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Research Article

Climatic Characteristics of Heavy Snowfall and the Water Vapor Transport Characteristics in Typical Snowfall Events in Hunan Province of China

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Due to the unique topography and geographical location, severe snowfall is the main disastrous weather in winter in the Hunan Province of China. Based on the daily precipitation data in Hunan Province from 1961 to 2021, the regional heavy snowfall processes are classified by using the synoptic diagnostic method. In addition, the water vapor transport characteristics of typical heavy snowfall processes are analyzed by the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) air mass backward trajectory model. Then, the responses of the differences in water vapor transport to heavy snowfall under different weather situations are discussed. The results show that the spatial distribution of climatic mean heavy snowfall days in Hunan Province is extremely uneven, and the heavy snowfall days decrease from north to south, with the most in the Dongting Lake area and the least in the Nanling Mountains. In the past decades, snowstorms mainly occur in local areas, and there are fewer widespread snowstorms. The frequency of heavy snowfall days generally shows a decreasing trend, with three peaks all appearing before 1990. After the 2010s, the number of days and stations of heavy snowfall decreased noticeably, and so did the number of regional heavy snowfall processes. This result indicates that global warming has remarkable effects on the snowstorm events in Hunan Province. Heavy snowfall mainly occurs from December to February, and peaks from mid-January to early February. Over the past 61 years, more than 50% of heavy snowstorm events occurred after 2000. According to the main weather systems affecting regional heavy snowfall processes, these weather processes in Hunan Province can be classified into three categories: southern branch trough (SBT) type, blocking high collapse (BHC) type, and stepped trough type. Among them, the SBT type accounts for more than 60% of the heavy snowfall events in Hunan. In terms of the SBT type and the stepped trough type, the water vapor from the high-latitude inland and low-latitude sea surface accounts for a comparable proportion, each accounting for nearly 50%. For the SBT type, the proportion of the water vapor from warm-humid airflows is slightly higher than that from cold-humid airflows. However, in terms of the stepped trough type, the water vapor transported by cold-humid airflows from the north contributes more than that by warm-humid airflows. For the BHC type, the specific humidity and the water vapor from the high-latitude inland contribute 70% of heavy snowfall processes. In addition, the contribution of the two southwesterly water vapor channels to heavy snowfall processes is small. The water vapor sources differ remarkably for different heavy snowfall types, but all of them are dominated by the water vapor transport in the middle and lower troposphere, which is the main reason why the formation of snowfall areas under different weather types is obviously different.

1. Introduction

Snowstorms are the most common meteorological disaster in winter in China. The southern China is with abundant moisture and may experience severe snowstorm disasters under specific weather backgrounds, which greatly affect agriculture, electricity, transportation, and other industries and threaten social and public safety. The cryogenic freezing rain and snow disaster with a 100-year return period ravaged southern China in early 2008 [1–5], and Hunan was affected most severely, with a direct economic loss of more than 68 billion yuan [6]. Thus, this disaster is recognized as an extraordinary meteorological disaster. From the end of 2021 to the beginning of 2022, many provinces (cities) in the Yangtze River Basin and its south experienced heavy snowfall. In particular, the snowfall intensity in Hongjiang City, Dongkou County, Shaoyang City, Longhui County, and Shaoyang County of Hunan Province broke the historical extremes, and the heaviest snowfall periods appeared during the Spring Festival period, greatly affecting the public safety.

Recently, scholars have conducted snowstorm-related studies and achieved meaningful conclusions [7–11]. Most of the studies on the climatic characteristics of snowfall and snowstorm events in China focused on northern China [12–16]. It is pointed out that the snowfall intensity in the northern Tibetan Plateau varies under the influence of different weather systems [17]. Under a warm-humid climate, snowstorm days and extreme snowfall in northern Xinjiang showed a significant increase trend [18, 19]. The distribution of heavy snowfall in Jilin Province under the influence of the Jianghuai cyclone is closely related to the large terrain, and the snowfall in mountainous areas is much higher than the snowfall in the plain areas [20]. The study of heavy snowfall in southern China indicates that heavy snowfall mainly occurs from mid-January to early February [21]. Heavy snowfall in southern China includes "wet snow" mixed with sleet, and "dry snow" dominated by pure snow, with complex rain and snow phases and relatively in less frequency than in northern China. In general, the research on heavy snowfall in southern China is mostly focused on the analysis of individual cases. The studies of two extreme snowstorms in Hunan Province in January 2011 and December 2018 both indicated that the Ural blocking high and the southern branch trough (SBT) were considerably stronger than in the same period of previous years, and thus they were the critical circulation background leading to the long duration and high intensity of the snowfall processes [22, 23].

At present, there are few investigations into the climatic characteristics of heavy snowfall in southern China, and the differences in the causes of heavy snowfall in different weather situations are not clear. Hunan is located to the south of the Yangtze River Basin in China and belongs to the subtropical humid monsoon climate zone. The landscape of this region is dominated by hills, with mountains on the east, west, and south (Figure 1). The snowstorm in Hunan is mainly wet snow. In addition, since the frequency of heavy snowfall in southern China is significantly less than that in northern China, there are few systematic studies on the heavy snowfall in southern China, and thus it is more difficult to extract related forecast indicators.

Water vapor is crucial for precipitation formation and plays a vital role in precipitation intensity and falling zones [24, 25]. The phase of winter precipitation is mainly snow. There are differences in the water vapor characteristics of heavy snowfall under different circulation backgrounds. Early studies often used the vertical integration of whole-layer water vapor flux to represent the water vapor condition, and they judged the main water vapor transport according to the distribution of water vapor flux or wind field in the lower troposphere [26–29]. In recent years, research on water vapor characteristics of snowstorm events have been carried out by many studies based on the Euler method. The results showed that the water vapor sources of regional snowstorms mainly come from the western Pacific Ocean, the Japan Sea, the East China Sea, and the Yellow Sea. The rapid growth of water vapor after the air mass transports through the sea surface, influenced by air-sea interactions, is an essential reason for the occurrence of snowstorms [30, 31]. In addition, the convergence of air masses with different water vapor sources is the key factor in the enhancement of snowstorm processes [32]. In southern China, the southwesterly water vapor in front of the SBT plays an important role in snowfall [33–35], with the main water vapor source being from the Bay of Bengal and the South China Sea [36, 37]. The second water vapor source of vapor in eastern China is the western Pacific warm pool [38–41]. The latest research showed that the backward trajectory tracking method based on the Lagrangian method can better describe the water vapor transport trajectory and the change of water vapor along the water vapor surface than the traditional Euler method. The advantage is that the moving reference frame is used to carry out the advection and diffusion of the air mass. By tracking the three-dimensional position evolution of the air mass above the snowstorm area, the three-dimensional position physical quantity changes of each air mass at different times are obtained, including the change of height, temperature, humidity, and wind information, and the contribution rate of different water vapor sources to the precipitation area is quantitatively calculated [42–44]. Recently, the HYSPLIT model has been applied to the heavy snowfall-related studies [45–53]. However, there are few studies on the water vapor characteristics of heavy snowfall processes [54, 55], and the research mainly focuses on the water vapor analysis of a single snowstorm process.

