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Characteristics of Atmospheric Diffusion Conditions During Winter Foehn Weather Processes in Urumqi (Postprint)

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Abstract

Using hourly surface meteorological data, second-level sounding data, and wind profiler radar data, we analyzed the variation characteristics of boundary layer and near-surface meteorological diffusion conditions during the evolution of low-level foehn winds in Urumqi from 2013 to 2017. The results indicate that: (1) The atmospheric diffusion conditions in Urumqi are generally most favorable in summer and worst in winter (maximum mixing layer thickness 0.44×10^{3} m, ventilation coefficient 1.52×10^{3} $m^2 \cdot s^{-1}$, inversion layer thickness 768 m, temperature difference across the inversion layer 4.82 °C, static stability index 6.36), with December and January in winter being extremely unfavorable for pollutant dispersion. (2) During the five stages of low-level foehn evolution in winter, the atmospheric mixing layer thickness and ventilation coefficient exhibit a decreasing-increasing pattern; the mixing layer thickness reaches its minimum (0.30×10^{3} m) and the ventilation coefficient its smallest value (0.62×10^{3} $m^2 \cdot s^{-1}$) during the peak foehn period; the inversion layer thickness and intensity, and static stability index show an increasing-decreasing trend, with the strongest inversion (10.9 °C), inversion layer thickness (0.99×10^{3} m), and maximum static stability index (9.7) occurring during the peak period. (3) During the development and peak periods of the low-level foehn process, atmospheric pressure decreases at all stations, temperature increases and wind speed strengthens at high-altitude stations, while temperature decreases and wind speed diminishes in low-altitude areas below the foehn layer, demonstrating that the foehn renders the atmosphere more stable in regions beneath the foehn layer, which is detrimental to pollutant dispersion. (4) Overall, the foehn weakens horizontal diffusion capacity and vertical exchange capacity, makes the atmosphere prone to condensation, and diffusion conditions are re-established after its cessation. In operational practice, the development trend of foehn can be utilized to predict the evolution of boundary layer diffusion conditions and

surface meteorological elements, providing a reference basis for air pollution forecasting and pollution control in the Urumqi urban agglomeration.

Full Text

Characteristic Analysis of Atmospheric Diffusion Conditions During Winter Foehn Weather Processes in Urumqi

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Abstract

Using hourly surface meteorological data, second-level radiosonde data, and wind profile radar data from 2013 to 2017, this study analyzes the evolution characteristics of low-altitude foehn and atmospheric diffusion conditions in the boundary layer and near-surface layer in Urumqi. The results show that: (1) Atmospheric diffusion conditions in Urumqi are generally most favorable in summer and worst in winter (maximum mixed layer thickness = 0.44×10^{3} m, ventilation coefficient = 1.52×10^{3} $m^2 \cdot s^{-1}$, inversion layer thickness = 768 m, inversion layer temperature difference = 4.82 ℃, static stability index = 6.36), with December and January being extremely unfavorable for pollutant diffusion. (2) During the four stages of low-altitude foehn evolution, atmospheric mixed layer thickness and ventilation coefficient exhibit a decreasing-increasing pattern, reaching minimum values during the foehn' s vigorous period (0.30×10^{3} m and 0.62×10^{3} $m^2 \cdot s^{-1}$, respectively). Inversion layer thickness and intensity, as well as the static stability index, show an opposite increasing-decreasing trend, peaking during the vigorous period (inversion layer thickness = 808 m, temperature difference = 10.9 ℃, static stability index = 0.99×10^{1}). (3) During the development and vigorous periods of foehn processes, station pressure decreases, high-altitude stations experience temperature increases and wind speed enhancement, while low-altitude areas below the foehn layer show temperature decreases and wind speed reduction, indicating that foehn makes the atmosphere below the foehn layer more stable and unfavorable for pollutant diffusion. (4) Overall, foehn weakens horizontal diffusion capacity and vertical exchange capability, making the atmosphere prone to condensation; diffusion conditions are reestablished after the foehn ends. In operational forecasting, the development trend of foehn can be used to predict boundary layer diffusion conditions and the evolution of surface meteorological

elements, providing a reference for air pollution forecasting and control in the Urumqi urban agglomeration.

Keywords: low-altitude foehn; boundary layer diffusion conditions; meteorological elements; Urumqi

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Urumqi, the capital of Xinjiang, serves as the political, economic, and cultural center of the region, a crucial land transportation hub connecting China with Central Asia and Europe, and an important window for China' s westward opening and international economic-cultural exchanges. With the Belt and Road Initiative, Urumqi' s strategic position in western China and Central Asian economic development has become increasingly prominent. However, despite relatively lagging economic development for years, this important border city has long suffered from severe air pollution, ranking among the top three most polluted cities in China alongside Taiyuan and Beijing in 2013. Although several large-scale pollution control efforts have been implemented, satellite observations and ground monitoring data continue to show that Urumqi remains one of China' s most severely polluted cities.

