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RESEARCH ARTICLE

Study on Cloud Characteristics in Western Liaoning, China Based on Millimeter-Wave Cloud Radar

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ABSTRACT

Based on the millimeter-wave cloud radar detection data from the western region of Liaoning Province, China (hereinafter referred to as western Liaoning) in 2020, the vertical structure characteristics of clouds were studied. The analysis results show that: (1) The occurrence frequency of clouds is 25.50%, while single-layer clouds occurrence frequency is 19.45% accounted for the largest proportion. The diurnal variation of occurrence rates differs across seasons. High clouds have the highest occurrence frequency, accounting for 40.03% of all clouds. (2) The average rainfall intensity of cloud precipitation throughout the year is 3.1 mm/h, and the precipitation mainly originates from single-layer and double-layer clouds. The rainfall intensity weakens as the number of cloud layers increases, and the precipitation of multi-layer clouds is mainly produced by low-layer clouds. (3) The average thickness of the cloud interlayer for precipitating clouds is 1.4 km, with 82.1% of cloud interlayer thicknesses being less than 2 km. The average thickness of the cloud interlayer for non-precipitating clouds is 1.84 km, with 70.8% of cloud interlayer thicknesses being less than 2 km. The cloud interlayer thickness generally decreases with the increase in the number of cloud layers.

Keywords: Millimeter-Wave Cloud Radar; Cloud Vertical Structure Characteristics; Cloud Interlayer; Cloud Occurrence Rate

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1. Introduction

The vertical structure of clouds largely determines whether clouds can produce precipitation and whether the resulting precipitation can reach the ground, and also affect the radiation budget of the atmosphere and the surface. The accurate description of the cloud vertical structure is the difficulty of the numerical model, and it is also the premise of the weather modification for rainfall enhancement operation [1–4]. Therefore, it is necessary to study the characteristics of cloud vertical structure based on long-term observation data.

Currently, most devices capable of detecting vertical meteorological element data include L-band sounding radar, laser ceilometers, and satellite remote sensing, etc. Domestic and foreign scholars have conducted extensive research and analysis on the vertical structure characteristics of clouds. For instance, Cloudsat satellite provides data products to help understand the cloud structure characteristics and cloud process rules of the real atmosphere, and improve the understanding of weather systems and cloud microphysical structures. Zhong et al. and Chen et al. analyzed the cloud vertical structure characteristics of typical weather systems using CloudSat satellite observation data [5, 6]. Liu et al. used CloudSat satellite observation data from May 2006 to May 2013 to analyze the horizontal and vertical distribution characteristics and physical causes of eight types of clouds (cirrus clouds, altostratus clouds, altocumulus clouds, stratus clouds, stratocumulus clouds, cumulus clouds, nimbostratus clouds, and cumulus congestus clouds) at different heights and seasons over the Qinghai-Tibet Plateau, providing effective verification information for evaluating the simulation capability of numerical prediction models for cloud systems [7]. Wang et al., Chen et al. and Zhang et al. used Cloudsat satellite observation data to study the vertical structure characteristics of clouds [8–10]. Liu et al. used CloudSat satellite observation data to analyze and compare the vertical structure characteristics of precipitating and non-precipitating clouds in Northeast China [11]. As a long-term operational observation method of the meteorological department, sounding can obtain the vertical profiles of meteorological elements at different heights. At present, many scholars have used sounding data to study cloud recognition and vertical characteristics. Identification using sounding data was first proposed abroad, including temperature dew point difference method , relative humidity method and second derivative method of temperature and relative humidity [12–14]. Most Chinese scholars use the relative humidity threshold method to study the vertical structure characteristics of clouds using sounding data. Zhou et al. analyzed the vertical structure of clouds by using the relative humidity threshold method with sounding data, and the calculation results were compared with CloudSat millimeter-wave cloud radar, verifying the feasibility of the relative humidity threshold method for determining the vertical structure of clouds [15]. Sun et al. analyzed the cloud vertical distribution characteristics in Shenyang by using L-band sounding data based on the relative humidity threshold method [16]. However, the former used polar-orbiting satellite data, which cannot continuously detect a fixed area, while the latter used L-band sounding data, which detects no more than four times a day, with each detection lasting about an hour, and cannot conduct long-term uninterrupted detection of a fixed area either.