In summary, this study first defines the criteria of heavy snowfall and regional heavy snowfall in Hunan Province. On this basis, the climatic characteristics of heavy snowfall in Hunan Province from 1961 to 2021 are studied, which is helpful for forecasters to grasp the spatiotemporal distribution characteristics of heavy snowfall in southern China under complex terrain. Through the analysis of the circulation situation of regional heavy snowfall events, the main synoptic types are determined. Then, typical cases under the influence of different weather systems are selected. The characteristics of water vapor transport in heavy snowfall areas are investigated by the backward trajectory based on the Lagrange method, and the causes of different types of heavy snowfall weather are discussed. This study innovatively adopts the new standard to carry out the

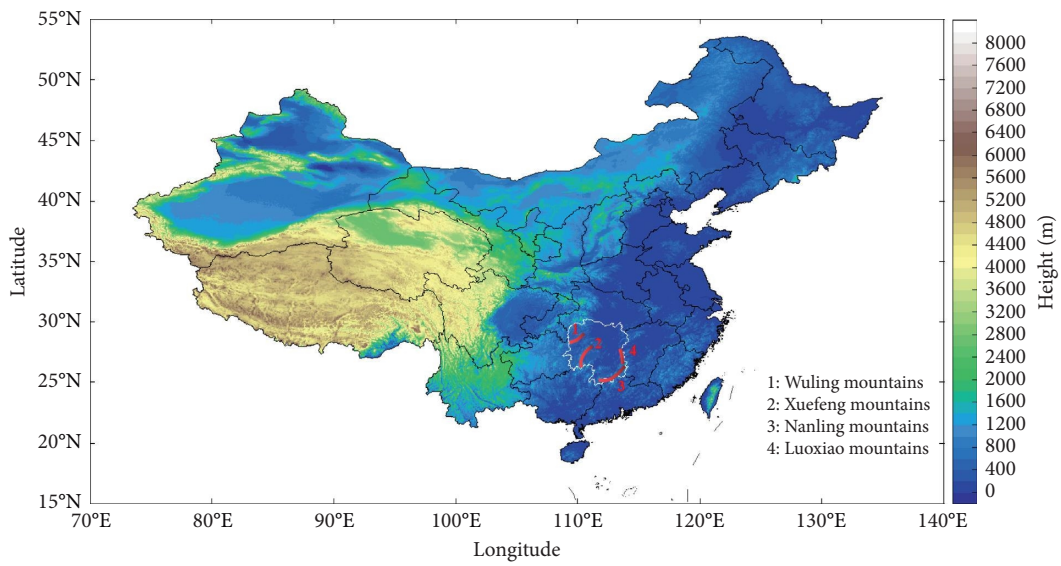


Figure 1: Topography of China (shaded area; unit: m). The range enclosed by the white solid line is Hunan Province, and the red line segments represent the different mountains.

classification of heavy snowfall in southern China, and determines the main water vapor sources of regional snowstorms in Hunan. The results can help us better understand the main influencing systems of heavy snowfall, and objectively and quantitatively understand the main water vapor channels affecting heavy snowfall in Hunan. The results of this study may further improve the snowstorm forecasting technology and provide available indicators for forecasters.

2. Data and Methods

2.1. Data. Two types of data are used in this study. One is the surface observation data from 97 national meteorological stations from 1961 to 2021 (62 years) provided by the Hunan Provincial Climate Center, including rainfall amount and snowfall amount. The other is the GDAS (global data assimilation system) data provided by the National Centers for Environmental Prediction/National Center for Atmospheric Research, with the spatiotemporal resolutions of $1^\circ \times 1^\circ$ and 6 hours.

2.2. Criteria for Identifying Heavy Snowfall. The snowfall in Hunan Province is mainly wet snow, with sleet and snow appearing successively or alternately, so it is difficult to define heavy snowfall according to the grade of precipitation (GB/T 28592-2012). In this study, heavy snowfall is defined according to the increment of snow depth, namely, $\Delta H = H_{n+1} - H_n$ (H_{n+1} denotes the snow depth on the nth + 1 day and H_n indicates the snow depth on the nth day). This method applies the current snow depth criteria of snowstorms in southern China and also comprehensively considers the conditions for the occurrence of snowfall (not only snow cover). In this research, heavy snowfall can be classified into snowstorms, heavy snowstorms, and extraordinary snowstorms according to the following conditions. For a single station (excluding Nanyue Mountain station), $\Delta H \geq 5$ cm denotes a snowstorm, $\Delta H \geq 10$ cm denotes a heavy snowstorm, and $\Delta H \geq 20$ cm denotes an extraordinary snowstorm. Note that the daily data are counted from 12:00 UTC (coordinated universal time) to 11:00 UTC of the next day. A day is considered to be a local heavy snowfall day when less than 10 of the 97 national stations in Hunan Province experience heavy snowfall on that day. If 10 or more stations experience heavy snowfall on a given day, then that day is considered as a regional heavy snowfall day. A widespread heavy snowfall day can be identified if 30 or more stations experience heavy snowfall that lasts for 2 days. We do not consider the local snowstorm days in this study, and the regional heavy snowfall lasting for 3 days or more is considered as a regional heavy snowfall process. According to the main influencing system at 500 hPa, the regional heavy snowfall processes are classified.

2.3. HYSPLIT Model and Simulation Scheme. The HYSPLIT model based on the Lagrangian method is a professional model developed by the National Oceanic and Atmospheric Administration and the Australian Bureau of Meteorology for calculating and analyzing the transport and dispersion trajectories of air masses. This study mainly uses this model to track the evolution characteristics of water vapor air mass along the water vapor transport trajectory.

The specific steps of this method are as follows. First, the snowstorm region of different types of typical regional heavy snowfall events is selected as the simulation area (four vertices of the region are determined by latitude and longitude). Second, the initial tracking heights are 500 m, 1500 m, and 3000 m. The level below 500 m is taken as the near-surface layer, the level between 500 m and 1500 m is taken as the lower troposphere, and the level between 1500 m and 3000 m is taken as the middle troposphere. Finally, the initial time of trajectory tracking selects the strongest snowfall period of each process ($t - t + n$). The three-

dimensional backward trajectory is tracked for 5 days for four times a day (00 :00, 06:00, 12:00, and 18:00 UTC), and the hourly trajectory point position and the physical quantity field (temperature, height, specific humidity, pseudoequivalent potential temperature, and water vapor flux) are output. During the strongest snowfall period of the process, all the initial points of the trajectory are reback-tracked and simulated for 5 days every 6 hours. The backward simulation of all the initial points of the trajectory is completed, and the contribution rate and proportion of each channel in the simulation area are obtained.

Due to the huge number of calculated trajectories, the cluster analysis method is used to cluster the trajectories. The principle is to merge and group multiple trajectories according to the closest trajectory path. Specifically, the spatial variance of each cluster is defined as the sum of squares of the distance between each trajectory in the cluster and the corresponding point of the average trajectory of the cluster, and each trajectory is regarded as a cluster. The spatial variance of all possible combinations of two clusters is calculated. Two clusters are randomly merged into a new cluster so that the sum of spatial variances (TSV) of all clusters after merging is smaller than that before merging. The process is conducted until all trajectories are merged into one cluster. According to the change of TSV, when the TSV increases sharply, the clusters of the combination are not similar. Therefore, the number of clusters before the point where the TSV increases sharply is selected as the number of backward trajectory clusters. The clustering method is mainly used to analyze the main transport channels and the proportion of air masses.

2.4. Calculating Contribution Rates of the Specific Humidity and Water Vapor Flux of Water Vapor Channels. By referring to previous studies [56, 57], [58], the specific humidity and water vapor contribution rate (Q_s) of water vapor channels can be expressed as

$$Q_s = \frac{\sum_1^m q_{\text{last}}}{\sum_1^n q_{\text{last}}} \times 100\%, \tag{1}$$

where q_{last} denotes the specific humidity or water vapor flux at the terminal position of the channel, m is the number of trajectories contained in the channel, and n is the total number of trajectories.

