January 1 in 2022

6 Conclusions

(1) The maintenance of deep cold center in middle and high latitudes created favorable conditions for the occurrence of cold wave weather in eastern Yunnan.

(2) The circulation at 500 hPa was "north-ridge and south-trough" circulation, and was the main system affecting the winter weather in eastern Yunnan in the middle and high latitudes. The movement of the transverse trough guided the cold advection after the trough to the south, and the convergence of the strong cold air and the south branch trough in the east of Yunnan was one of the necessary conditions for the strong rain and snow weather.

(3) The – 4 ℃ isotherm over 700 hPa was maintained in the middle of Qujing, and it was between – 6 and – 2 ℃ in Qujing. The position of the – 4 ℃ isotherm was a favorable indicator for judging snowfall in Qujing, that is, it was usually the area where snow occurred. The upper and low south branch jet in the Bay of Bengal were established. The upper southern branch jet at 500 hPa

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4 Conclusions

It assists in providing relevant data for the Wuzhou Climate Yearbook every year. Due to the issues of error prone and low efficiency in manual operations, automated processing is particularly important for filling climate yearbook. In this paper, it introduces how to design a Wuzhou Meteorological Statistical Yearbook System based on Python, and briefly explains the implementation of each functional module of the system. The implementation of this system is of great significance for the statistical work of the Wuzhou Climate Yearbook.

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exceeded 30 m/s, and the lower south branch jet at 700 hPa reached 22 m/s (at the strongest time), which provided powerful thermal and dynamic conditions and abundant water vapor for the heavy snowfall weather.

(4) From the analysis of θ_{se}, it is found that the low layer always had certain warm and wet conditions during the heavy snowfall, and the rising and sinking movement coexisted. The relationship between the rising and sinking movement led to the southward movement of the θ_{se} steep area, which provided enough dynamic lifting and condensation conditions for the snowfall. The snowfall occurred near the steep area and in the warm-wet unstable region.

(5) The vertical distribution of temperature had a good indication of precipitation form. The middle and lower troposphere was controlled by warm advection, and there was a warm inversion layer, while the upper layer was controlled by strong cold advection, which was conducive to the transformation of ice crystals into snowflakes, so that they fell to the ground in the form of snowflakes.

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