The study of macro and micro characteristics of cloud has always been a hot and difficult problem in atmospheric physics research. It is found that millimeter wave radar has unique advantages in observing the evolution and characteristics of clouds. The millimeter wave cloud radar is good at observing details of rain cloud system, providing good support for the development of lighter cloud prediction and cloud research of macro and micro physics properties. Clothiaux et al. proposed a method to distinguish signal and noise based on ground-based cloud radar observation data, which laid a foundation for cloud radar to accurately identify clouds and study the macro and micro characteristics of clouds. They used this method to invert the cloud base and cloud top height of cirrus, stratus and other clouds based on echo intensity [17]. UTTAL et al. analyzed the macro-characteristics of winter clouds over the continental United States. It was pointed out that the cloud base height was mainly distributed at 2.5 km and 7.5 km, and the cloud thickness was usually 2 km [18]. The U.S. Department of Energy initiated atmospheric radiation (Atmosphere Radiation Measurement, ARM). The project uses multiple millimeter-wave cloud radars to continuously observe clouds for a long time. Based on the cloud radar observation data of the project, many researchers have studied the macro and micro characteristics of clouds in different regions. Intrieri et al. used ground-based cloud radar data to statistically analyze the macroscopic characteristics of clouds such as cloud occurrence frequency, cloud height, and cloud number in the Arctic region. It is found that the annual occurrence frequency of clouds in the Arctic is 85%, and the monthly average minimum height of cloud base and the maximum height of cloud top are between 0.25–1.0 km and 2.5–5.5 km, respectively[19]. Comstock et al. studied the macroscopic characteristics of cirrus clouds in the tropics based on data of lidar radar and millimeter wave cloud radar[20]. Hollars et al. used the project's 35 GHz cloud radar observation data on Manus Island to invert the cloud top height and compared it with the satellite inversion results[21]. Hawkinson et al. conducted a comparative analysis of cloud-top products performance using data from cloud lidars and cloud radars located at the U.S. Department of Energy ARM Project's Cloud and Radiation Testbed (CART) site[22]. Chinese scholars started late in using millimeter wave cloud radar to detect clouds. There are also many research results. Fang et al. studied the vertical structure of clouds in Wuhan, China, finding that the cloud-top positions observed by millimeter-wave cloud radar were basically consistent with those from satellite data[23]. Cui et al. conducted a preliminary statistical analysis of the diurnal variation characteristics of cloud-top and cloud-base height, cloud thickness, cloud cover, and the number of cloud layers in the Longmen area of Guangdong during the summer of 2016, from May to August, concluding that the frequency of multi-layer clouds appeared in the afternoon is high, mixed clouds occur least frequently in summer, and the occurrence frequency of water clouds is relatively stable[24]. Tian et al. used Ka-band millimeter-wave cloud radar data from the Liupanshan Meteorological Station in Ningxia from September 2017 to August 2018 to statistically analyze the occurrence frequency and macro characteristics of different clouds at the top of Liupanshan Mountain[25]. Huo et al., Zhu et al. and Qiu et al. used millimeter-wave cloud radar to observe and analyze the distribution and variation of cloud base, cloud top, and cloud thickness in Beijing, at the top of Cuiying Mountain in Yuzhong, Lanzhou, and in Shou County, Anhui Province, respectively, exploring the occurrence frequency and variation characteristics of single-layer, double-layer, and three-layer clouds[26–28]. At present, there are also studies using frequency-modulated continuous wave radar for cloud detection. Pinsky et al. used frequency-modulated continuous wave radar to study turbulence in isolated convective clouds, calculating the lateral structure function and vertical velocity spectrum of convective clouds at different stages of evolution and cloud-top heights[29].

In this paper, the cloud radar data are utilized to analyze the vertical structure characteristics of clouds in western Liaoning, including the height of cloud base and cloud top, and the distance between cloud layers in multi-layer clouds (cloud interlayer thickness). Using cloud radar data compensates for the disadvantages of CloudSat data and L-band sounding data, providing the statistical characteristics of the vertical structure with higher spatial and temporal resolution, to improve the accuracy and scientificity of weather modification operations for rainfall enhancement.

2. Data Preprocessing

2.1. Data Sources

The observational equipment used in this study is located at the Fuxin National Basic Meteorological Station in western Liaoning. The primary data used are from the HMB-KPS type millimeter-wave cloud radar (be manufactured by AEROSPACE NEWSKY TECHNOLOGY CO., LTD in Wuxi City, Jiangsu Province, China). The rainfall intensity data comes from the raindrop spectrum observation data obtained by the DSG5 precipitation sensor, and the weather phenomenon data comes from monthly surface meteorological records. The millimeter-wave cloud radar conducts continuous vertical observations, capable of detecting data from 0 to 20 km in the vertical direction, with a time resolution of 1 minute. The specific performance indicators are shown in **Table 1**.

