Postprint: Near-Surface Specific Humidity Distribution and Profile Characteristics in Urban and Suburban Areas of Urumqi

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Abstract

Using specific humidity data from 10 layers of 5 meteorological towers at 100 m height in urban and suburban areas of Urumqi, as well as L-band sounding radar data from the Urumqi Meteorological Station, the characteristics of specific humidity profiles within the 2 km boundary layer, the seasonal and diurnal variation characteristics of specific humidity in the near-surface layer in urban and suburban areas, and the causes of humidity inversion in Urumqi were analyzed in detail. The following results were obtained: (1) The seasonal differences in specific humidity in Urumqi are significant, with the minimum in winter, slightly larger values in spring and autumn, and the maximum in summer. Summer specific humidity is approximately 4-5 times that of winter, while autumn specific humidity is only 1 $g \cdot kg^{-1}$ greater than that of spring. Except in winter, specific humidity tends to decrease with increasing altitude, with the most significant decrease occurring in summer, while the vertical variation of specific humidity in winter is very small. The minima of the specific humidity profile appear at similar heights during both day and night, and there are multiple minima. The diurnal variation of specific humidity is greatest in summer and winter, with opposite phases: in summer it is larger at night and smaller during the day, while in winter the opposite is true. In winter, specific humidity in suburban areas is lower than in urban areas; in other seasons, the difference in specific humidity between urban and suburban areas is not significant. (2) Humidity inversion phenomena exist within 2 km, with the occurrence probability of humidity inversion exceeding 35%, being highest in January and lowest in July. The maximum height of humidity inversion exceeds 1,500 m in January, while in July it can reach 1,900 m, with a maximum thickness of 1,550 m. The maximum intensity of humidity inversion can reach 2.5 $g \cdot kg^{-1} \cdot (100\ m)^{-1}$ in July and October, while it is minimum in January. (3) Humidity inversion in January is often accompanied by temperature inversion. The temperature inversion layer alters the vertical distribution structure of water vapor, with humidity inversion phenomena occurring from the top of the surface-decoupled inversion layer. Humidity inversion is also related to water vapor transport. This study can effectively reveal the seasonal characteristics of air humidity and provides an approach for investigating the meteorological factors involved in the formation of urban air pollution.

Full Text

Characteristics of Specific Humidity Distribution and Profiles in the Urban and Suburban Surface Layer of Urumqi

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Abstract

Using L-band radar sounding data and 100-m meteorological tower observations from urban and suburban areas of Urumqi, this study analyzes the specific humidity distribution and profile characteristics within the atmospheric boundary layer. The results reveal: (1) Seasonal variation is significant, with winter having the lowest specific humidity, spring and autumn slightly higher, and summer the highest (about 4–5 times that of winter). Specific humidity decreases with height in all seasons except winter where vertical variation is minimal. Multiple minima appear in humidity profiles at similar heights during day and night. (2) Diurnal variation is greatest in summer and winter with opposite phases: summer shows higher humidity at night and lower during day, while winter shows the opposite pattern. In winter, suburban humidity is lower than urban areas, with little difference in other seasons. (3) Moisture inversion occurs within the 2 km boundary layer with probability exceeding 35%, reaching maximum thickness of 1550 m. The strongest inversion occurs in July (2.5 $\text{g} \cdot \text{kg}^{-1}$ per 100 m) with maximum height over 1900 m, while January shows the weakest inversion. Moisture inversion is often accompanied by temperature inversion, which alters the vertical water vapor distribution structure. The inversion typically appears from the top of the elevated temperature inversion layer and is also related to water vapor transport. This study effectively reveals seasonal humidity characteristics and provides insights for studying meteorological factors affecting

urban air pollution formation.

Keywords: boundary layer; specific humidity; profile; Urumqi City

1. Data and Humidity Calculation Methods

1.1 100-m Tower Data

The terrain of Urumqi slopes downward from the southern suburbs to the northern suburbs. Five 100-m meteorological towers were installed along this gradient at the following locations (Figure 1): Yannan Overpass (southern suburb, 87°34 E, 43°42 N, 1009 m a.s.l.), Shuita Mountain (urban area, 87°38 E, 43°49 N, 890 m a.s.l.), Liyu Mountain (urban area, 87°34 E, 43°50 N, 821 m a.s.l.), Hongguang Mountain (near northern suburb, 87°38 E, 43°54 N, 717 m a.s.l.), and Midong (northern suburb, 87°41 E, 44°01 N, 568 m a.s.l.). Each tower has identical specifications with instruments installed at 10 levels. All levels are equipped with VAISALA HMP45D temperature and humidity sensors (temperature range: -40°C to +60°C, resolution: 0.1°C; humidity range: 0-100%, resolution: 1%) and VAISALA PTB220 barometric pressure sensors (pressure range: 500-1100 hPa, resolution: 0.1 hPa). All instruments were calibrated before installation. The tower temperature, humidity, and pressure data underwent strict quality control and processing before use.