The causes of severe air pollution in Urumqi are multifaceted, involving not only excessive anthropogenic emissions but also complex terrain and meteorological conditions strongly influenced by topography. Located at the northern foothills of the Tianshan Mountains on the southern edge of the Junggar Basin, Urumqi features dramatic topographic relief with extensive mountainous areas. The terrain is high in the south and northeast, low in the central and northern areas, with the highest point at Bogda Peak (5445 m) and the lowest at the southern side of the Qinggeda Lake channel (490.6 m)—a horizontal distance of only 75 km but a vertical difference of 4954 m. The urban area sits on an alluvial plain on the northern foothills of the central Tianshan Mountains, surrounded by mountains on three sides (east, west, and south), forming a "trumpet-shaped" terrain opening to the north at 580–920 m elevation (average 800 m). This unique topography, combined with the Dabancheng wind gap in the middle of the Zhongtianshan Canyon and the Turpan Basin at the canyon' s southern end, creates frequent low-altitude foehn events in winter under stable weather conditions, which play a key role in forming heavy pollution events in the Urumqi urban agglomeration.

Since the 1990s, meteorologists such as Zhang Jiabao and Meng Qihui have observed that when sea-level pressure over the Sayan Mountains to Mongolia region exceeds that over Central Asia–Ili region and the southern slope of the Tianshan Mountains exceeds the northern slope, strong gap winds often appear from the Zhongtianshan Canyon to its northern end. This southeast wind (locally called "southeast gale") can affect Urumqi year-round with variable duration, typically reaching force 6–7 (average maximum force 8, occasionally exceeding 12). During these events, relative humidity drops sharply, temperature rises abruptly, and skies become exceptionally clear—classic foehn characteristics. Previously, it was believed that this winter wind occurred only above the inversion layer, with near-surface wind speeds remaining small or calm due to a ~1500 m thick inversion layer over the Junggar Basin that prevented the sinking foehn airflow from breaking through. Li Xia et al. classified foehn that reaches the ground as "grounded foehn" and that occurring only aloft as "low-altitude foehn," while European Alpine research terms this mid-upper level phenomenon "sandwich foehn." Further research revealed that low-altitude foehn occurs on 128.5 days annually in Urumqi, most frequently in winter (47.0 days, 52.2% frequency), particularly in January (17.5 days, 56.5% frequency). Foehn not only increases inversion thickness and atmospheric stability but also forms convergence with valley winds or cold air pools from the Junggar Basin (creating "micro-foehn fronts") that trap pollutants in the urban area, causing frequent heavy pollution events.

Forecasters have observed that low-altitude foehn, as a weather process, produces different boundary layer structures and meteorological elements at different stages, resulting in varying atmospheric horizontal and vertical diffusion capacities and corresponding air quality fluctuations. However, research on atmospheric diffusion capacity during different foehn stages remains scarce. This study uses Urumqi wind profile radar data from 2013 to 2017 to identify low-altitude foehn events, dividing them into five stages (pre-foehn, development, vigorous, decline, post-foehn) to analyze spatiotemporal evolution characteristics of boundary layer diffusion conditions and surface meteorological elements, providing references for air pollution forecasting and control in the Urumqi urban agglomeration.

1. Data and Methods

1.1 Data

Meteorological data include Urumqi upper-air and surface data from 2013 to 2017. Upper-air data consist of second-level radiosonde data (temporal resolution 1 s, vertical resolution ~5 m) from Urumqi Meteorological Station, representing quality-controlled archived data from Xinjiang Meteorological Information Center. Wind profile radar data (temporal resolution 6 min) from CFL-03 type radar accurately reflect weather process evolution and finely depict vertical airflow changes during short-duration heavy precipitation events. Surface meteorological elements use hourly observations from 11 automatic weather stations in the study area (main urban zone), categorized by location: north urban (Anningqu, 660–915 m), south urban (Wulabo, Hongyanchi, 1000–1075 m), city center (Economic Zone, Heishantou, High-tech Zone, Xinyi Road, Kaziwang, 700–850 m), west urban (Bagang, Radar Station, 920–940 m), and southeast urban (Urumqi, Shui Mogou, 660–915 m).

