Analysis of Characteristics of Snow Accumulation and Its Meteorological Influencing Factors during a Snowstorm Process in Ulanqab City

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Abstract Based on the data of national observation stations of CMISS system, artificial encrypted observation data of snow depth, ERA5 reanalysis data, the snowfall process in Ulanqab City from March 17 to 19, 2022 was analyzed. It is found that the influencing system of the snowfall process was upper-air trough combined with ground inverted trough. Snowfall was not proportional to snow depth, and the relationship between the maximum snow depth and total snowfall varied in different value intervals. A large intensity of snowfall was a necessary condition for the formation of abundant accumulated snow when ground temperature was higher than 0 ℃. After the formation of accumulated snow, ground temperature changed less, and it was easy to produce accumulated snow as ground temperature was lower. The lower the temperature, the more conducive to the generation of accumulated snow.

Key words Snowstorm; Accumulated snow; Snow-to-liquid ratio; Influencing factors

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Snow is a solid covering formed by the accumulation of snow on the ground surface. The vertical depth from the snow surface to the ground is the snow depth. It can be the sum of snow depth during one or more snowfall processes. In the field of weather, attention is paid to the change of snow depth in a short period of time, mainly including whether a snow weather process can produce snow and snow depth. At present, the simple snowfall forecast can no longer meet the demand, and the understanding, research and development of snow formation mechanism, influencing factors and forecasting technology are still in the initial stage in China, so it is difficult to provide effective scientific and technological support for forecasting business. In this paper, based on the confidential meteorological observation data near the surface, the characteristics of snow cover and its influencing factors were analyzed to provide reference for the forecast of snow depth in the future.

1 Data and methods

The data used in this study included hourly ground observation data, conventional upper-air observation data and artificially encrypted snow depth data of China Regional National Station from March 17 to 18, 2022. Snow depth was observed at 08:00, 14:00 and 20:00. In addition, ERA5 0.25° ×0.25° reanalysis data was used, and the temporal resolution was 1 h.

2 Snowfall process and its characteristics

The snowfall process occurred from March 17 to 19, 2022, and the precipitation was mostly concentrated from 02:00 to 22:00 on the 17th and from 07:00 to 22:00 on the 18th. Zhuozi County was the center of heavy precipitation, and the process precipitation was generally more than 10 mm, with the maximum of 23.7 mm in Zhuozi County. The secondary precipitation center was in Xinghe County. The maximum precipitation intensity appeared in Siziwang Banner from 07:00 to 08:00 on the 18th, and the hourly snowfall was 5.9 mm (Fig. 1).

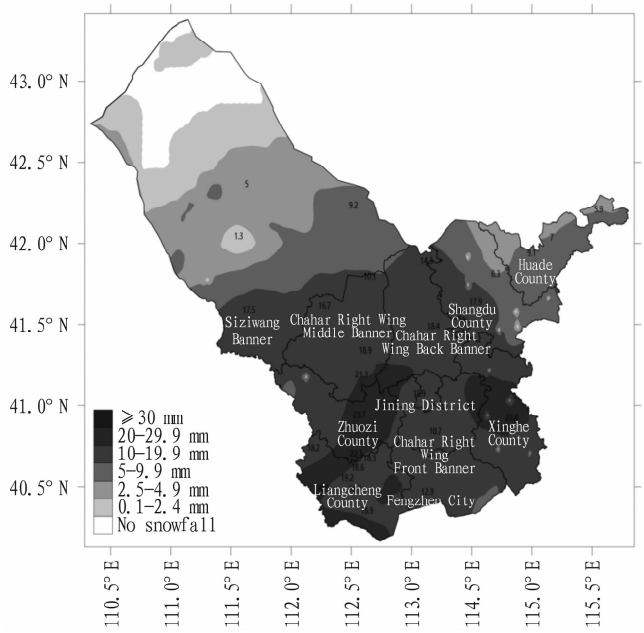

Fig. 1 Cumulative snowfall in Ulanqab from 20:00 on March 16 to 20:00 on March 18, 2022

The cumulative snowfall within 6 h was mainly 0 - 10 mm, and could reach more than 10 mm locally. Seen from snow depth,

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the newly increased snow depth within 6 h was positive or negative. The snow depth decreased by 14 cm in Chahar Right Wing Back Banner from 20:00 on the 18th to 08:00 on the 19th, and increased by 11 cm in Siziwang Banner from 20:00 on the 17th to 08:00 on the 18th, 13 cm in Chahar Right Wing Back Banner and 12 cm in Shangdu County during 08:00 – 14:00 on the 18th, respectively. From the melting ratio, it was 2.5 cm/mm in Chahar Right Wing Front Banner from 14:00 to 20:00 on the 17th, greater than 1.5 cm/mm, while the rest was less than 1.5 cm/mm, because the snow process was mainly wet snow process.