2.2. Data Preprocessing

Precipitation phenomena refer to weather conditions where solid, liquid, or mixed-state precipitation falls from the sky. Visibility obstruction phenomena occur when the air becomes turbid due to the presence of water vapor condensates, dry suspended solids, etc., resulting in reduced visibility. Both types of weather phenomena have a certain impact on millimeter-wave cloud radar detection. According to the calculations regulated by the World Meteorological Organization (WMO), the average annual precipitation days for the climate value in the Fuxin area (the cumulative annual average during the 30-year period from 1991 to 2020) is 70.1

Table 1. Major performance indicators of millimeter-wave cloud radar.

Item	Performance Indicators
Radar system	Pulse Doppler, single transmission and dual reception, fully solid state, pulse compression
Operating frequency	35 GHz ± 500 MHz (Ka band)
Detection range	Distance: 120 m to 20 km; Echo intensity: −45 to +30 dBz; Radial velocity: −18 to 18 $m{\cdot}s^{-1}$; Velocity spectrum width: 0 to 4 $m{\cdot}s^{-1}$
Resolution	Distance ≤30 m; Echo intensity ≤0.1 dBz; Radial velocity ≤0.1 $m{\cdot}s^{-1}$; Velocity spectrum width ≤0.1 $m{\cdot}s^{-1}$; Linear depolarization ratio ≤0.1 dB

days. In 2020, precipitation occurred for a total of 76 days, which are 5.9 days more than the climate value, accounting for 20.8% of the whole year. Visibility obstruction phenomena occurred on 82 days, accounting for 22.4% of the whole year, with fog accounting for 2.2%, light fog for 19.4%, and haze for 0.8%.

Based on the distribution of the above weather phenomena, during the actual processing of cloud radar data, cloud data with rainfall intensity equal to 0 and the cloud base or cloud top height of the first layer cloud less than 0.5 km are excluded. In addition, there are numerous duplicate data entries and anomalies in the cloud radar data, such as the cloud base height of the upper cloud layer being lower than the cloud top height of the lower cloud layer. In the statistical analysis, we mainly focused on the classification and discussion of single-layer, double-layer, and three-layer clouds.

3. Analysis of Cloud Vertical Structure Characteristics in Western Liaoning

3.1. Observation Statistics

In this paper, the vertical observation duration is calculated monthly, and the ratio of the total duration of radar vertical observations to the total duration of a natural month is defined as the data acquisition rate. As shown in **Figure 1**, in 2020, there were significant missing observations in February, while the data acquisition rates for the other months all reached over 96%.

3.2. Characteristics of Cloud Occurrence Rate

3.2.1. Annual and Monthly Occurrence Rates

The radar's vertical detection provides a single profile of data directly overhead, with a fixed and small-range field of view, making it impossible to directly calculate the cloud cover. Based on the characteristics of radar data detection, the occurrence duration of cloud profiles in a certain period (such as hours, days, months, etc.) is selected to calculate its proportion to the total observation duration, being capable of estimating the occurrence of regional clouds, which is called the cloud occurrence rate in this paper. When calculated on an annual basis, it is called the annual occurrence rate, and when calculated monthly, it is called the monthly occurrence rate. As shown in **Figure 2**, in 2020, the cloud occurrence frequency was 25.40%, with single-layer clouds being the most predominant, accounting for 19.45%, while clouds with four or more layers accounted for only 0.21%.

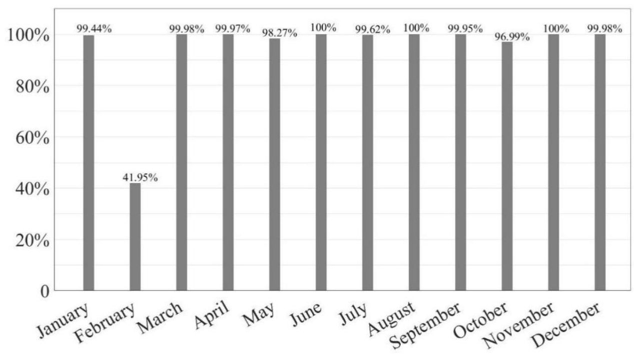

Figure 1. Data acquisition rates by month in 2020.

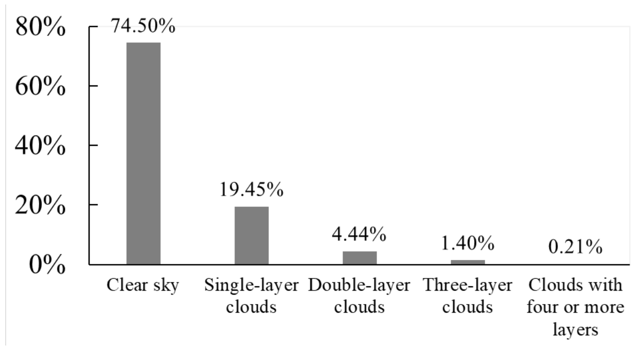

Figure 2. Cloud occurrence frequency of single-layer clouds and multi-layer clouds in 2020.