3. Climatic Characteristics of Heavy Snowfall

3.1. Spatial Distribution Characteristics of Heavy Snowfall. Figure 2(a) shows the spatial distribution of heavy snowfall days in Hunan Province from 1961 to 2021. As can be seen, the distribution of heavy snowfall days is uneven, and there are more heavy snowfall days in the north and less in the south (gradually decreasing from north to south). The heavy snowfall days are the most in the Dongting Lake area, followed by the windward slope of the Xuefeng Mountains and the leeward slope of the Dawei Mountains, and the least in the Nanling Mountains. The annual average of heavy snowfall days in Hunan Province is 0–7.2 days·(year)$^{-1}$, with a large-value center (exceeding 6 days (year)$^{-1}$) located in Anhua County. The second peak of heavy snowfall days appears along the Xuefeng Mountains and the Dawei Mountains of Liuyang City, with the value ranging from 3 days·(year)$^{-1}$ to 3.6 days·(year)$^{-1}$. Note that, parts of the counties in southern Yongzhou City do not have heavy snowfall days. This phenomenon is related to the topography of Hunan Province, which is surrounded by mountains on three sides and is opened towards the north. When the cold air moves southward, it first invades Hunan Province from the opening in the northeast. The temperature in the Dongting Lake area (in the north of Hunan) drops rapidly. Thus, in this area, snowfall can persist for a long time, and there are more heavy snowfall days.

The maximum snow depth in Hunan Province decreases with latitude (Figure 2(b)), and it is large in the north and small in the south. The large-value center of snow depth ($H = 40$ cm) appears in Linli of northern Hunan Province. The maximum snow depth is mostly 20–30 cm in northern Hunan Province, 20–25 cm in central Hunan Province, 10–15 cm in southern Hunan Province, and the smallest in Jiangyong County.

3.2. Interdecadal Characteristics of Heavy Snowfall. From 1961 to 2021, there were a total of 339 heavy snowfall days in Hunan Province (Figure 3). In terms of the interdecadal evolution, the heavy snowfall days are the most in the 1960s and 1980s, both exceeding 70 days (Figure 3(a)). Since the 1990s, the frequency of heavy snowfall days has fluctuated and shows a decreasing trend. In the 21st century, the heavy snowfall days decreased dramatically to 30 days. The number of stations with heavy snowstorms peaked in the 1970s, mainly due to the widespread heavy snowstorm on February 9, 1977 (83 stations, exceeding 85% of the stations in Hunan Province). The number of stations with heavy snowstorms is the least in the 2010s and basically the same in all other decades. The statistics of the heavy snowfall days of various types show that there are 251 days of local heavy snowfall, 67 days of regional heavy snowfall, and 21 days of widespread heavy snowfall in Hunan Province. The days of widespread heavy snowfall are similar in all decades. From the 1960s to the 2000s, the total number of regional heavy snowfall days differs by less than 3 days and varies slightly. However, it decreased rapidly in the 2010s. Local heavy snowfall days account for more than 55% of heavy snowfall days in all decades, especially in the 1960s when local heavy snowfall days accounted for nearly 80% of heavy snowfall days. Evidently, the impacts of global warming on heavy snowfall in the 21st century are clear in Hunan Province, and the days and range of heavy snowfall display a noticeable decreasing trend.

3.3. Interannual Variations of Heavy Snowfall. For the annual variation of heavy snowfall days from 1961 to 2021 (Figure 4), the annual average of heavy snowfall days in Hunan Province is 5.5 days, showing a gradient decreasing trend in general. The first peak was 14 days in 1964, the second peak was 12 days in 1977 and 1989, and the third

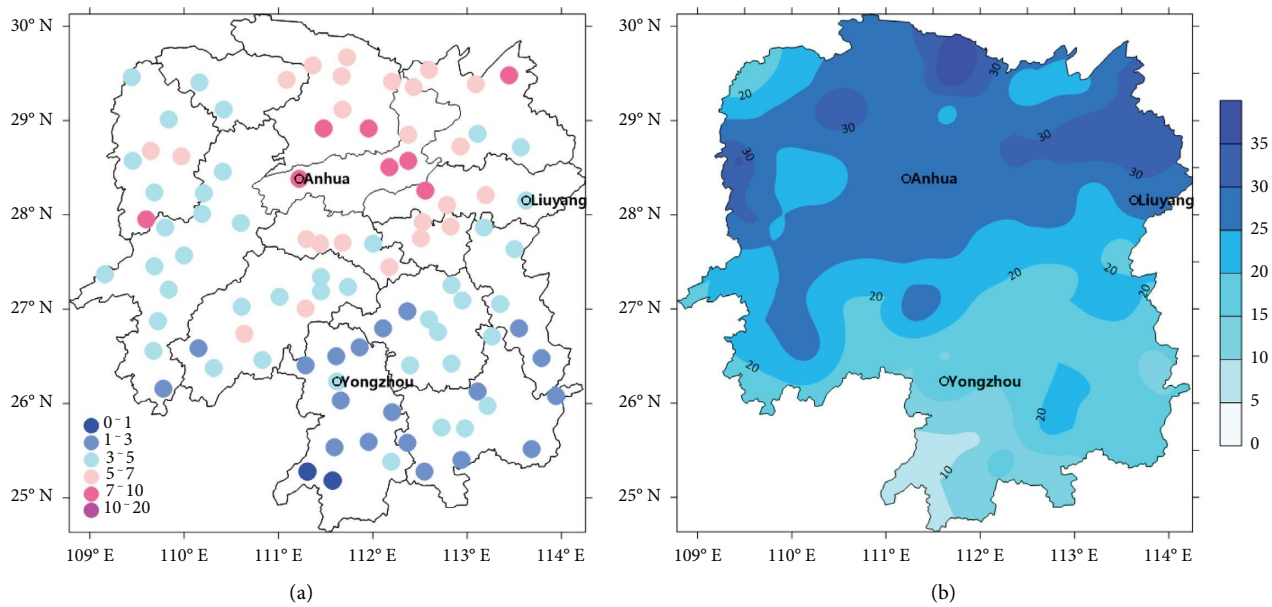
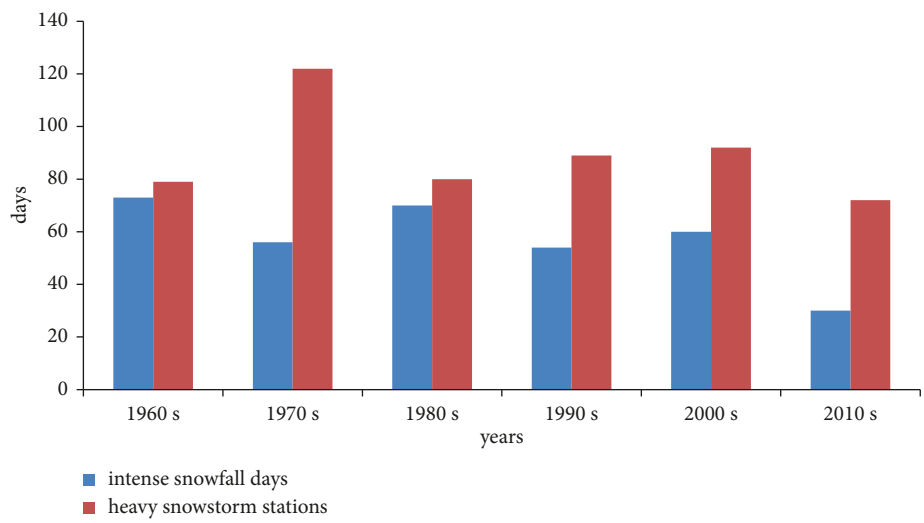
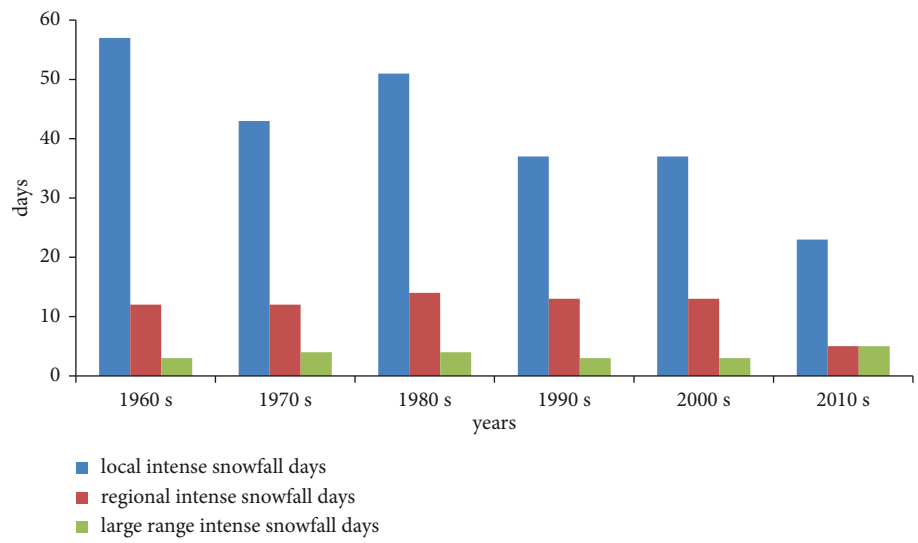