Seen from precipitation phase, the precipitation in Ulanqab started in the early morning, and the ground temperature was generally low, below 0 ℃ in most areas, so the initial precipitation phase in most areas of the city was snow. Under the influence of temperature change, 11 counties had experienced many changes of rain and snow, and some stations had a reversal of precipitation phase of rain, sleet, snow and rain. Among them, Huade County and Zhuozi County only had phase transition of snow and sleet, and there was no rain in the precipitation process.

3 Variation characteristics of snow depth

3.1 Spatial variation From the distribution of the maximum snow depth in the process, it is seen that there was snow in 11 stations in the city, and it was more than 5 cm. The snow depth in most of the eastern areas was shallower, ranging from 4 to 7 cm. The maximum snow depth was 18 cm in Chahar Right Wing Back Banner and 17 cm in Shangdu County. The maximum snow depth in Siziwang Banner, Chahar Right Wing Middle Banner and Zhuozi County was 15 cm. From the snowfall and snow depth of each station, it is found that the snowfall in Shangdu County and Chahar Right Wing Back Banner was obviously less than that of Zhuozi County and Xinghe County, but their snow depth was much greater than that of Zhuozi County and Xinghe County (Fig. 2). It can be seen that snowfall was not necessarily proportional to snow depth.

3.2 Temporal variation Seen from the temporal variation of snow depth (Fig. 3), the maximum peak was mainly concentrated during 14:00 – 20:00 on the 18th. The snow mainly fell in two periods. In the first period, there was less snow in Siziwang Banner, and snow depth was only 1cm. In the later period, the snow stopped, and the snow completely melted as the temperature rose. In the second stage, there was a short snowstorm, and snow depth increased sharply. The snow in Chahar Right Wing Middle Banner melted from 14:00 to 20:00 on the 17th, and then snowing was continued, so snow depth increased. The snow depth in Chahar Right Wing Front Banner and Fengzhen City remained stable after peaking at 20:00 on the 17th. The snow depth in other stations gradually increased, reached the maximum during 14:00 – 20:00 on the 18th, and then the snow slowly melted away. After the snow stopped in most stations, snow depth changed slightly, and remained basically stable until 08:00 on the next day. However, the snow in Chahar Right Wing Back Banner melted at night, and snow depth dropped greatly by 08:00 on the next day. It can be seen that in the process of snowfall, the changes of snow depth in different regions were different.

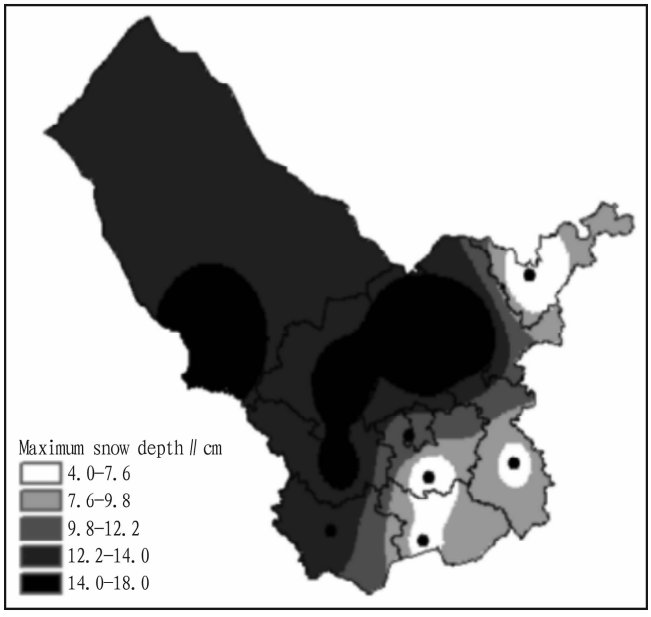

Fig. 2 Maximum snow depth in Ulanqab from 20:00 on March 16 to 20:00 on March 18, 2022