1.2 L-band Radar Sounding Data

The Urumqi National Meteorological Station conducts L-band radar soundings at 07:00 and 19:00 local time (Urumqi local time). This study uses sounding data from typical months representing the four seasons to analyze the seasonal distribution characteristics of specific humidity profiles within the boundary layer.

1.3 Humidity Calculation

The towers directly measure relative humidity, which was converted to specific humidity for analysis using the following formula:

$$q = \frac{0.622 \times f \times E_w \times 1000}{P \times 100 - f \times E_w}$$

where f is relative humidity (as a decimal, not percentage), P is the near-surface atmospheric pressure (hPa) synchronized with temperature T, and q is specific humidity ($\mathrm{g \cdot kg^{-1}}$). The saturation vapor pressure over a pure water flat surface E_w is calculated as:

$$\begin{aligned}\lg E_w =& 10.79574\left(1-\frac{T_1}{T}\right)-5.02800\lg\left(\frac{T}{T_1}\right)\\ &+1.50475\times10^{-4}\left[1-10^{-8.2969\left(\frac{T}{T_1}-1\right)}\right]\\ &+0.42873\times10^{-3}\left[10^{4.76955\left(1-\frac{T_1}{T}\right)}-1\right]+0.78614\end{aligned}$$

where E_w is saturation vapor pressure (hPa), $T_1 = 273.16$ K is the triple point temperature of water, and T is absolute temperature (K).

2. Results and Analysis

2.1 Vertical Humidity Profiles within the 2 km Boundary Layer

Figure 2 shows the mean vertical distribution of specific humidity in the atmospheric boundary layer at 07:00 for typical months in Urumqi, calculated from L-band radar sounding data. Specific humidity is highest in summer and lowest in winter, with minimal vertical variation in winter. Spring and autumn values are similar, consistent with the seasonal variation of the atmospheric boundary layer structure observed by L-band radar.

Within the 2 km boundary layer, specific humidity decreases with height, consistent with observations from the Tibetan Plateau, central plains, Heihe region, and tropical ocean areas. However, Urumqi also exhibits significant moisture inversion, which can be analyzed from the twice-daily sounding profiles. Statistical results are shown in Table 1. The probability of moisture inversion is highest in January and lowest in July, but overall exceeds 35% in all months. The maximum height of moisture inversion reaches 1500 m in January and can exceed 1900 m in July, with a maximum thickness of 1550 m. The strongest inversion occurs in July and October at 2.5 $\mathrm{g\cdot kg^{-1}}$ per 100 m, while the weakest occurs in January.

Moisture inversion in Urumqi is often accompanied by temperature inversion. The presence of inversion layers alters the vertical structure of water vapor distribution, creating discontinuities in both temperature and moisture. Temperature inversion layers cause water vapor to accumulate at their tops, forming moisture inversion. This relationship is particularly evident during snowfall events. On January 1 and 6, 2014, elevated temperature inversions were observed at 950–1100 m, with corresponding moisture inversion appearing above the inversion layer top. The moisture inversion height and distribution range correspond closely with the temperature inversion.

Moisture inversion is also related to water vapor transport. On July 4, 2013, strong moisture inversion occurred below 850 m, coinciding with a wind direction shift from northerly to southerly at 700 m, indicating that moisture inversion is associated with horizontal advection of moist air in the boundary layer.

2.2 Annual Variation Characteristics of Humidity

Figure 5 shows the monthly mean specific humidity variation at each tower. All towers exhibit clear seasonal variation, though values differ by location. The lowest monthly mean specific humidity occurs in January (1.17-1.63 $g \cdot kg^{-1}$), while the highest occurs in July (7.33-8.14 $g \cdot kg^{-1}$). The maximum specific humidity appears around midnight in the southern suburbs and urban areas, but near sunrise in the northern suburb of Midong. The minimum specific humidity in summer and autumn occurs around 14:00, lagging the maximum temperature by 2-3 hours. In winter, the minimum specific humidity occurs around 08:00, lagging the maximum temperature by about 1 hour.

2.3 Annual Mean Diurnal Variation Characteristics of Humidity

Figure 6 presents the annual mean diurnal variation of specific humidity at different heights for the five towers. The annual mean specific humidity shows clear diurnal variation: high at night and low during the day. The maximum annual mean specific humidity occurs at 22:00-01:00 (4.31-4.35 $g \cdot kg^{-1}$), lagging the maximum temperature by 3-4 hours. The minimum occurs at 14:00-17:00 (3.75-3.86 $g \cdot kg^{-1}$). After sunrise, as surface temperature rises, specific humidity in the lower near-surface layer decreases sharply. For example, at Hongguang Mountain, specific humidity decreases from 4.33 $g \cdot kg^{-1}$ at 08:00 to 4.19 $g \cdot kg^{-1}$ at 14:00. Moisture inversion exists within the 0-100 m layer throughout the day, with multiple inversion layers present.