Figure 2: Spatial distributions of (a) the annual average heavy snowfall days (unit: days) and (b) the maximum snow depth (unit: cm) in Hunan Province from 1961 to 2021.



(a)

Figure 3: Continued.



(b)

Figure 3: (a) Heavy snowfall days and the number of stations with heavy snowstorms, and (b) the proportions of the days of different heavy snowfall types in the 1960s, 1970s, 1980s, 1990s, 2000s, and during 2010–2021 (2010s).

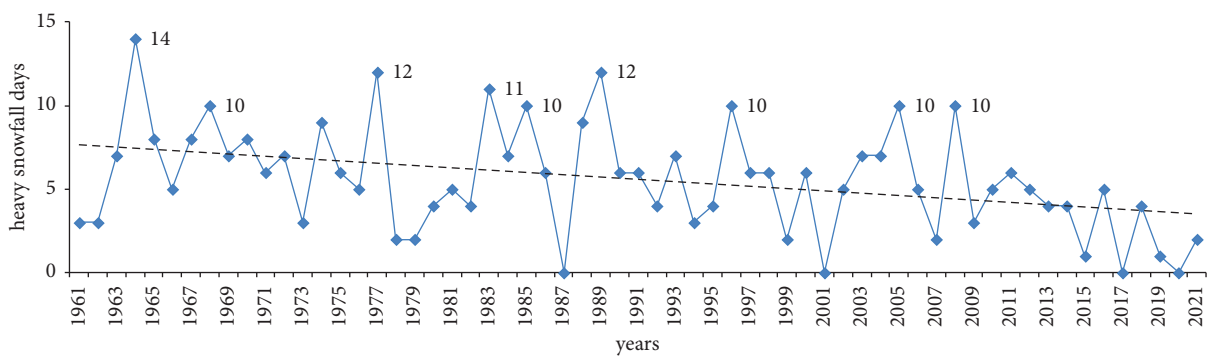


Figure 4: Annual variations of heavy snowfall days in Hunan Province from 1961 to 2021. The black dashed line presents the linear trend line of the heavy snowfall days.

peak was 11 days in 1983. No heavy snowfall days appeared in Hunan Province in 1987, 2001, 2017, and 2020. After 1990, the heavy snowfall days in most years are 3–7 days. In the past 21 years (2000–2021), only 10 heavy snowfall days were recorded in 2008. The anomaly analysis indicates a total of 31 years with fewer heavy snowfall days than the average, and 65% of the years with fewer heavy snowfall days appear after 1990 (Figure 5(a)). After 2010, all the years, except 2011, have fewer heavy snowfall days. The maximum bias of heavy snowfall days reached 151% in 1964, and there are only 12 years with an excess of 60% or more. After 2000, only in 2005 and 2008, the number of heavy snowfall days exceeded the average by more than 50%.

Moreover, the stations with heavy snowfall and the stations with heavy snowstorms can better reflect the influenced area of weather processes and extreme snowfall characteristics, and the frequency and interdecadal variation of extreme snowfall events in Hunan can be obtained by the analysis of heavy snowfall stations (Figure 5(b)). The results indicate that in Hunan Province, there are a total of 17 years with heavy snowfall in more than 50 stations, and the heavy snowfall with higher number of stations appears in 1977 (131 stations) and 2011 (109 stations). In the past 10 years, heavy snowfall with the most stations occurred in 2011 and 2021. Furthermore, there are a total of 10 years with extraordinary snowstorms in the 61 years. After 2000, a total of five years had extraordinary snowstorms. Extraordinary snowstorms with higher number of stations occurred in 1995, 1972, and 1977. As mentioned above, there were 10 stations with extremely heavy snowfall in 1995, and in 1977, the coverage of heavy snowfall was wide and extremely heavy snowfall occurred. Although the heavy snowfall days decreased after the 20th century, heavy snowstorm events, especially extraordinary snowstorms, showed an increasing trend.

3.4. Monthly and Ten-Day Characteristics of Heavy Snowfall. The analysis of the monthly heavy snowfall data from the past 61 years (figure omitted) suggests that heavy snowfall in Hunan Province mainly occurs from December to the

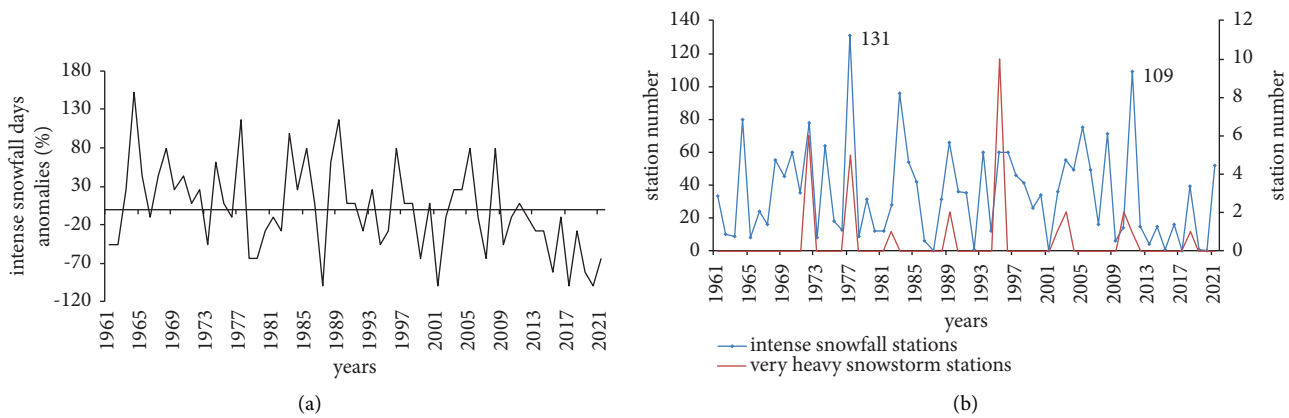


Figure 5: (a) Annual variation of the heavy snowfall day anomalies and (b) the stations with heavy snowfall and extraordinary snowstorms in Hunan Province from 1961 to 2021.

following March, with December–February being the most frequent period in winter. The days and stations of heavy snowfall in January are the highest, followed by February, and the lowest in March. The heavy snowfall weather in Hunan Province starts in early December and ends in mid-March, with the earliest on December 6, 1982, and the latest on March 21, 1998 (Figure 6(a)). The peak of heavy snowfall days is from mid-January to early February. However, heavy snowfall days are less than 10 days in March and early December, especially only one day in late March.