According to the commonly used climatological method for seasonal classification, this paper defines March to May as spring, June to August as summer, September to November as autumn, and the rest as winter. As shown in **Figure 3**, the cloud occurrence frequency is lower from January to April and from October to December, while it is higher from May to September. Fuxin is located in a temperate semi-arid continental seasonal climate zone, with winter and summer monsoons alternately moving. It is dry and cold in winter and warm and humid in summer, leading to a characteristic pattern of more clouds in summer and fewer clouds in winter. In each month, the cloud occurrence frequency decreases with the increase in the number of cloud layers.

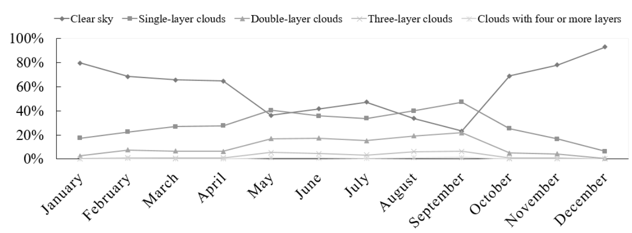

Figure 3. Cloud occurrence frequency of single-layer and multi-layer clouds by month in 2020.

3.2.2. Hourly Occurrence Rate

Compared to satellite or manually observed meteorological data, radar fixed-point observation data have an absolute advantage in temporal resolution, allowing the study of macro- and microscopic physical changes of clouds on a smaller time scale. The diurnal variation of cloud occurrence rates in western Liaoning can be understood by counting the cloud occurrence rate on an hourly basis. During the calculation process, the occurrence rate for each of the 24 hours per day is first calculated on an hourly basis. Then, the average occurrence rate for the same hour in a month is calculated, followed by the seasonal average values. The results are shown in **Figure 4**. In **Figure 4**, the gray bars represent the total average of the hourly occurrence rate, with a distribution of around 26% across different periods, and the differences between the periods are not significant. However, the occurrence rate is relatively higher between 12:00 and 18:00 and relatively lower during other periods. The diurnal variation of occurrence rates differs across seasons. In spring and summer, the occurrence rate increases from midday (11:00) to evening (19:00) and then gradually decreases after 19:00, with an increase of about 8%. In winter and autumn, although there are some variations in occurrence rates during certain continuous periods, the increase and decrease are less pronounced, and the diurnal variation characteristics are not as significant as in spring and summer.

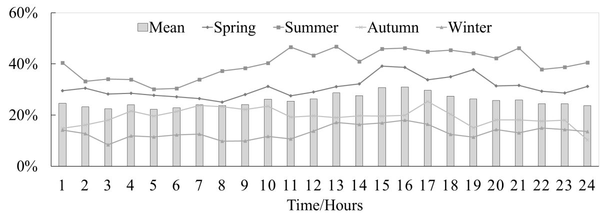

Figure 4. Total diurnal variation of cloud occurrence rate in 2020 and distribution characteristics in different seasons.

3.2.3. Occurrence Frequency of Low, Middle, and High Clouds

Clouds with cloud base heights less than 2.5 km are defined as low clouds, those between 2.5 km and 5 km as middle clouds, and those higher than 5 km as high clouds. This section focuses on the occurrence frequency, cloud thickness, and diurnal variation characteristics of low clouds in non-precipitating single-layer and multi-layer clouds. **Figure 5** shows the occurrence frequency, thickness distribution, and diurnal variation characteristics of the occurrence frequency of low, middle, and high clouds. It can be seen that high clouds have the highest occurrence frequency, accounting for 40.03% of all clouds. The occurrence frequencies of low and middle clouds are not significantly different, at 31.78% and 28.19%, respectively. The average thickness of middle clouds exceeds that of low and high clouds, reaching 2.9 km, while the average thicknesses of low clouds and high clouds decrease in turn, at 2.2 km and 1.7 km, respectively. Regarding the diurnal variation characteristics of occurrence frequency, the occurrence frequency of low clouds during both day and night shows an increasing trend first and then a decreasing trend. The occurrence frequency of middle clouds decreases gradually from nighttime to noon and then increases in the afternoon. The occurrence frequency of high clouds gradually decreases before noon and increases after noon.

