Preliminary Observational Study of the Physical Structures of Two Fog Types in the Liupan Mountains (Postprint)

Authors: Zhangli Dang, Mu Jianhua, Yan Jun, Cao Ning, Chang Zhuolin, Mu Jianhua

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Abstract

Using conventional surface observation data (visibility, temperature, relative humidity, wind, etc.) from Longde, Jingyuan, and Liupanshan meteorological stations and vertical observation data of temperature and relative humidity from microwave radiometers obtained during the observation of alpine fog in the Liupan Mountain area in 2020, this study preliminarily analyzes the circulation patterns and vertical evolution characteristics of temperature and humidity during widespread fog events and fog events occurring only at the mountaintop in the Liupan Mountain area. The results indicate that both widespread fog processes and mountaintop-only fog processes in the Liupan Mountain area are caused by the influence of warm and moist airflow ahead of a trough, leading to cooling and humidification. During both types of fog processes, surface relative humidity exceeds 95%, with prevailing southerly winds. Visibility at Longde and Jingyuan meteorological stations is mostly above 200 m, while visibility at Liupanshan meteorological station is below 200 m for more than half of the time. Fog at Liupanshan meteorological station forms and dissipates rapidly, with strong dense fog lasting for a relatively long duration. The thickening of the inversion layer occurs earlier than the appearance of strong dense fog, with deep vertical development. When the fog reaches maturity, the inversion layer thickness reaches 1130 m. At Longde meteorological station, the inversion layer thickness also increases with fog development, but it is far less than that at Liupanshan meteorological station, while the inversion intensity at Liupanshan meteorological station is weaker than that at Longde meteorological station. With the development of fog, there is a noticeable upward extension of relative humidity, with relative humidity exceeding 90% extending to 1040 m. Meanwhile, when strong dense fog occurs at Liupanshan meteorological station, the microwave radiometer at Longde meteorological station can observe a saturated

zone at approximately 600 m, which is of significant importance for analyzing the vertical evolution of typical alpine fog in the Liupan Mountain area.

Full Text

Preliminary Observational Study of Physical Structures of Two Types of Fog in the Liupan Mountain Area

DANG Zhangli[1,2], MU Jianhua[1,2], YAN Jun[1], CAO Ning[1,2], CHANG Zhuolin[1,2]

[1] Key Laboratory for Meteorological Disaster Monitoring and Early Warning and Risk Management of Characteristic Agriculture in Arid Regions, China Meteorological Administration, Yinchuan 750002, Ningxia, China
[2] Ningxia Weather Modification Center, Yinchuan 750002, Ningxia, China

Abstract: Using routine surface observation data of visibility, temperature, relative humidity, and wind from Longde, Jingyuan, and Liupanshan meteorological stations, along with vertical temperature and humidity profiles from a microwave radiometer collected during mountain fog observations in the Liupan Mountain area in 2020, this study preliminarily analyzes the circulation patterns and vertical evolution characteristics of temperature and humidity during large-scale fog events and mountaintop-only fog events. The results show that both types of fog processes are caused by warm, moist airflow ahead of a trough, leading to cooling and humidification. During both processes, surface relative humidity exceeds 95% with prevailing southerly winds. Visibility at Longde and Jingyuan stations is mostly above 200 m, while at Liupanshan station it remains below 200 m for more than half of the time. Fog at Liupanshan station forms and dissipates rapidly, with strong dense fog persisting for extended periods. The inversion layer thickens earlier than the appearance of strong dense fog, reaching a thickness of 1130 m when the fog matures. Although the inversion layer at Longde station also thickens with fog development, it remains far thinner than at Liupanshan station, while the inversion intensity at Liupanshan station is weaker than at Longde station. As fog develops, relative humidity exhibits significant upward extension, with values above 90% reaching 1040 m. Meanwhile, when strong dense fog occurs at Liupanshan station, the microwave radiometer at Longde station can observe a saturated zone of approximately 600 m, which is significant for analyzing the vertical evolution of typical mountain fog in the Liupan Mountain area.