Figure 6(b) shows the ten-day variations of the stations with heavy snowfall and extraordinary snowstorms in Hunan Province from 1961 to 2021. The peak of stations with heavy snowfall appears in mid-January, accounting for 23% of the total stations. The stations with heavy snowfall in late January, early February, and late December exceed 300. Moreover, the extraordinary snowstorms mainly occur in mid-December-mid-January and in early February, with most stations in early February. The comprehensive analysis of the period and area affected by heavy snowfall weather reveals that the possibility of extreme snowfall weather is the highest in early February.

4. Water Vapor Transport Characteristics of a Typical Heavy Snowfall Process

The 60 regional heavy snowfall processes in Hunan in the recent 61 years can be divided into three types: the SBT type, the blocking high collapse (BHC) type, and the stepped trough type. The SBT type accounts for the highest percentage (61% of the total occurrences), followed by the stepped trough type (31%) and the BHC type (8%). The main influencing system of heavy snowfall of the SBT type is the SBT or the small fluctuations in it (500 hPa). Combined with the shear or the northeasterly backflows at lower layers, we find that the SBT moves eastward or has small fluctuations moving out eastward, which causes a snowstorm process. The weather situation of the BHC type manifests as maintaining the meridional circulation of "two-trough and one-ridge" or "one-trough and one-ridge" in the middle and high latitude regions of 500 hPa. In addition, the Ural blocking high shifts from a north-south pattern to a northeast-southwest pattern. After the collapse of the blocking high, the phenomenon of the transverse trough turning vertical occurs, driving the cold air behind the cold vortex to rotate southward. The blocking high splits with the short-wave trough in the mid-latitude plateau area and moves eastward, and the warm and wet air in front of the trough converges with cold air, resulting in snowstorms. For the stepped trough type, the large-scale circulation in the middle and high latitudes is mainly the large inverted Ω-type meridional circulation with a pattern of "two-trough and one-ridge." With the eastward movement of the high-pressure ridge in Lake Baikal, the transverse trough in front of the ridge moves eastward, and a low vortex center is located in the Okhotsk Sea. The active plateau trough and the SBT of the Bay of Bengal move to Hunan Province, and are in the same phase, which leads to the breaking out of snowstorm weather.

In this study, three heavy snowfall processes with different weather situations are selected. The evolution of water vapor in low and middle layers with locations and time is investigated by using the backward trajectory tracking and clustering methods to discuss the response of differences in water vapor transport characteristics to heavy snowfall under different weather situations.

4.1. A Heavy Snowfall Case of the Southern Branch Trough Type. A snowstorm weather process of the SBT type occurred on February 17-18, 2014. Moderate to heavy snowfall occurred in most areas south of central Hunan Province, and eight counties and cities experienced snowstorms. The precipitation phase was mainly pure snow. According to the heavy snowfall area, the region enclosed by the four points, (110°E, 26.75°N), (112°E, 26.75°N), (111.5°E, 28.5°N), and (113.5°E, 28.5°N), was selected as the simulation area. The initial simulation time was 12:00 UTC on February 17, 2014, and a total of 1296 trajectories were clustered for backward trajectory simulation. The clustered trajectories can be classified into four categories based on the sharp increase in the total spatial variance (TSV).

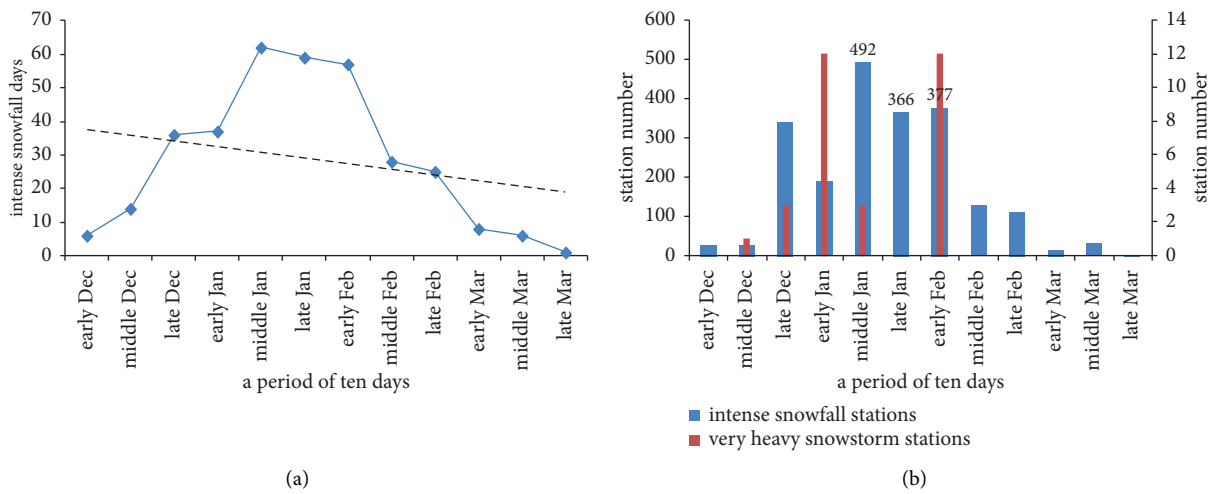


Figure 6: (a) Ten-day variations of heavy snowfall days and (b) the stations with heavy snowfall and extraordinary snowstorms in Hunan Province from 1961 to 2021.

The trajectory analysis (Figure 7(a) and Table 1) demonstrates that the North China Plain channel is the main transport channel, with 48.23% trajectories and about 37% contributions of specific humidity and water vapor. For this channel, the trajectory length is relatively short, and a large amount of water vapor comes from the sea surface near the Shandong Peninsula and enters Hunan Province through the Yangtze River Basin at a slow speed. The trajectories with water vapor from the Indo-China Peninsula account for 18.29%, and the contribution of specific humidity and water vapor is about 23%. Thus, this water vapor channel is the second transport channel. In this channel, the water vapor obtains growth due to air-sea interactions as it passes through the South China Sea. The Bay of Bengal channel, as the third water vapor transport channel, has 17.75% of the trajectories, and the contribution of specific humidity and water vapor is about 19%. Its water vapor mainly originates from the Indian Ocean. The Arabian Sea channel has the least water vapor contribution (18%), with a longer transport trajectory length and faster air mass moving speed.

Figure 7(b) shows the altitude evolution of water vapor channels. As can be seen, the water vapor of channel 6 for the SBT type comes from the Shandong Peninsula. The initial altitude of the air mass trajectory is about 850 hPa, and the altitude of air masses transported along the North China Plain gradually decreases. The transport of cold and wet air not only provides water vapor for the heavy snowfall area but also facilitates the formation of a cold air cushion. The water vapor in channels 2, 4, and 5 all originates from the low-latitude sea surface. The trajectory height for channel 2 is around 650 hPa. The warm and humid air passes through the Indian Peninsula, lifts rapidly over the Xuefeng Mountains, and then sinks after crossing the mountains to reach the heavy snowfall area. However, the trajectory altitudes of channels 4 and 5 are around 850–800 hPa. The water vapor varies slightly in altitude during transport and lifts up in climbing through the Xuefeng Mountains.

Overall, the heavy snowfall case of the SBT type has four water vapor transport channels, which originate from the Shandong Peninsula, the Indo-China Peninsula, the Bay of Bengal, and the Arabian Sea. The contribution of water vapor originating from the Shandong Peninsula is the largest. The three water vapor channels from the low-latitude sea surface all consist of warm and humid air, which moves with the 500 hPa SBT. The combined contribution of specific humidity and water vapor is more than half.