4. Analysis of the Vertical Structure Characteristics of Non-Precipitating Clouds and Precipitating Clouds

4.1. Distribution of Cloud Layers

Based on the rainfall intensity data measured by the raindrop spectrometer, the cloud samples are divided into non-precipitating clouds and precipitating clouds. The occurrence frequencies of single-layer and multi-layer clouds in each cloud sample are listed in **Table 2**. Regarding cloud layer distribution, cloud formation is mainly composed of single-layer clouds. Precipitation mainly comes from single-layer clouds, followed by double-layer clouds. With the end of the single-layer precipitation cloud precipitation process, the cloud dissipates and forms multi-layer clouds. Based on the occurrence frequency, the proportion of single-layer clouds in precipitation clouds is lower than that in non-precipitation clouds, which is consistent with the observation facts.

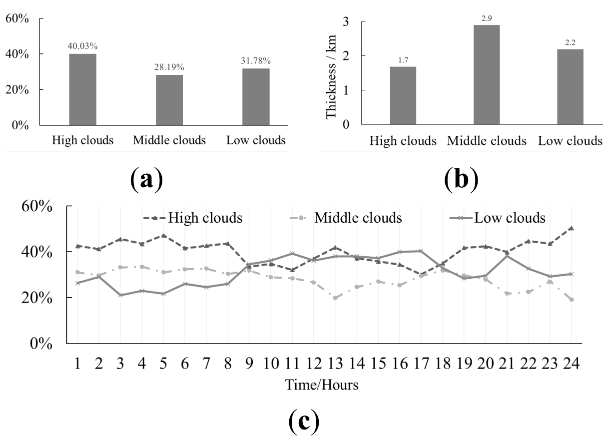

Figure 5. The occurrence frequency (**a**), thickness (**b**), and diurnal variation characteristics of the occurrence frequency (**c**) of low, middle, and high clouds.

Table 3 shows the relationship between the cloud layer distribution and rainfall intensity of precipitating clouds. Throughout the year, the average rainfall intensity of cloud precipitation in this area is 3.1 mm/h. The rainfall intensity is greater in summer, while the intensity differences between other seasons are not significant. From the perspective of cloud layer distribution, as the number of cloud layers increases, the rainfall intensity weakens, which is related to the development and evolution of precipitating clouds. Especially in the dissipation stage of single precipitation cloud, the precipitation intensity weakens obviously. Precipitating clouds are cloud families with vertical development, such as nimbostratus clouds and cumulonimbus clouds. As precipitation weakens, the cloud body can transform and evolve into multi-layer clouds. The main body of nimbostratus clouds can transform into cirrus clouds, altocumulus clouds, or altostratus clouds, etc., while cumulonimbus clouds can transform into stratocumulus clouds, as well as cirrus clouds, altocumulus clouds, and altostratus clouds. The weather system in Liaoning area is dominated by the Westerlies System, and the system in the middle troposphere at 500hPa is usually an upper trough or high-altitude cold vortex. Among them, the Northeast China Cold Vortex is an important weather system that causes sudden strong convective weather in the region. The Northeast China Cold Vortex may occur throughout the year, but the probability of occurrence in summer is significantly larger than that in winter [30]. This is consistent with the observational facts that the rainfall intensity of both single-layer and multi-layer clouds in summer are the strongest.

4.2. Distribution Characteristics of Cloud Interlayers

A cloud-free area between two cloud layers is defined as the cloud interlayer. For the diagrammatic drawing of the cloud interlayer, see **Figure 6**. Due to the relatively low humidity within the cloud interlayer, the falling raindrops or ice crystals tend to evaporate or sublimate in this area. Therefore, the thickness of the cloud interlayer is also a crucial factor to be considered in artificial precipitation enhancement operations. **Table 4** lists the average thickness of cloud interlayers between different cloud layers across different seasons. It can be seen that the average thickness of cloud interlayers of precipitating clouds in western Liaoning is 1.4 km, with 82.1% of interlayer thicknesses being below 2 km. The average thickness of cloud interlayers is the greatest in summer (1.98 km) and the smallest in spring (0.65 km). For non-precipitating clouds, the average thickness of cloud interlayers is 1.84 km, with 70.8% of interlayer thicknesses being below 2 km. The average thickness of cloud interlayers is the greatest in summer (2.70 km) and the smallest in winter (0.69 km). Overall, cloud interlayers are thicker in summer and autumn and thinner in winter and spring. Comparing the thickness of cloud interlayers with different numbers of cloud layers, it is observed that the thickness of the cloud interlayer generally decreases as the number of cloud layers increases. Analyzing the variation in cloud interlayer occurrence frequency with height (**Figure 7**) reveals that in spring

Table 2. Distribution frequency of non-precipitating and precipitating cloud layers (unit: %).