Keywords: fog; physical structure; observational study; Liupan Mountain area

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Fog is a weather phenomenon where horizontal visibility decreases to below 1 km due to numerous water droplets or ice crystals suspended in the near-surface air. The direct and indirect impacts of fog on human activities have attracted multidisciplinary attention. Many scholars have conducted extensive research on fog, investigating the circulation backgrounds and boundary layer characteristics of fog over different underlying surfaces in North China, Northwest China, and Zhanjiang. These studies have found that fog formation involves warm advection input, water vapor convergence, and is accompanied by inversion layers and increased relative humidity in the lower atmosphere. Mountain fog occurs at high altitudes of 1–2 km and is primarily generated by the passage of high-altitude clouds. Research on mountain fog began early both domestically and internationally, with some alpine stations in central Europe operating for over 100 years. China established its earliest mountain station on Hengshan in Hunan. Mountain fog is closely related to local topography, radiation inversion, and other factors, with distinct spatiotemporal distributions across regions. Guo Lijun et al. found that clouds and fog over Mount Lu occur predominantly in autumn, winter, and spring. Fei Dongdong et al. observed that mountain fog in Hubei occurs under low wind speeds, predominantly southeasterly winds, with inversion layers in the near-surface layer, cloud-ground contact, and sustained high relative humidity in the lower atmosphere during fog dissipation with rising cloud base height. Deng Xuejiao et al. analyzed a heavy fog event in the Nanling Mountains and found that fog formation is accompanied by inversion development and relative humidity increase, with saturated zones in the lower humidity layer extending toward the surface and cloud base grounding. Single-layer strong inversion structures favor fog development and maintenance, while multi-layer weak inversion structures tend to cause fog dissipation. You Hong et al. analyzed typical mountain fog processes along the Eshan section of the Kunluo Expressway in Yunnan and found inversion or neutral layers at 850–800 hPa above the fog region, with stronger inversion layers corresponding to denser mountain fog.

The Liupan Mountain area is located in southern Ningxia, on the northeastern edge of the Tibetan Plateau, representing a typical temperate mountain forest ecosystem and important water source conservation area on the western Loess Plateau. With strong water vapor transport, the region receives abundant moisture carried by southerly monsoons in summer, creating high relative humidity zones. The eastern slope is steep while the western slope is gentle. Liupanshan Meteorological Station (35.7°N, 106.2°E) is situated at the highest altitude (2845.2 m) in the region, with an average of 153.4 fog days annually. Due to topographic influences, significant differences in fog days occur within a 20 km range. In 2020, the Ningxia Meteorological Disaster Prevention Technology Center conducted cloud and fog observation experiments at the Liupan Mountain Atmospheric Science Field Experiment Base. This study selected the longest-duration and most intense two types of fog processes from these experiments to investigate the influence of different meteorological elements on fog processes and preliminarily analyze differences in physical structures during these events, which is important for improving cloud and fog monitoring, early warning, numerical simulation, artificial fog dissipation, and tourism resource development in the Liupan Mountain area.

2 Data and Methods

This study analyzes the circulation background, macroscopic physical structure, and vertical evolution characteristics of temperature and relative humidity during two types of fog processes in the Liupan Mountain area using meteorological station surface observation data, Longde microwave radiometer data, and ERA5 reanalysis data from the 2020 observation period. The macroscopic physical structure observations utilize national meteorological observation station equipment for temperature, pressure, relative humidity, and visibility. Vertical structure observations employ a METEK MWP-967KV microwave radiometer that retrieves vertical profiles from 0–10 km, with 0–100 m vertical resolution of 25 m, 100–500 m resolution of 50 m, 500–1200 m resolution of 100 m, and above 1200 m resolution of 250 m, at 1-minute temporal resolution. The radiometer was installed at Longde National Meteorological Observation Station and calibrated with liquid nitrogen each quarter during the observation period. Circulation background analysis uses ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts, providing global 0.25°$×$0.25° gridded data of geopotential height, humidity, temperature, water vapor flux, water vapor flux divergence, and wind fields.

3.1 Large-Scale Fog Process

3.1.1 Process Overview Based on visibility time series from Liupanshan, Jingyuan, and Longde stations (Figure 2), we analyzed the fog weather process without separating brief weakening periods during sustained fog events. At Liupanshan station, fog began at 20:41 with minimum visibility of 1409 m, dense fog lasting 506 minutes. At Longde station, fog began at 19:09 with minimum visibility of 188 m, strong dense fog lasting 403 minutes. At Jingyuan station, fog began at 22:30 with minimum visibility of 423 m, dense fog lasting only 2 minutes, without reaching strong dense fog stage. Analysis of visibility temporal changes across the Liupan Mountain area reveals that mountaintop fog (Liupanshan station) persists longest. The eastern slope (Jingyuan station) experiences approximately 1-hour fog events as the cloud base lowers over the mountaintop, with synoptic systems moving westward. The western slope (Longde station) experiences rapid fog development; although shortest in duration, its minimum visibility is lower than the eastern slope, indicating that synoptic systems accelerate and intensify during passage.