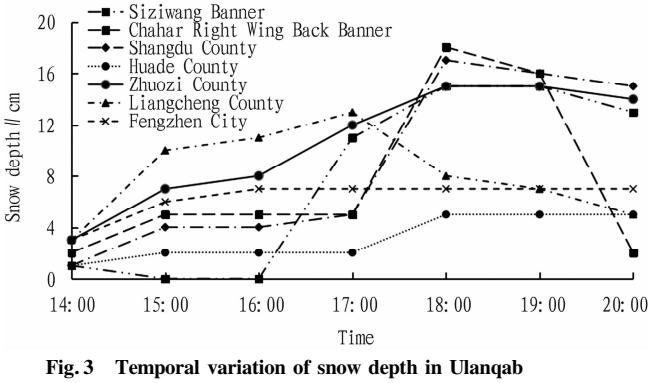

Fig. 3 Temporal variation of snow depth in Ulanqab

4 Influencing factors of snow depth

4.1 Relationship between snowfall and snow depth

4.1.1 Characteristics of changes in snow-to-liquid ratio. The average of snow-to-liquid ratio in each station from 08:00 on the 17th to 08:00 on the 18th was 0.63 cm/mm. Seen from spatial distribution, there were significant differences in different regions. Among them, snow-to-liquid ratio was less than 0.4 cm/mm in Huade County and Xinghe County and greater than 0.8 cm/mm in Siziwang Banner, Shangdu County, and Jining District. In the city, the maximum was up to 0.92 cm/mm, appearing in Siziwang Banner, while the minimum 0.34 cm/mm appeared in Xinghe County (Fig. 4).

Among the 11 stations, the snow-to-liquid ratio in most areas first increased, then decreased, and finally increased again. Xinghe County and Fengzhen City had a large range of changes. Among them, from 02:00 to 08:00 on the 17th, the cumulative snowfall in Siziwang Banner was 2.0 mm, with less snowfall. Snow depth was only 1 cm, and snow-to-liquid ratio was 0.5 cm/mm. From 06:00 to 08:00 on the 18th, there was a short-term snowstorm,

and cumulative snowfall reached 10.9 mm. As a result, there was a sudden increase in snow depth, with an increase of 11 cm, and snow-to-liquid ratio was 1.0 cm/mm. From 09:00 to 20:00 on the 18th, cumulative snowfall was 4.6 mm, and the newly increased snow depth was 4 cm; snow-to-liquid ratio was 1.15 cm/mm, reaching the maximum in this period.

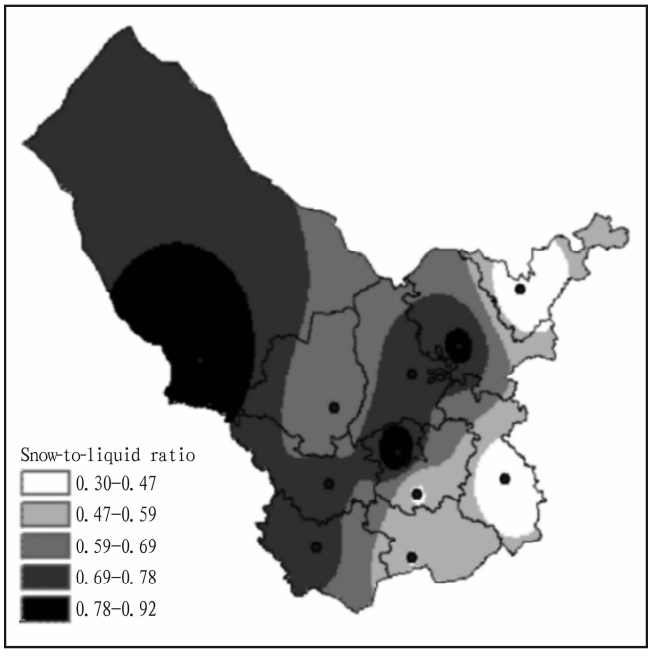

Fig.4 Snow-to-liquid ratio in Ulanqab City from 08:00 on March 17 to 18:00 on March 18 in 2022

4.1.2 Relationship between total snowfall and snow depth. Fig.5 shows the relationship between total snowfall and maximum snow depth in each station in the city from 08:00 on the 17th to 20:00 on the 18th. It can be seen that there were certain differences in the relationship between maximum snow depth and total snowfall in various numerical ranges. On the whole, the greater the snowfall, the deeper the snow. However, as the snowfall and snow depth increased, the dispersion between the two gradually increased. Snow depth was mainly divided into three intervals: 0–5, 5–15, and 15–25 cm. Among them, the correlation was the strongest at 0–5 cm and the smallest at 15–25 cm. When total snowfall was the largest, snow depth was actually small, and the maximum snow depth occurred at 15–20 cm. It can be seen that snowfall was not directly proportional to snow depth. From the correlation between total snowfall and snow depth in various stations in the city, it is found that their correlation coefficient was 0.69. Linear fitting was performed using the least squares method, and the fitting equation obtained was $Y=0.632\,5X$, indicating that the ratio of snow depth to snowfall in various regions of Ulanqab City during this snowfall process was 0.63.