Number of Cloud Layers	Single-Layer Clouds	Double-Layer Clouds	Three-Layer Clouds	Clouds with Four or More Layers
Non-precipitating cloud	83.9	14.8	1.2	0.1
Precipitating cloud	76.2	19.7	3.6	0.4

Table 3. Relationship between cloud layer distribution of precipitating clouds and rainfall intensity (unit: mm/h).

Time Classification	Annual Average	Spring	Summer	Autumn	Winter
Single-layer clouds	3.4	2.7	4.4	2.8	3.3
Double-layer clouds	2.8	0.7	7.1	1.5	1.9
Three-layer clouds	0.7	0.3	1.4	1.0	0.3
Total cloud cover	3.1	2.1	4.8	2.4	2.5

and winter, the cloud interlayers' occurrence frequency is the highest in the range of 3 to 6 km, while in summer and autumn, it is in the range of 5 to 9 km.

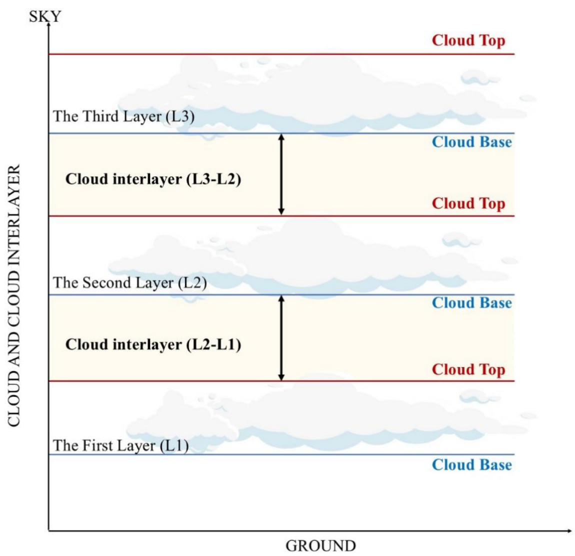

Figure 6. The diagrammatic drawing of the cloud interlayer.

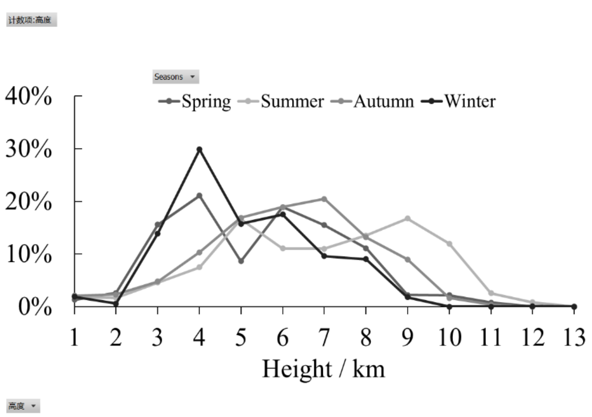

Figure 7. Variation in cloud interlayer occurrence frequency with height by seasons.

4.3. Characteristics of Cloud Vertical Structure

Figures 8 and **9** visually display the differences in vertical structure between single-layer and multi-layer clouds in precipitating and non-precipitating clouds across different seasons. Because the cloud radar cannot identify the cloud base height of low-layer clouds under precipitation conditions, only the average cloud top height position of low-layer precipitating clouds is provided in the figures. As observed in the figures, except in winter, the top height of single-layer precipitating clouds is higher than that of single-layer non-precipitating clouds in other seasons. This may be related to the lack of cloud sample data in February. The intensity of rain has a great influence on the attenuation of cloud radar detection. Sometimes the radar signal will be completely attenuated in moderate rain and heavy rain. When there is heavy rainfall (50mm/h), the attenuation of 35GHz cloud radar is 2dB/km, and the attenuation of 95GHz cloud radar is 8dB/km[31, 32]. In some extreme cases of heavy rainfall, the radar penetration observation of storms is limited to a few kilometers, and the storm top cannot be observed from the ground. Therefore, the cloud top height of the top layer of multi-layer precipitating clouds is generally lower than that of multi-layer non-precipitating clouds, possibly due to severe attenuation under the condition of heavy precipitation, which affects the statistical results. Precipitation is produced by low-layer clouds. When precipitation occurs, multi-layer clouds will form a 'seeding cloud-precipitation cloud' mode. The mode happens because the raindrops or ice crystals those fall from the high-level clouds are not completely evaporated or sublimated in the thin cloud interlayer, so when they fall to the low level clouds, the cold cloud' Bergeron Process

Table 4. Average thickness of cloud interlayers between different cloud layers in the Fumeng area of Fuxin (unit: km).