2.4 Seasonal Diurnal Variation Characteristics of Humidity

Figure 7 shows the seasonal mean diurnal variation of specific humidity at different heights. In summer, the diurnal variation is most pronounced, with higher humidity at night and lower during the day. The maximum appears around 22:00 (7.39-8.14 $g \cdot kg^{-1}$) and the minimum around 14:00 (4.01-4.24 $g \cdot kg^{-1}$). In winter, the pattern reverses: humidity is lower at night and higher during the day, with maximum around 14:00 (1.72-1.78 $g \cdot kg^{-1}$) and minimum around 08:00 (1.42-1.53 $g \cdot kg^{-1}$). Spring and autumn show transitional patterns, with spring variation being less obvious.

Moisture inversion within 0-100 m is present year-round. In summer, the strongest inversion occurs at Midong (8.1 $g \cdot kg^{-1}$ per 100 m), likely due to its location at the oasis-desert interface. The inversion is weaker in winter across all sites.

2.5 Seasonal Variation Characteristics of Humidity Profiles

Figures 8-11 show seasonal specific humidity profiles for the five towers. In spring (Figure 8), profiles show a general decrease with height but with multiple inversion layers. The maximum humidity gradient in spring occurs at 20-40 m, with values of -1.9 to -1.2 $g \cdot kg^{-1}$ per 100 m across different towers.

In summer (Figure 9), the maximum humidity appears in the latter half of the night, possibly because stronger evaporation requires more time for air cooling and subsidence to return moisture to the surface layer. The maximum humidity gradient in summer is -8.1 $g \cdot kg^{-1}$ per 100 m at Midong.

In autumn (Figure 10), the humidity gradient is similar to spring but with slightly larger values. The maximum gradient ranges from -3.4 to -0.9 $g \cdot kg^{-1}$ per 100 m across towers.

In winter (Figure 11), moisture inversion is weak, with maximum gradients of only -0.9 to -0.6 $g \cdot kg^{-1}$ per 100 m. The vertical distribution is relatively stable with little variation.

3. Near-Surface Humidity Profiles Under Different Stratification Conditions

Analysis of near-neutral, stable, and unstable stratification conditions at four towers (excluding Shuita Mountain due to non-contemporaneous data) reveals that moisture inversion occurs under all stratification types, though with varying intensity (Figure 13). Using logarithmic coordinates for height, the humidity profiles deviate from logarithmic patterns under near-neutral conditions, possibly due to classification methods and sample representativeness. Multiple moisture inversion layers exist under all stability conditions.

4. Conclusions

1. Within the 2 km boundary layer, specific humidity in Urumqi is approximately 2 $g \cdot kg^{-1}$ in winter, 5 $g \cdot kg^{-1}$ in spring and autumn, and 9 $g \cdot kg^{-1}$ in summer. Specific humidity decreases with height, with the most significant decrease in summer and minimal change in winter. Within the 0–100 m layer, the maximum humidity gradient in spring occurs at 20–40 m, with values of -1.9 to -1.2 $g \cdot kg^{-1}$ per 100 m. In summer, the strongest inversion (-8.1 $g \cdot kg^{-1}$ per 100 m) occurs in the northern suburb of Midong, while the strongest inversion in the urban area is -5.2 $g \cdot kg^{-1}$ per 100 m. In autumn, the maximum gradient is -3.4 to -0.9 $g \cdot kg^{-1}$ per 100 m, and in winter it is only -0.9 to -0.6 $g \cdot kg^{-1}$ per 100 m.
2. Seasonal and diurnal variations of specific humidity are significant in both urban and suburban areas. The lowest specific humidity occurs in January and the highest in July. In summer and autumn, humidity is higher at night and lower during the day, while in winter the pattern is opposite. In spring, diurnal variation is less pronounced. The maximum humidity appears around midnight in the southern suburbs and urban areas, but near sunrise in the northern suburbs.
3. Moisture inversion occurs year-round in Urumqi with probability exceeding 35%. The inversion is often accompanied by temperature inversion and is related to water vapor transport. The maximum inversion height

exceeds 1900 m in summer and 1500 m in winter, with a maximum thickness of 1550 m. The inversion is strongest in summer and weakest in winter.

This study reveals the seasonal characteristics of atmospheric humidity in Urumqi and provides a basis for understanding meteorological factors affecting urban air pollution.

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