4.1.3 Impact of snowfall intensity on snow depth. During this snowfall process, when snow began to happen in the 11 stations, 2 m temperature was below 0 ℃, ranging from −6.7 to −1.4 ℃. The ground temperature changed from −4.1 to −0.1 ℃, and the maximum appeared in Fengzhen City, up to −0.1 ℃. As snow accumulated, 2 m temperature was below 0 ℃, but 2 m temperature in the eastern region increased compared with the initial snowfall; the ground temperature in the entire city was around 0 ℃. It was above 0 ℃ in the southern region and below 0 ℃ in the northern region and Zhuozi County. Among them, the lowest temperature in Huade County was around −2.9 ℃. When snow accumulated in each station in the city, the ground temperature was higher than the initial snowfall.

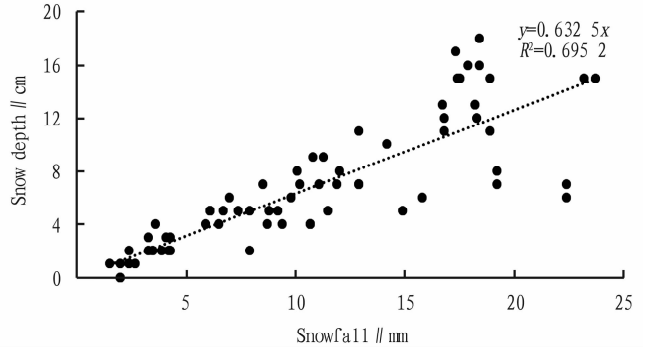

Fig.5 Relationship between total snowfall and snow depth

Although the ground temperature in the southern region was higher than 0 ℃, 2 m temperature was lower than 0 ℃. Before the appearance of snow, the hourly snowfall in the southern region was about 1 mm, but snow depth was shallow. At 05:00 on the 17th, the snow in Siziwang Banner accumulated, and both the air temperature and the ground temperature gradually rose. From 05:00 to 08:00, snowfall continued but was weak. At 08:00, the ground temperature rose to 0.1 ℃, and the snow began to fall intermittently; snow on the ground began to melt, so there was no change in snow depth. After 09:00, the ground temperature gradually rose, and the highest temperature reached 12.7 ℃. After the occurrence of snowfall in Liangcheng County, both the air temperature and the ground temperature gradually increase, and the ground temperature was always about 0 ℃. The hourly snowfall from 06:00 to 08:00 was 1.0, 1.1 and 1.9 mm, respectively, so snow depth was 3 cm at 08:00.

The reason may be that snowfall started in the early morning, and the temperature was lower than 0 ℃, so the snowfall phase in the whole city was snow. Meanwhile, the ground temperature was lower than 0 ℃, and the snowfall was strong. The snow that fell to the ground would not melt, and the subsequent snow accumulated layer by layer. On the contrary, if the temperature was lower than 0 ℃, but the ground temperature was above 0 ℃, and the hourly snowfall was about 0.3 mm/h, the snowfall was weak. Snow depth did not change after snow accumulated in the early stage. If the ground temperature was above 0 ℃, but snowfall was strong, and the snow that fell to the ground had no time to melt. The subsequent snow accumulated on the surface of melted snow.

It can be seen that the intensity of snowfall had an effect on snow depth, and the high intensity of snowfall was the necessary condition for producing abundant snow when the ground temperature was higher than 0 ℃.

4.2 Effects of ground temperature on snow depth Based on the data of 0 cm ground temperature and snow cover in various sta-

tions in the city, the threshold of ground temperature at the time of snow cover, the change of ground temperature before and after the appearance of snow cover, and its influence on snow depth cover were analyzed.

4.2.1 Characteristics of ground temperature before and after the appearance of snow cover. When snow began to accumulate, the 0 cm ground temperature in various stations in the city was −2.9 – 0.6 ℃, mainly concentrated at about 0 ℃. Among them, the 0 cm ground temperature in 10 stations was ≤0 ℃, and only the ground temperature in Chahar Right Wing Front Banner was 0.6 ℃.

From the changes in ground temperature before and after the formation of snow cover, it is found that the ground temperature in all stations increased or was stable. The snowfall in Siziwang Banner came to an end after 08:00 on the 17th. Under the influence of sunlight, the ground temperature rose sharply, and the snow melted completely. In the other regions, during the duration of accumulated snow, due to the low thermal conductivity of snow, the snow layer obstructed the heat loss of the surface soil and the heat change caused by the temperature change above the snow surface, playing the role of heat insulation. Therefore, the ground temperature changed little after the formation of accumulated snow, and the range of change was within 0.2 ℃, indicating that the formation of accumulated snow had an impact on the ground temperature.

