Postprint: Variation Characteristics of Atmospheric Water Vapor on the Western Side of Liupan Mountain, Ningxia, Based on Microwave Radiometer Observations

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Abstract

Using data from a German-made microwave radiometer over 2 years at Longde Meteorological Station and concurrent 1-hour precipitation data, the temporal distribution characteristics of atmospheric water vapor content and cloud liquid water content on the western side of the Liupan Mountains were analyzed using statistical methods, and 92 precipitation cases of different types and magnitudes were analyzed to obtain the variation characteristics of pre-precipitation jump times. Statistical analysis with precipitation background removed shows: (1) The atmospheric water vapor content and cloud liquid water content on the western side of the Liupan Mountains exhibit significant seasonal variations, with summer being the season with the highest atmospheric water vapor content, averaging 23.44 mm and accounting for 47.7% of the annual mean water vapor content. (2) The diurnal variation of atmospheric water vapor content and cloud liquid water content shows a single-valley single-peak distribution, with maximum peaks occurring in the afternoon in spring, summer, and autumn, and at 11:00 in winter; the low-value regions of atmospheric water vapor content occur around sunrise in spring, summer, and autumn, and at 22:00 in winter. (3) In 87.0% of precipitation cases, the atmospheric water vapor content was above 12.00 mm before precipitation occurred, and its value increased with increasing precipitation magnitude. (4) Significant jump phenomena in cloud liquid water content occurred before precipitation, with strong manifestations in spring and summer; the pre-precipitation jump time varied according to precipitation type and magnitude. The research conclusions provide valuable reference for determining the timing of weather modification operations.

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Characteristics of Atmospheric Water Vapor Variation on the Western Side of Liupan Mountain in Ningxia Based on Microwave Radiometer

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1. Study Area Overview

The data used in this study were obtained from the Longde National Meteorological Observation Station (106°06 E, 35°36 N, 2079 m) in Longde County, Guyuan City, Ningxia Hui Autonomous Region. The station is located on the western side of the Liupan Mountains, approximately 800 m from the highest peak, with its specific geographical location shown in Figure [Figure 800: see original paper]. The Liupan Mountains are one of the few northwest-southeast oriented mountain ranges in western China (forming an angle of nearly 30° with the north-south direction), situated in the southwestern part of Ningxia Hui Autonomous Region and the eastern part of Gansu Province. The mountain ridge exceeds 2500 m in elevation, with the highest peak, Migang Mountain, reaching 2942 m. The Liupan Mountains constitute an important water conservation area and scenic spot on the Loess Plateau, serving as the source of the Jing River, Qingshui River, and Hulu River. Located at the edge of the East Asian monsoon region, the Liupan Mountains act as a gateway for warm and moist oceanic airflows entering the inland areas of northwest China and represent a critical region for atmospheric water vapor transport. Due to the unique topographic effects, as airflow crosses the mountains, cloud droplets often grow into precipitation particles within a short period before reaching the leeward slope through orographic convergence and lifting, frequently generating precipitation in this region. Consequently, the area experiences numerous rainy and foggy days, with foggy days reaching 153.4 days annually.

2. Data Sources and Processing

The Longde National Meteorological Observation Station is equipped with a German RPG-HATPRO-G4 ground-based microwave radiometer that has accumulated over a year of data, enabling effective monitoring of atmospheric water vapor characteristics on the western side of the Liupan Mountains. This instrument employs multi-channel parallel measurement technology, offering high temporal and spatial resolution, all-weather and all-day observation capabilities, and can continuously monitor and obtain data products including atmospheric temperature and humidity profiles, integrated atmospheric water vapor content, cloud liquid water content, and cloud base height in real time. To verify the applicability of this microwave radiometer, Sun Yanqiao et al. [11] conducted quality control experiments using three inspection methods on the microwave radiometer data and compared them with synchronous radiosonde data. The results indicated that data quality was optimal under clear skies, followed by cloudy conditions, and slightly poorer during precipitation, with correlation coefficients remaining at relatively high levels across all height layers. Tian Lei et al. [13] compared data from this instrument with synchronous radiosonde observations and found high correlation coefficients for observed average temperature profiles and water vapor density profiles, demonstrating the reliability and usability of the instrument' s data.