Type		Cloud Interlayer	Spring	Summer	Autumn	Winter	Annual Average
Precipitating clouds	Double-layer clouds	L2-L1	0.92	2.38	1.63	1.05	1.48
	Three-layer clouds	L2-L1	0.92	1.74	1.33	0.25	1.04
		L3-L2	0.91	1.60	1.25	1.78	1.36
	All clouds		0.95	1.98	1.54	0.98	1.40
Non-precipitating clouds	Double-layer clouds	L2-L1	1.26	2.88	1.44	0.68	1.89
	Three-layer clouds	L2-L1	0.68	2.99	1.33	0.90	2.21
		L3-L2	0.82	0.89	0.77	1.65	0.96
	All clouds		1.24	2.70	1.42	0.69	1.84

or warm cloud precipitation mechanism is initiated in the low level cloud. Therefore, the cloud interlayer thickness of precipitating clouds is significantly thinner than that of non-precipitating clouds in multi-layer clouds in general.

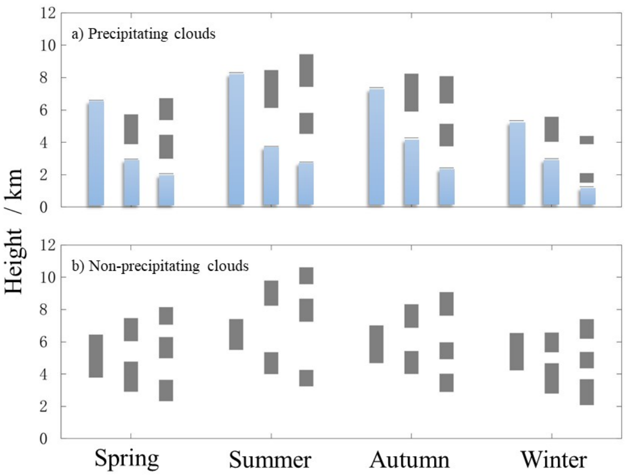

Figure 8. Average positions of single-layer and multi-layer clouds in (**a**) precipitating clouds and (**b**) non-precipitating clouds across different seasons.

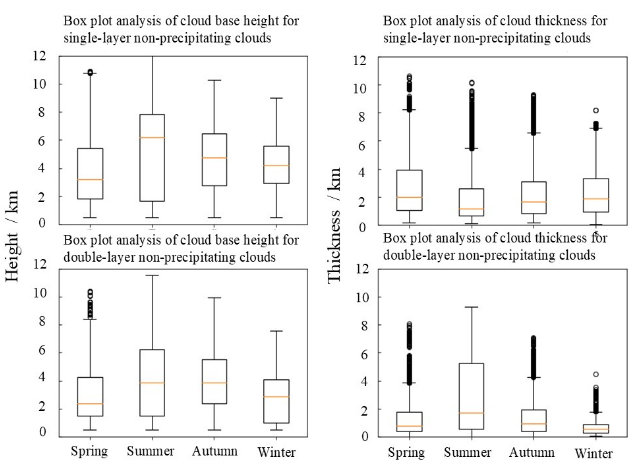

Figure 9. Box plot diagrams of cloud base height and cloud thickness of single-layer and the first layer of double-layer non-precipitating clouds.

5. Conlusions

Western Liaoning is in the combination zone of the Inner Mongolian Plateau, the North China Plain and the Northeast China Plain. It is in the eastern part of the farming-pastoral ecotone in northern China, which is a temperate semi-humid and semi-arid area[33, 34]. In addition, Monsoon climate bring more heat, less rain to western Liaoning. As a result, the vegetation coverage is low and the ecosystem is relatively fragile. Artificial precipitation enhancement is the most immediate and effective measure to increase water resources with the lowest cost, which plays a role in regulating the seasonal and regional uneven distribution of cloud water resources. The region attaches importance to the development of artificial precipitation enhancement to improve the ecological environment. Clouds are the main research objects of weather modification. Therefore, based on millimeter-wave cloud radar, we study the cloud occurrence rate, cloud layer and cloud interlayer distribution, vertical structure characteristics of precipitation cloud and non-precipitation cloud. The main points of our study can be summarized as follows:

(1) Cloud occurrence rate

In 2020, the cloud occurrence frequency was 25.50%, while 36.3% in Beijing, China[26] and 85% in Arctic[19], it is found that the cloud occurrence frequency is obviously different between extratropical region and latitude area. The diurnal variation in cloud occurrence rates varies across different seasons. In spring and summer, the occurrence rate increases significantly from noon (11:00) to evening (19:00) and then gradually decreases after 19:00, with an increase of about 8%. High clouds have the highest occurrence frequency, accounting for 40.03% of all clouds, while low and middle clouds have similar occurrence frequencies of 31.78% and 28.19%, respectively.