4.2. A Snowstorm Case of the Blocking High Collapse Type. A snowstorm case of BHC type occurred on December 25–27, 2021. The cold wave, heavy snowstorm, freezing rain, and other disastrous weather occurred successively in Hunan Province, accompanied by a northerly gale of level 4–5. A total of 85 stations (covering 90% of Hunan Province) recorded snowfall or sleet, 34 counties and cities experienced snowstorms, and 8 counties and cities experienced heavy snowstorms. According to the heavy snowfall center, the area of 109.5°E–113.5°E, 27°N–28.5°N was selected as the simulation area. The initial simulation time was 00:00 UTC on December 25, 2021. A total of 2856 trajectories were clustered for backward trajectory simulation. Four clustering trajectories were selected based on the TSV variations. The water vapor transport channels and evolution analysis (Figure 8(a) and Table 1) show that the trajectories with the North China Plain channel account for 43.52% of the total in middle and low layers, and the contribution rate of specific humidity and water vapor is about 47%. The trajectory length is relatively short for this channel, indicating that nearly half of the trajectories come from North China. These trajectories carry a large amount of water vapor from the North China Plain through Central China into Hunan Province at a slow speed. The trajectories with high-latitude inland channels account for 29.27% of the total, and the contribution rate of specific humidity and water vapor is about 23%. In this channel, the

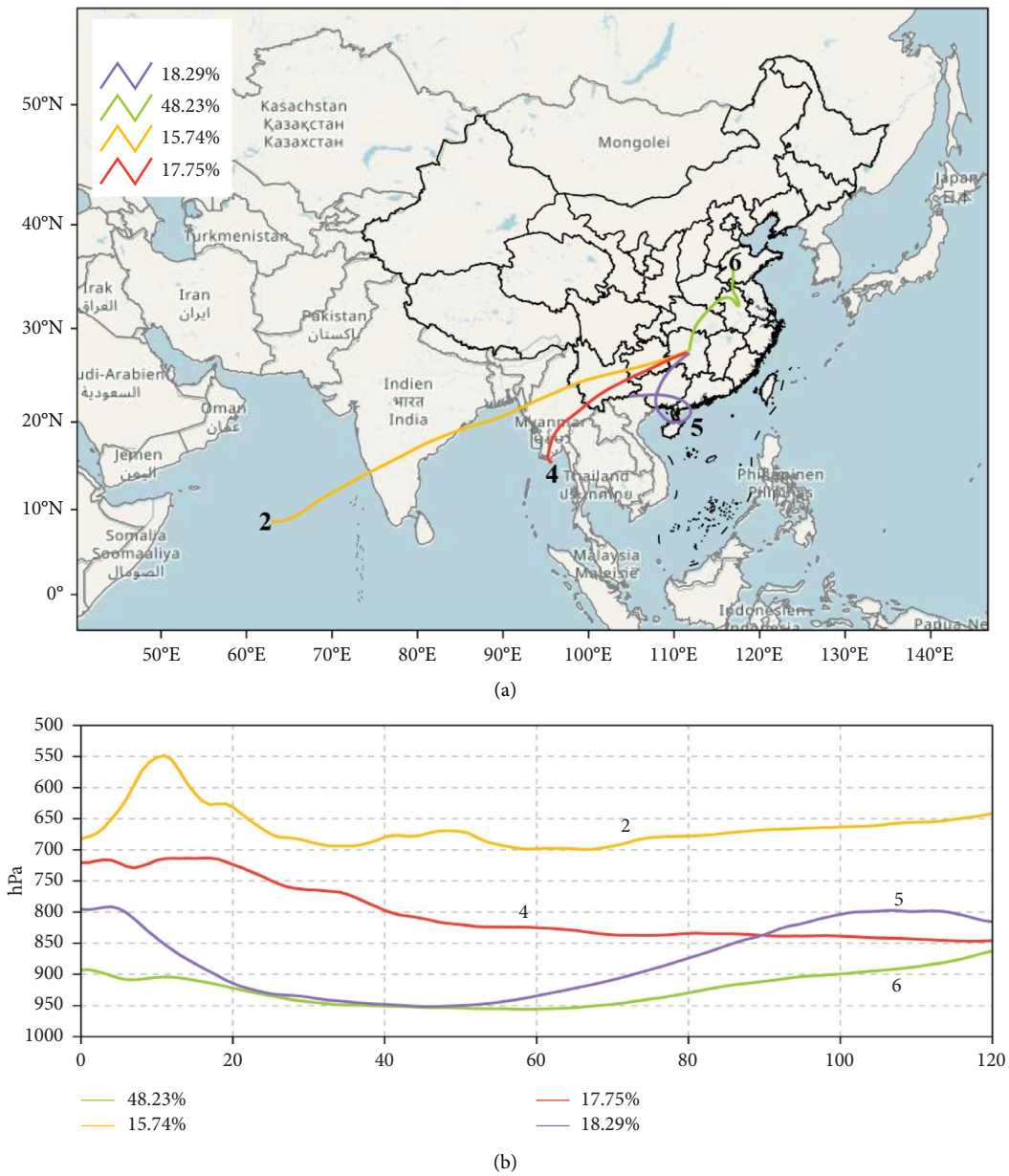


Figure 7: (a) Spatial distribution of water vapor channels and (b) altitude variations of water vapor channels in the heavy snowfall process of the southern branch trough (SBT) type.

water vapor mainly originates from the northwestern foothills of the Baikal Mountains and enters Hunan Province through Mongolia-North China-Central China. The trajectory length is relatively longer, and thus air masses move fast. Furthermore, the trajectories with the Persian Gulf channel account for 18.21% of the total, and the contribution of specific humidity and water vapor is about 20%. The water vapor mainly comes from the vicinity of the Persian Gulf and enters Hunan through the Indian Peninsula and Indo-China Peninsula, with a rapid movement of air masses. The specific humidity and water vapor contribution of the Bay of Bengal channel is the least (about 11%), and the trajectories only account for only 9% of the total. The water vapor enters Hunan Province through the Indo-China Peninsula at a slow speed.

From the altitude evolution of water vapor channels (Figure 8(b)), it can be found that channel 1 originates from the northwestern foothills of the Baikal Mountains, with a trajectory altitude of about 650 hPa and rapid sinking of cold air into Hunan. Channel 6 originates from the North China Plain, with a trajectory altitude of around 850 hPa. In this channel, the water vapor climbs slowly over the Dabie Mountains due to the topography and ascends near the Yangtze River Basin. The cold air mass of channels 1 and 6 finally forms a cold air cushion on the north side of the snowstorm area, which facilitates the climb of warm and humid airflows in the southwest and enhances the baroclinity in the snowstorm area (small pseudoequivalent potential temperature θ_{se}; Table 1). The trajectory altitude of

Table 1: Total trajectories, contributions of specific humidity and water vapor flux, pseudoequivalent potential temperature, and temperature in each channel for various heavy snowfall processes.