4.2.2 Effects of ground temperature on snow depth. According to the 24-h snow-to-liquid ratio and newly-increased snowfall from 08:00 on the 17th to 08:00 on the 18th, the stations in the city were divided into three categories. The first type included Chahar Right Wing Front Banner, Xinghe County and Fengzhen City, with the newly-increased snowfall of above 5 mm and snow-to-liquid ratio of less than 0.5 cm/mm. The second type included Chahar Right Wing Back Banner and Shangdu County, where the newly-increased snowfall was less than 5 mm and snow-to-liquid ratio was more than 0.5 cm/mm. In the third type of stations, snow-to-liquid ratio was proportional to newly-increased snowfall. The first type of stations were mainly distributed in the southern area of the city, with a large amount of newly-increased snowfall but less newly-increased accumulated snow. The second type of stations were mainly distributed in the north of the city, with a small amount of newly-increased snowfall but a large amount of newly-increased accumulated snow.

It is found that in the first type of stations, 0 cm ground temperature was −0.3 – 0.4 ℃ before the formation of accumulated snow and −0.1 – 0.6 ℃ during the formation of accumulated snow. Within 6 h after the formation of accumulated snow, the ground temperature in Chahar Right Wing Front Banner gradually decreased, and the ground temperature in Xinghe County and Fengzhen city was maintained at 0.1 and 0 ℃. In the second type of stations, ground temperature was −1.6 – −3.1 ℃ before the formation of accumulated snow and −2.2 – −2.9 ℃ during the formation of accumulated snow. Within 6 h after the formation of accumulated snow, ground temperature gradually rose gradually in the first three hours, and then the ground temperature was maintained at −0.1 and 0 ℃. In the third type of stations, 0 cm ground temperature ranged from −4.1 to −0.1 ℃ before the formation of accumulated snow and from −2.9 – 0 ℃ during the formation of accumulated snow. Within 6 h after the formation of accumulated snow, ground temperature gradually increased. It can be seen that the ground temperature in the first type of stations was obviously higher than that of the second type before the formation of accumulated snow. When snow accumulated, the ground temperature of the first type of stations was higher than that of the second type. 6 h after the formation of accumulated snow, among the first type of stations, the ground temperature in Chahar Right Wing Front Banner gradually declined, and the rest remained stable. In the second type of stations, the ground temperature gradually increased in the first three hours and remained stable in the last three hours. After stable maintenance, the ground temperature in the first type of stations was higher than that of the second type of stations. As the ground temperature was high, most of the snow melted, and it was easy to produce accumulated snow when the ground temperature was low. However, because there were only 11 snow observation stations, it is not possible to obtain the threshold of ground temperature for significant melting of snow in Ulanqab City based on the available data.

5 Conclusions and discussion

5.1 Conclusions Based on the observation data of 2 m temperature, ground temperature, 2-min average wind speed, 10-min average wind speed, snowfall, phase states of precipitation such as hourly rain, sleet and snow identified by the precipitation viewing instrument, artificial encrypted observation data of snow depth, and ERA5 reanalysis data of 11 national observation stations in Ulanqab City from March 17 to 19, 2022 in CMISS system, the snowfall process in Ulanqab City from March 17 to 19, 2022 was analyzed, and the following conclusions were reached.

(1) The influencing system of the snowstorm process was the high-altitude short-wave trough with the ground inverted trough, and low-altitude shear line and jet stream. Snowstorm appeared in Ulanqab City, and it was heavier in the the south than the north.

(2) During the snowfall process, snowfall was not proportional to snow depth. After snowfall stopped in most stations, snow depth changed slightly, and remained basically stable until 08:00 on the next day. However, the snow in Chahar Right Wing Back Banner melted at night, and snow depth reduced greatly by 08:00 on the next day.

(3) The average of snow-to-liquid ratio in various stations in the city was 0.63 cm/mm, and there was a big difference in spatial distribution.

(4) The relationship between the maximum snow depth and total snowfall varied in different intervals. On the whole, the snow depth rose with the increase of snowfall, but the dispersion between snowfall and snow depth also increased gradually with the increase of snowfall and snow depth.

5.2 Discussion Because the artificial encryption observation stations in the city were sparse, the existing analysis was limited to individual cases, and whether the conclusions are universal needs

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to be further verified through statistical analysis of several individual cases. At the same time, if the scope is expanded to the central part of Inner Mongolia, and the threshold of the ground temperature and air temperature after snow melting can be studied after the increase of observation stations.

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