During data processing, second-level data were averaged to minute-level data, and universal time was converted to Beijing time. Previous studies have shown that one source of error for microwave radiometers is the liquid water attached to the radome, which leads to overestimated brightness temperature measurements. Therefore, to avoid precipitation impacts on detection accuracy, all precipitation periods were excluded from the analysis. Extreme value checks and internal consistency checks were applied to eliminate outliers, and mathematical statistical analysis methods were employed for data analysis. The study attempted to obtain seasonal, monthly, and diurnal variations of atmospheric cloud water on the western side of the Liupan Mountains and analyzed variation characteristics of atmospheric water vapor content and cloud liquid water content immediately before precipitation to identify their indicative significance for precipitation occurrence.

3. Results and Analysis

3.1 Seasonal and Monthly Variation Characteristics of Atmospheric Water Vapor and Cloud Water on the Western Side of Liupan Mountain Figure [Figure 2: see original paper] illustrates the seasonal variations of atmospheric water vapor content, cloud liquid water content, and 1-hour precipitation. The Liupan Mountains are located at the edge of the East Asian monsoon region, with abundant sunshine in summer and dry, cold conditions in winter. Atmospheric water vapor content and cloud liquid water content reach their maximum in summer (23.44 mm and 0.09 mm, respectively), with atmospheric water vapor content accounting for 47.7% of the annual average. Spring and autumn values are 9.23 mm and 12.26 mm, respectively, representing 24.9% and 18.8% of the annual average. Winter exhibits the lowest atmospheric water vapor content (4.26 mm) and minimal possibility of cloud formation, with both atmospheric water vapor content and cloud liquid water content (0.02 mm) significantly lower than other seasons, comprising only 7.4% of the annual average.

Figure [Figure 3: see original paper] shows the monthly mean values of atmospheric water vapor content, cloud liquid water content, and precipitation. Atmospheric water vapor content and cloud liquid water content gradually increase from January to July, particularly showing significant growth since the beginning of summer, which closely correlates with the marked increase in precipitation frequency and amount in the Liupan Mountains during summer. Both parameters exhibit a gradually decreasing trend from August to December, reaching minimum values in January. This distribution pattern primarily results from the influence of the southwestern monsoon from the Indian Ocean and the southeastern monsoon from the Pacific Ocean during summer, which establishes stable water vapor transport channels. In contrast, winter is mainly affected by the Siberian and Inner Mongolia high-pressure systems bringing northwesterly and northeasterly winds, resulting in less water vapor and cold temperatures. Although Ningxia is located inland with relatively weak monsoon influence, it remains within the monsoon-affected region [18].

Precipitation frequency was calculated as the ratio of days with precipitation $ $0.1 mm (counted as precipitation days) to the total number of days in the calculation period. Summer exhibits the highest precipitation frequency (46.7%) and the greatest magnitude, while autumn and spring have lower frequencies (37.9% and 34.8%, respectively). Winter precipitation primarily occurs as snowfall with a frequency of 18.3%. These results demonstrate significant seasonal variations in atmospheric cloud water conditions and precipitation on the western side of the Liupan Mountains, with water vapor concentrated mainly in summer and autumn, accounting for 72.6% of the annual water vapor content.

3.2 Diurnal Variation of Atmospheric Water Vapor and Precipitation on the Western Side of Liupan Mountain By averaging microwave radiometer-retrieved atmospheric water vapor content, cloud liquid water content, and precipitation data to hourly means and then calculating seasonal averages for each hour, the diurnal variation characteristics on the western side of the Liupan Mountains were obtained (Figure [Figure 4: see original paper]). The diurnal variation trends of atmospheric water vapor content and cloud liquid water content are similar across seasons, exhibiting a single-valley, single-peak pattern. In spring, summer, and autumn, the peak occurs in the afternoon (13:00–15:00), while in winter it appears at 11:00. The low-value zones occur around sunrise in spring, summer, and autumn, but at night (22:00) in winter. Cloud liquid water content peaks also occur in the afternoon during spring, summer, and autumn, consistent with the timing of atmospheric water vapor content peaks, while the winter maximum appears in the early morning (05:00) with a minimum in the evening (18:00).