Heavy snowstorm types	Physical quantities	High-latitude inland channel (channel 1)	Somali jet channel (channel 2)	Eurasian channel (channel 3)	Bay of Bengal channel (channel 4)	Indo-China Peninsula channel (channel 5)	North China Plain channel (channel 6)
SBT type	Total trajectories		204		230	237	625
	Contribution of specific humidity (%)		17.87		18.62	22.65	36.79
	Contribution of water vapor flux (%)		17.87		18.65	22.68	36.73
	Pseudoequivalent potential temperature (K)		306.43		298.42	293.05	280.29
BHC type	Total trajectories	836		520	257		1243
	Contribution of specific humidity (%)	22.76		19.72	10.81		46.70
	Contribution of water vapor flux (%)	22.74		19.72	10.83		46.70
	Pseudoequivalent potential temperature (K)	274.02		300.19	298.29		286.34
Stepped trough type	Total trajectories	3839		1123	2237		
	Contribution of specific humidity (%)	45.40		18.26	36.34		
	Contribution of water vapor flux (%)	45.38		18.32	36.30		
	Pseudoequivalent potential temperature (K)	278.08		296.51	291.94		

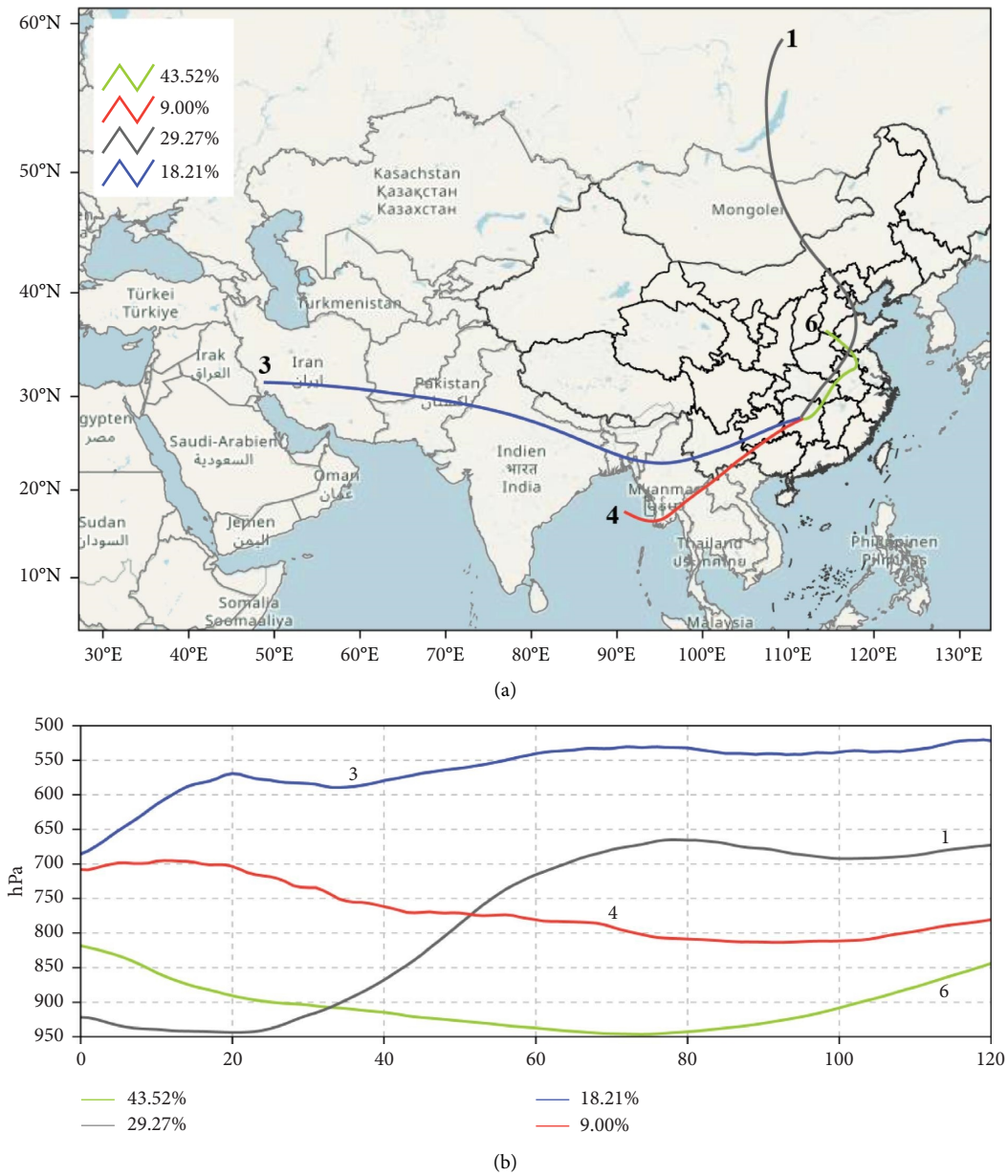


Figure 8: (a) Spatial distribution of water vapor channels and (b) altitude variations of water vapor channels in the snowstorm process of the blocking collapse (BHC) type.

channel 3 is around 500 hPa, and this channel carries part of the warm and humid air through the Indian Peninsula to the snowstorm area of Hunan Province. Then, the warm and humid air converges with cold air to gradually sink to about 700 hPa in the snowstorm area. However, the trajectory altitude of channel 4 is around 800 hPa, which lifts after landing due to the forcing of the Xuefeng Mountains.

Overall, for the snowstorm case of the BHC type, four water vapor transport channels originate from the northwestern foothills of the Baikal Mountains, North China, the vicinity of the Persian Gulf, and the Bay of Bengal. The contribution of the specific humidity and water vapor from the two northern channels is the largest, accounting for more than 70% of the total. Water vapor continues to be transported southward, carried by the cold and wet air in the lower and middle layers, and the two northern water vapor channels are the main transport channels.

4.3. A Heavy Snowfall Case of Stepped Trough Type. A snowstorm case of stepped trough type occurred on January 17–21, 2011. Widespread and persistent rain and snow weather occurred, with average rainfall (snowfall) of 23.9 mm in Hunan Province. In this case, 69 counties (cities) experienced snowstorms, and the snow depth in some areas broke the historical records. The region of 109.5°E–113.5°E, 27°N–29°N was selected as the simulation area. The initial time of the simulation was 00:00 UTC on January 17, 2011. A