3.1.2 Circulation Pattern Analysis Weather systems are primary factors in fog formation, development, and dissipation. Analysis of the large-scale fog process shows that at 500 hPa, Eurasia was under a two-trough-one-ridge pattern, with the southern branch trough extending to the Bay of Bengal and Liupan Mountain area located in the southwestern flow ahead of the trough with obvious warm advection. At 700 hPa, the region was in the southwestern flow ahead of a low vortex and shear line influence area, with clear wind speed convergence decreasing from 18 $m \cdot s^{-1}$ in Yunnan to 4 $m \cdot s^{-1}$ near Liupan Mountain. Both 500 hPa and 700 hPa levels were influenced by southwestern flow with relative humidity exceeding 70%. At the surface, Liupan Mountain area was in a uniform pressure field ahead of a cold high. This large-scale fog process resulted from combined influences of a low pressure near Lake Baikal, a southern branch trough, an eastward-moving shortwave trough at mid-levels, and a surface uniform pressure field, forming a systematic cloud-fog-precipitation weather process.

Fog formation and maintenance require specific moisture conditions. Water vapor flux increased from 1 $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$ before fog to a maximum of 3 $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$ during the most developed stage, decreasing to 1 $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$ at fog dissipation. During dense fog, wind speed was minimal with an average of 0.8 $m \cdot s^{-1}$ and prevailing southerly winds. Comprehensive analysis shows that before Liupanshan fog began at 18:00, 700 hPa specific humidity was 4 $g \cdot kg^{-1}$, and near-surface (800 hPa) specific humidity was 3 $g \cdot kg^{-1}$, allowing fog formation. At Jingyuan station, specific humidity reached 3–4 $g \cdot kg^{-1}$ at 22:00. The water vapor flux maximum zone was located in southern Ningxia, moving westward toward Shaanxi under southerly flow, reaching its peak in Liupan Mountain area after midnight on the 3rd. As wind direction turned northerly, water vapor flux decreased. Although both mountaintop and slopes were affected by synoptic systems, the mountaintop at over 2800 m remained in cloud until the large-scale cloud system moved away and visibility improved.

3.1.3 Surface Meteorological Element Changes Surface meteorological elements directly reflect changes before and after fog events. At Liupanshan station, temperature decreased continuously from 0.3°C before fog to -5.8°C, while relative humidity increased from 73% to 98% during dense fog. Wind speed decreased from 2.7–5.8 $m \cdot s^{-1}$ before fog to 1.7 $m \cdot s^{-1}$, then intensified to a maximum of 10.3 $m \cdot s^{-1}$ during dense fog, weakening to 1.7 $m \cdot s^{-1}$ at dissipation. From pre-fog to development stage, Liupanshan station experienced southerly winds, shifting from southwest to southeast and then east during dense fog, and turning northeasterly during weakening and dissipation.

At Longde station, temperature decreased from 7.7°C before fog to -2.0°C, remaining relatively stable at -1.8 to -2.0°C during development to dissipation. Relative humidity increased from 73% to 98% until fog dissipation. Wind speed varied greatly before fog, from calm to 4.1 $m \cdot s^{-1}$, decreasing continuously to below 3 $m \cdot s^{-1}$ during development to dissipation with prevailing southerly winds. At Jingyuan station, temperature decreased from 4.3°C to 1.6°C during fog, with both weakening and dissipation stages showing temperature decreases to -1.6°C. Relative humidity increased from 73% to 98%, remaining around 1.6°C during development and weakening stages. Maximum wind speed was 2.9 $m \cdot s^{-1}$ with wind direction shifting from northwesterly to southeasterly.

3.1.4 Vertical Distribution of Temperature and Relative Humidity Using microwave radiometer data from Longde station, we analyzed vertical distribution characteristics of relative humidity and temperature across different regions (Figure 4). To clearly display inversion layer distribution, temperature profiles only show values at inversion or isothermal heights. Overall, temperature above Longde station decreases with height and time, with maximum temperatures occurring near the surface before 14:00. After 14:00, temperature drops and near-surface inversion begins at 18:00, thickening over time to reach maximum thickness at 08:00, about 2 hours before Liupanshan station's minimum visibility time. Inversion intensity persists at 5.4°C for 17 minutes, gradually disappearing under precipitation influence, then reappearing after precipitation ends.