1.2 Selection and Stage Division of Low-Altitude Foehn Cases

Selection Criteria: Low-altitude foehn is manually identified from wind profile diagrams (Fig. 2) when a persistent airflow ($ $6 hours) appears below 4200 m in Urumqi with wind direction maintained at 101.25°–225.00° and speed $ 8m·s^{-1}$. For example, if wind direction and speed meet criteria from 08:00 on December 11 to 20:00 on December 13, 2014, this is recorded as one foehn event. Using 6-hour duration as the benchmark ensures the low-altitude foehn significantly affects Urumqi' s boundary layer diffusion conditions throughout the day.

From 451 effective observation days during winter months (November–March) in 2013–2017, 405 low-altitude foehn events were identified, with durations ranging from 6 to 190 hours (average 73.0 hours). Duration frequency distribution shows: 36.0% of events last <24 hours, 73.0% <72 hours, and 14.0% >72 hours. To highlight meteorological condition changes during different foehn stages, this study further screened 8 cases with duration $ $72 hours for detailed analysis.

Stage Division: Based on maximum wind speed, each low-altitude foehn event is divided into: (1) Pre-foehn (12 hours before foehn appearance), (2) Development period (when maximum wind speed increases to >8 m · s^{-1}), (3) Vigorous period (maximum wind speed >8 m · s^{-1}), (4) Decline period (maximum wind speed decreases to $ 8m·s^{-1}$ until event end), and (5) Post-foehn (12 hours after foehn ends).

1.3 Calculation Methods for Boundary Layer Meteorological Parameters

Mixed layer thickness, inversion parameters, ventilation coefficient, and static stability index are calculated following established methods.

Maximum Mixed Layer Thickness (MMD): Using the Holzworth method, daily maximum mixed layer thickness is calculated from 08:00 sounding temperature profiles and daily maximum surface temperature. The process involves finding the maximum temperature between 09:00–18:00, then ascending dry-adiabatically from this point until intersecting the 08:00 sounding temperature profile. The intersection height above ground represents the daily maximum mixed layer thickness.

Ventilation Coefficient: Calculated as:

$$vent = \int_0^{MMD} U(z)dz$$

where *vent* is ventilation coefficient (m^2 · s^{-1}), MMD is maximum mixed layer thickness, and $U(z)$ is horizontal wind speed at height z.

Inversion Parameters: Inversion layer thickness (ΔH) is the height difference between inversion top and bottom; inversion intensity is the temperature difference (ΔT) divided by thickness (ΔH).

Static Stability Index (ASITS): Calculated using sounding and near-surface hourly temperature data combined with daily precipitation:

$$ASITS = \lambda \cdot \frac{\delta}{r} \cdot \frac{PBLU(z)}{PBL - PBLU(z)}$$

where λ is a scaling parameter (taken as 1 for dimensionless quantity), δ depends on precipitation amount r (mm), $PBLU(z)$ is wind speed at maximum mixed layer height, and PBL is boundary layer average wind speed.

2. Results and Analysis

2.1 Overall Characteristics of Atmospheric Diffusion Conditions in Urumqi

2.1.1 Monthly Variation Characteristics Analysis of monthly and seasonal variations in boundary layer parameters (mixed layer thickness, inversion, ventilation coefficient, static stability index) from 2013–2017 reveals:

The static stability index peaks in December–January (0.37$×10$^{1}–2.72×10${1})anddeclinesthereafter, showing cyclevariation(Fig.3).Wintervaluesare2–3timeshigherthansummerminima(0.44×10$^{1}), consistentwithotherstu m$^2 \cdot s^{-1}$) and reaching minimum in winter (1.52$×10^{3}$ m$^2 \cdot s^{-1}$), with the latter being only 8% of the former. This seasonal pattern aligns with turbulence intensity variations. Inversion layer thickness and temperature difference exhibit similar monthly patterns, maximizing in winter (808 m and 5.4 ℃ respectively) and minimizing in summer (113 m and 0.2 ℃). These characteristics correspond well with Urumqi' s air quality deterioration periods.

Compared with other Chinese cities, Urumqi' s winter ventilation coefficient is 50% higher than Lanzhou' s, indicating better winter transport efficiency. However, its static stability index is comparable to Beijing and Yinchuan but significantly higher than Jinan, Harbin, and Zhengzhou, and 2.0-3.0 times higher than Xi' an and Taiyuan. Overall, Urumqi' s atmospheric diffusion conditions are worst in winter (especially December–January) and best in summer, ranking poorly nationwide.