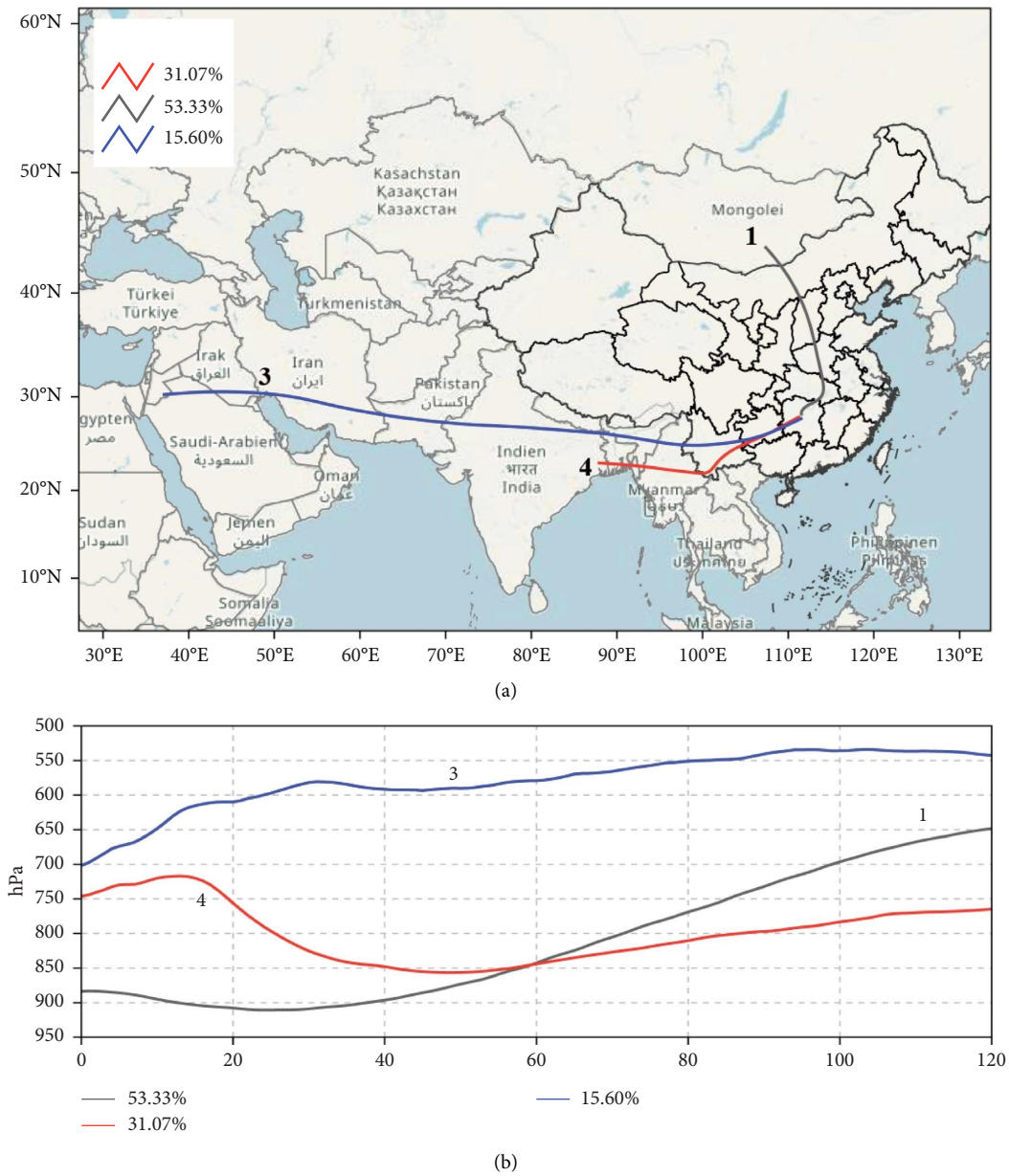


Figure 9: (a) Spatial distribution of water vapor channels and (b) altitude variations of water vapor channels in the heavy snowfall process of the stepped trough type.

total of 7,199 trajectories were clustered for backward trajectory simulation. The trajectories can be divided into three categories based on the TSV variations. From the water vapor transport channels and evolution analysis (Figure 9(a) and Table 1), we find that the high-latitude inland channel is the main transport channel among the three water vapor transport channels. The trajectories with this channel account for 53.33% of the total in the middle and low layers, and the contribution of specific humidity and water vapor is about 46%. Nearly half of the trajectories originate from the vicinity of Mongolia, and they carry a large amount of water vapor from the North China Plain to Hunan through Central China at a slow-moving speed. The trajectories with the water vapor transport channel from the Bay of Bengal account for 31.07% of the total, and the contribution of specific humidity and water vapor is about 36%. The water vapor enters Hunan from the Bay of Bengal through the Indo-China Peninsula at a slow-moving speed. The trajectories with the Eurasian continental channel are the least, accounting for 15.6% of the total, with the contribution of specific humidity and water vapor being about 18%. In this channel, the water vapor enters Hunan Province from Eurasia through the Indo-China Peninsula, and the air masses move rapidly. In terms of the altitude evolution of the water vapor channels (Figure 9(b)), channel 1 originates from Mongolia, and its trajectory altitude is around 650 hPa. In this channel, the cold air sinks to invade Hunan Province. The trajectory altitude of channel 4 is around 750 hPa, and

the air masses of this channel are forced to lift through the Xuefeng Mountains after landing. Channel 3 has a trajectory altitude of around 500 hPa, which carries parts of warm and humid air through the Indian Peninsula to the snowstorm area of Hunan Province.

In conclusion, the snowstorm case of the stepped trough type has three water vapor transport channels, which originate from Mongolia, the vicinity of the Red Sea, and the Bay of Bengal. The water vapor from Mongolia contributes the most, which is carried by wet and cold air in the middle and low layers to Hunan Province. The second largest contribution is from the water vapor from the southwesterly water vapor channel, which is transported by warm and humid air in the middle and upper layers and superimposed with the low-level water vapor to reach Hunan Province.

5. Conclusions

The snowstorm in southern China is mainly wet snow. Its forecast is difficult, and we should comprehensively consider snowfall amount and snow depth. In this study, the climatic characteristics of heavy snowfall in a representative province of southern China, namely, Hunan Province, are analyzed based on the meteorological data from 1961 to 2021. Based on the synoptic diagnosis, the heavy snowfall processes in Hunan Province are classified into three types: SBT type, BHC type, and stepped trough type. On this basis, the HYSPLIT air mass backward trajectory tracking model is used to explore the differences in water vapor transport for different types of typical heavy snowfall weather processes. The main conclusions are as follows.

The spatial distribution of heavy snowfall days in Hunan Province is extremely uneven, which decreases from north to south, with the most frequent heavy snowfall days in the Dongting Lake area and the least in the Nanling Mountains. Over the years, snowstorms mainly occurred in local areas, and the heavy snowfall days generally show a gradient decreasing trend. After the 2010s, the heavy snowfall days and the stations with snowstorms decreased considerably. Global warming has had noticeable impacts on the weakening trend of heavy snowfall in Hunan Province.

The heavy snowfall in Hunan Province mainly occurs from December to the following February, with most heavy snowfall days between mid-January and early February. More than 50% of the heavy snowstorms in 61 years occurred after 2000.

The regional heavy snowfall processes in Hunan Province are mainly divided into the SBT type, BHC type, and stepped trough type. The heavy snowfall processes of the SBT type account for the most (61% of the total), followed by the stepped trough type.

The water vapor sources of heavy snowfall weather under three different situations are different, but all of them are dominated by the water vapor transport in the middle and lower troposphere. For the SBT type, more than half of the water vapor comes from the low-latitude sea surface, mainly originating from the Shandong Peninsula. The warm-humid air is transported by the SBT and the 700 hPa southwesterly airflow to Hunan Province. In terms of the stepped trough type, the warm and humid water vapor from the low-latitude sea surface contributes the most, which is mainly transported from the middle and upper troposphere and superimposed with the humid-cold water vapor in the middle and low layers from Mongolia. Regarding the BHC type, the contribution of specific humidity and water vapor from the high-latitude inland accounts for more than 70%, and the humid-cold air is mainly transported from the middle and low layers to affect Hunan Province.

The results show that heavy snowfall is nonuniformly distributed in Hunan. The frequency of heavy snowfall near large terrains such as the Nanling Mountains and Xuefeng Mountains is the highest. There are obvious differences in water vapor transport under different weather types. The conclusion of this study can provide technical support for the refined forecast of heavy snowfall in Hunan, and provide some references for the classification of snowfall under different weather types in Hunan in winter. Based on the existing research results, the composite analysis of atmospheric circulation can be used to study the location and intensity of different weather types of snowstorm areas, and to track the water vapor sources of the same type of heavy snowfall through multisample collection, which is helpful for forecasters to grasp the water vapor characteristics of heavy snowfall in southern China. The next step of this study is to carry out the following work:

(1) The terrain influence on the spatial and temporal distribution of heavy snowfall, including the Dongting Lake and the large terrain of Nanling Mountains

(2) The characteristics of water vapor transport in extreme snowstorm areas, and the influence of main water vapor sources and water vapor transport channels on snowfall area and intensity

Data Availability

The grid data used in this study are obtained from the following websites: https://rda.ucar.edu/datasets/ds083.2/index.html and https://www.psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html. The snowstorm cases used in this paper are from the snowstorm case datasets of the Hunan Meteorological Observatory.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Yan Hu conceptualised the study, developed the methodology, and wrote the data. Enrong Zhao curated the data and performed the formal analysis. Hongwu Liu developed the software and visualized the study. Lin Xu revised and edited the manuscript. Kexin Tan investigated and validated the study. Huanqian Liu supervised the study and administered the project. Qingxia Wang wrote and prepared the original draft.

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