Relative humidity at Longde station decreases rapidly with height (except during precipitation periods). Before precipitation, relative humidity shows several high-value periods from surface to 1800 m (relative height). As fog develops, relative humidity above 90% extends to 400 m (relative height), then to 1040 m. This may relate to Liupanshan station fog processes—comparison with visibility trends shows that when high relative humidity zones appear in the 1800 m range, Liupanshan station visibility decreases rapidly, indicating that lower-level relative humidity changes strongly impact upper-level visibility.

Comprehensive analysis of fog periods across different regions shows that before 18:00, Longde station's near-surface inversion and Liupanshan station's upper-level inversion indicate radiation cooling-induced fog. After 05:00, fog coinciding with precipitation periods shows that inversion or isothermal layers disappear with precipitation ending. Jingyuan station fog appears in the latter half of the night, consistent with typical radiation fog timing.

3.2 Mountain-Top Fog Process

3.2.1 Process Overview Based on visibility time series from Liupanshan, Jingyuan, and Longde stations (Figure 5), comparative analysis shows that Liupanshan fog began at 23:45 with visibility dropping to 611 m, rapidly evolving to strong dense fog at 23:46 with minimum visibility of 172 m. Strong dense fog persisted for more than half of the total fog duration. Jingyuan station visibility improved completely after 08:15, while Liupanshan fog began at 23:45, lasting 511 minutes with dense fog for 189 minutes and strong dense fog for 303 minutes.

3.2.2 Circulation Pattern At 500 hPa, airflow was smooth with Liupan Mountain area in westerly-southerly flow. At 700 hPa at 08:00, the region was in southerly flow ahead of a low pressure system with obvious warm advection, located at the convergence zone between cold air from central Gansu and southwestern warm-moist airflow, with relative humidity exceeding 70%. At the surface, Liupan Mountain area was in a uniform pressure field ahead of a cold high (1005–1010 hPa). Before fog onset at 22:00, near-surface specific humidity was 3 $g \cdot kg^{-1}$, increasing to 3–4 $g \cdot kg^{-1}$ during fog development under southerly flow, with water vapor flux reaching 1–3 $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$.

3.2.3 Surface Meteorological Element Changes Temperature decreased from -0.5°C before fog to -3.2°C, recovering to -0.8°C at dissipation, with maximum temperature of -3.3 to -2.1°C during development. Relative humidity increased from 73% before fog to 98% at peak, remaining above 90% from development through weakening stages. Wind speeds were greater than 6.0 $m \cdot s^{-1}$ from pre-fog to dense fog stages, with maximum speed of 15.8 $m \cdot s^{-1}$ during dense fog, decreasing to 3.7 $m \cdot s^{-1}$ during weakening. Wind direction was primarily southwesterly from pre-fog to dense fog stages, shifting from northwesterly to northeasterly during weakening to dissipation.

During Liupanshan fog, Jingyuan station maintained minimum temperature around 2.2°C with maximum relative humidity of 98% and average wind speed of 2.9 $m \cdot s^{-1}$, with wind direction shifting from northwesterly to southeasterly. Longde station maintained minimum temperature around -1.0°C with maximum relative humidity of 98% and average wind speed of 3.7 $m \cdot s^{-1}$, with wind direction shifting from northwesterly to southeasterly.

3.2.4 Vertical Distribution of Temperature and Relative Humidity Using Longde station microwave radiometer data, we analyzed the vertical temperature and humidity structure above Liupan Mountain area (Figure 7). Relative humidity first increased then decreased, peaking around 06:30, coinciding with persistent strong dense fog at Liupanshan station. A saturated zone (relative humidity 100%) appeared at 2281–2872 m (altitude), consistent with Liupanshan strong dense fog. This agrees with Fei Dongdong et al.'s conclusion that mountain fog develops deeply during mature stages, but Liupanshan fog developed even more deeply, reaching maximum thickness of 1040 m. Visibility exceeded 1000 m at 08:15, yet relative humidity remained above 90% at 1000 m until 09:11.

Temperature profiles show that near-surface temperature at Longde station first decreased, then increased, then decreased again, while temperature at Liupanshan station decreased continuously. Inversion appeared at 20:00, extending downward and upward with fog development, reaching maximum thickness of 1130 m. Inversion layer thickness increased earlier than strong dense fog appearance, dissipating with fog dissipation. The inversion layer was thickest at Liupanshan station (1130 m), much thicker than at Longde station (maximum 190 m), though inversion intensity was weaker at Liupanshan station (maximum 2.5°C) than at Longde station (maximum 5.4°C). Analysis of temperature profiles at 22:00, 02:00, and 08:00 shows different inversion intensities existed during fog development, with maximum intensity at 02:00 when inversion thickness reached 560 m.

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