The diurnal variation amplitude is greatest in summer, with an atmospheric water vapor content difference of 2.58 mm and cloud liquid water content difference of 0.27 mm between maximum and minimum values. Spring shows a larger diurnal variation than autumn, with atmospheric water vapor content ranging from 8.38-9.74 mm (difference of 1.36 mm) in spring and 11.69-12.88 mm (difference of 1.19 mm) in autumn. In winter, controlled by the northern cold high-pressure system with relatively stable atmospheric stratification, the diurnal variation amplitude is smallest (atmospheric water vapor content difference of 0.04 mm, cloud liquid water content difference of 0.02 mm). The time intervals from minimum to maximum values are 9 hours in spring, 8 hours in summer, 9 hours in autumn, and 13 hours in winter.

The primary precipitation periods occur at 20:00–03:00 in spring, 16:00–06:00 in summer, 22:00–04:00 in autumn, and 11:00–18:00 in winter. The diurnal variation characteristics of atmospheric water vapor content and cloud liquid water content are closely related to surface temperature. Before sunrise, surface temperature decreases, facilitating the formation of inversion layers in the lower atmosphere where water vapor continuously condenses and precipitates, causing atmospheric water vapor content to decline. After sunrise, surface and atmospheric temperatures gradually increase, and atmospheric convection transports water vapor to higher altitudes to form clouds, increasing both atmospheric water vapor content and cloud liquid water content until reaching afternoon maxima. Subsequently, as temperatures gradually decrease, water vapor condenses and precipitates, causing both parameters to decline again. In winter, the low-value zones appear in the evening because the lower temperatures at the mountain foothills inhibit convective development.

Water vapor variation is a rapid, complex, and multifaceted process. The specific timing of daily maximum and minimum values is not fixed, and the underlying reasons remain unclear, requiring more in-depth and detailed research for further explanation.

3.3 Variation Characteristics of Atmospheric Water Vapor Content and Cloud Liquid Water Content Before Precipitation

3.3.1 Variation Characteristics of Atmospheric Water Vapor Content Before Precipitation on the Western Side of Liupan Mountain Since microwave radiometer measurements contain significant errors during precipitation events, to identify variation characteristics before precipitation, we extracted atmospheric water vapor content values and cloud liquid water content data from 120 minutes before each precipitation event for statistical analysis. Table presents the weather conditions and atmospheric water vapor content 10 minutes before precipitation for 92 typical precipitation events (28 in spring, 36 in summer, 20 in autumn, and 8 in winter), classified by precipitation type and intensity (light rain: 0.1-9.9 mm, moderate rain: 10.0–24.9 mm, heavy rain: 25.0–49.9 mm).

The results show that before light rain events, the mean atmospheric water vapor content was 15.82 mm in spring, 30.76 mm in summer, and 19.43 mm in autumn.

Before moderate rain events, the mean values were 31.69 mm in spring, 22.04 mm in summer, and 25.00 mm in autumn, with 87.5% of cases exceeding 25.00 mm. Before heavy rain events (all occurring in summer), the mean atmospheric water vapor content was 37.84 mm, with 90.5% of heavy rain processes recording values greater than 33.49 mm. Overall, 87.0% of all precipitation cases had atmospheric water vapor content exceeding 12.00 mm before precipitation, with values increasing as precipitation magnitude increased.

3.3.2 Variation Characteristics of Cloud Liquid Water Content Before Precipitation on the Western Side of Liupan Mountain The data analysis revealed that cloud liquid water content exhibits a distinct jump increase before precipitation, most prominently in spring and summer, less so in autumn, and weakest in winter when precipitation occurs as snowfall. The timing of this pre-precipitation jump varies depending on precipitation amount and type. To further investigate the influence of precipitation characteristics on jump timing, 92 precipitation cases were classified by precipitation type and weather conditions, with cloud liquid water content data from 120 minutes before precipitation extracted for analysis.