(2) Cloud layer distribution

The formation of clouds is mainly single-layer clouds. In precipitating clouds, the occurrence rate of single-layer clouds is lower than in non-precipitating clouds, with precipitation mainly originating from single-layer and double-layer clouds. Regarding the relationship between the number of cloud layers and rainfall intensity, the average rainfall intensity of cloud precipitation in western Liaoning is 3.1 mm/h throughout the year, and the rainfall intensity is greater in summer, with little difference in other seasons. From the perspective of cloud layer distribution, as the number of cloud layers increases, the rainfall intensity weakens, which is related to the development and evolution of precipitating clouds. Chinese scholars Liu et al. and Sun et al. used CloudSat satellite observation data to analyze the differences in the structure of precipitation clouds and non-precipitation clouds in Northeast China, and the differences in cloud vertical structure under the influence of different weather systems in Liaoning [11, 35]. Our results are basically consistent with their results. Because our study area is smaller and millimeter wave cloud radar data has the advantage of high spatial and temporal resolution, the research results are more detailed in depicting the vertical structure characteristics of clouds. It contributes the guidance for artificial precipitation enhancement operators in western Liaoning to be more operable, scientific and reasonable.

(3) Cloud interlayer distribution

Chinese scholars have used L-band sounding radar and satellite data to analyze the distribution characteristics of cloud interlayers. Based on L-band sounding data using threshold method of relative humidity to recognize cloud, Sun et al. obtained that the thickness of cloud interlayer in Shenyang area of central Liaoning is mainly below 2 km [16]. The thickness of cloud interlayer in summer is the largest, followed by autumn, but there is no analysis of the thickness of precipitation cloud interlayer. In comparison, the average cloud interlayer thickness in the central and western regions of Liaoning are both less than 2 km, while more detailed statistical characteristics of cloud interlayer are obtained by analyzing cloud radar data in our study. The average thickness of cloud interlayers in precipitating clouds in western Liaoning is 1.4 km, with 82.1% of cloud interlayer thickness being less than 2 km. In non-precipitating clouds, the average thickness of the cloud interlayer is 1.84 km, with 70.8% being less than 2 km. Yi et al. analyzed the macroscopic characteristics of precipitation clouds in western Inner Mongolia by using L-band sounding radar, satellite cloud image and automatic station precipitation data, and obtained that the number of cloud interlayers of most precipitation clouds was less than or equal to 2 and the thickness of interlayers was less than or equal to 0.6 km [36]. Compared with these results, the thickness of precipitation cloud interlayer in western Liaoning is 1.4 km. The reason for the differences is that Yi et al. subdivided the adjacent precipitation cloud. Considering that the development and evolution of precipitation clouds are continuous, and the operators focus on the rainfall potential of precipitation clouds for artificial precipitation enhancement. Therefore, the precipitation cloud samples include adjacent precipitation cloud samples in this paper.

At present, most of the research results are applied to the direction of climate characteristics, regional model cloud parameterization selection, etc. [23–28], which were studied by scholars using cloud radar data to statistically analyze the cloud vertical structure characteristics. Neither precipitation classification of clouds nor analysis of cloud interlayer characteristics were studied. The innovation of this paper is to pay more attention to the application of research results in weather modification. Our team members used minute precipitation data to judge whether clouds rained and ulteriorly carry out classified statistical analysis. The statistical characteristics of cloud interlayer are also valued. Based on the research results, we established a vertical structure model of precipitation clouds in western Liaoning. These research results are conducive to the scientific selection of Catalyst seeding operation site and operation time during the artificial precipitation operation period. Moreover, it improved the prediction accuracy of artificial precipitation enhancement potential conditions, which provided scientific support for the development of ecological restoration artificial precipitation enhancement.

The results of this study are still inadequate: meteorological phenomena often have interannual changes, only one year's cloud radar data is used as the statistical sample in this study, which cannot fully represent the long-term vertical distribution characteristics and trends of clouds. In the future, air-ground joint observation experiments will be carried out in combination with aircraft, microwave radiometer, micro-rain radar, etc., to accumulate high-quality multi-source observation datasets, which will be used to conduct in-depth research on the climate distribution, evolution and vertical structure characteristics of clouds and the inversion and application of cloud particle spectrum.

Author Contributions

Conceptualization, formal analysis and writing the initial draft, N.S.; Project Administration and supervision, Y.L.; Writing—review and editing, B.X.; Data curation, P.W.; Visualization, M.Z.

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Conflicts of Interest

The authors declare no conflict of interest.

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