Figure [Figure 6: see original paper] shows the variation of cloud liquid water content 120 minutes before convective, continuous, and intermittent precipitation events. Convective precipitation (sudden onset and cessation, duration < 2 hours) demonstrates significant jump increases before precipitation, with jump times distributed 10–20 minutes before the event. Averaging all convective precipitation cases shows that cloud liquid water content begins to increase approximately 15 minutes before precipitation onset, with an increment of about 0.6 mm. Continuous precipitation (duration ≥ 2 hours) includes 8 light rain, 10 moderate rain, and 4 heavy rain events. Continuous light rain shows gradual increase without significant jumps, while continuous moderate rain exhibits an increase-decrease-increase pattern: gradual increase begins 40 minutes before precipitation, decreases at 10 minutes, then jumps again to near 0.6 mm immediately before precipitation. Continuous heavy rain shows a dramatic increase 20 minutes before precipitation, jumping to approximately 1.0 mm, with a final jump of about 0.3 mm at 4 minutes before precipitation. Intermittent precipitation cases (all light rain) show cloud liquid water content fluctuating between 0.3–0.8 mm, with a jump of approximately 0.2 mm occurring 12 minutes before precipitation, reaching maximum at 6.5 minutes, then decreasing slightly.

4. Conclusions and Discussion

Using ground-based microwave radiometer data and collocated automatic weather station precipitation data, this study analyzed the seasonal distribution characteristics of atmospheric water vapor content, cloud liquid water content, and precipitation on the western side of the Liupan Mountains. Unlike previous studies, this research further conducted classified statistical analysis of pre-precipitation atmospheric water vapor content values and cloud liquid water content jump times under different precipitation amounts and types, providing a fundamental reference for precipitation prediction in weather modification operations. The main conclusions are as follows:

1) Under non-precipitation conditions, atmospheric cloud water conditions on the western side of the Liupan Mountains exhibit significant seasonal variation, with water vapor concentrated mainly in summer and autumn, accounting for 72.6% of the annual average. Spring shows an increasing trend while autumn shows a decreasing trend. Summer has the maximum atmospheric water vapor content (23.44 mm) and highest precipitation frequency, while winter has the minimum (4.26 mm), representing only 7.4% of the annual average. Atmospheric water vapor content and cloud liquid water content gradually increase before precipitation and decrease afterward, with large annual fluctuations.

2) The diurnal variation trends of atmospheric water vapor content and cloud liquid water content are similar across seasons, showing a single-valley, single-peak pattern with the largest amplitude in summer and smallest in winter. In spring, summer, and autumn, both parameters peak in the afternoon and reach minimum values around sunrise; in winter, the peak occurs at 11:00 and the minimum at night (22:00). This variation pattern is closely related to surface temperature.

3) Before precipitation, 87.0% of precipitation cases had atmospheric water vapor content exceeding 12.00 mm, with values increasing as precipitation magnitude increased. Specifically, before light rain, mean atmospheric water vapor content was 15.82 mm in spring, 30.76 mm in summer, and 19.43 mm in autumn. Before moderate rain, 87.5% of cases exceeded 25.00 mm, with mean values of 31.69 mm in spring, 22.04 mm in summer, and 25.00 mm in autumn. Before heavy rain, mean atmospheric water vapor content was 37.84 mm, with 90.5% of cases exceeding 33.49 mm.

4) The pre-precipitation jump phenomenon in cloud liquid water content is most evident in spring and summer. The jump timing characteristics vary by precipitation type: convective precipitation shows jumps beginning 15 minutes before onset with increments of ~0.6 mm; continuous light rain shows gradual increase without significant jumps; continuous moderate rain shows an increase-decrease-increase pattern with a final jump to ~0.6 mm; continuous heavy rain shows a dramatic jump to ~1.0 mm at 20 minutes before precipitation and a final jump of ~0.3 mm at 4 minutes; intermittent precipitation shows a jump of ~0.2 mm at 12 minutes before precipitation.

These preliminary results can provide technical reference for predicting precipitation proximity and determining whether cloud systems are in precipitation-generating stages, and can offer reference values for weather modification operation indicators. However, practical application requires further index verification combined with other meteorological observation instruments for comprehensive decision-making.

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Note: Figure translations are in progress. See original paper for figures.