2.1.2 Seasonal Variation Characteristics Seasonal variations (Fig. 4) show: mixed layer thickness and ventilation coefficient are highest in summer (2.61$×10^{3}$ m and 14.49$×10^{3}$ m$^2 \cdot s^{-1}$) and lowest in winter (0.44$×10^{3}$ m and 1.52$×10^{3}$ m$^2 \cdot s^{-1}$). Inversion layer thickness, temperature difference, and static stability index are highest in winter (768 m, 4.82 ℃, 6.36) and lowest in summer (113 m, 0.48 ℃, 0.37). Spring and autumn values are intermediate. This pattern matches seasonal turbulence intensity variations and is consistent with other northern Chinese cities.

2.2 Comparative Analysis of Boundary Layer Diffusion Conditions During Different Winter Foehn Stages

2.2.1 Mixed Layer Thickness (MMD) Characteristics Lower mixed layer thickness is a sensitive parameter affecting pollutant concentration, especially PM2.5. During the five foehn evolution stages, MMD shows a decreasing-then-increasing pattern: pre-foehn (531 m) → development period (gradual decrease) → vigorous period (minimum 0.30×10^{3} m) → decline period (gradual increase to 0.34×10^{3} m) → post-foehn (recovery to 0.52×10^{3} m). The vigorous period' s minimum MMD indicates the lowest effective height for vertical diffusion of moisture and pollutants, leading to elevated near-surface pollutant concentrations.

2.2.2 Ventilation Coefficient The ventilation coefficient decreases from pre-foehn (1.66×10^{3} $m^2 \cdot s^{-1}$) through development (1.33×10^{3} $m^2 \cdot s^{-1}$) to vigorous period (minimum 0.62×10^{3} $m^2 \cdot s^{-1}$), then increases during decline (0.64×10^{3} $m^2 \cdot s^{-1}$) and post-foehn (1.32×10^{3} $m^2 \cdot s^{-1}$). This demonstrates that horizontal transport and diffusion capacity gradually weaken during foehn development, reaching worst conditions during the vigorous period when air pollution intensifies.

2.2.3 Inversion Layer Characteristics Inversion (temperature increasing with height) creates stable atmospheric conditions that inhibit pollutant diffusion. During winter low-altitude foehn, inversion layer temperature difference and thickness show increasing-then-decreasing patterns opposite to MMD and ventilation coefficient.

Temperature Difference: Pre-foehn average is 4.7 ℃, strengthening to 7.2 ℃ during development and peaking at 10.9 ℃ in the vigorous period, then weakening to 8.7 ℃ during decline and 4.6 ℃ post-foehn. All foehn stages exceed the winter monthly mean (5.4 ℃), indicating more stable boundary layer structures during foehn events.

Inversion Layer Thickness: Increases from pre-foehn (373 m) to development period (0.77×10^{3} m), peaks in vigorous period (0.99×10^{3} m), then decreases during decline (0.57×10^{3} m) and post-foehn (0.53×10^{3} m). The vigorous period' s maximum thickness (808 m) significantly exceeds winter monthly mean, demonstrating foehn' s role in strengthening inversions.

Inversion Intensity: Temperature change rate per 100 m increases from 1.04 ℃ $\cdot$ $(100m)^{-1}$ pre-foehn to 1.22 ℃ $\cdot$ $(100m)^{-1}$ during development, peaking at 1.48 ℃ $\cdot$ $(100m)^{-1}$ in the vigorous period, then weakening to 1.32 ℃ $\cdot$ $(100m)^{-1}$ post-foehn. This enhanced stability suppresses vertical pollutant transport.

2.2.4 Static Stability Index The static stability index follows the same pattern as inversion temperature difference, increasing from pre-foehn (0.44$×10^{1})throughdevelopment(0.62×10{1})topeakinvigorousperiod(0.99×10^{1}), thendecreasingduringdecline(0.64×1

$foehn(0.34\times 10^{\{1\}).Valuesexceeding0.44\times 10}${1}$ in development, vigorous, and decline periods confirm that foehn promotes atmospheric static stability, weakening horizontal and vertical diffusion capacity, with worst conditions during the vigorous period.

2.3 Spatiotemporal Evolution of Surface Meteorological Elements

Analysis of 8 typical foehn cases reveals distinct regional characteristics in Urumqi' s winter low-altitude foehn impact.

2.3.1 Sea Level Pressure During foehn development and vigorous periods, all stations show pressure decreases. High-altitude stations (Wulabo, Hongyanchi) experience the largest decreases ($ $3.3 hPa), with Wulabo showing maximum reduction (4.9 hPa) during the vigorous period. Low-altitude stations show smaller decreases (0.8–1.1 hPa). Post-foehn, pressures continue slowly decreasing (0.4–0.6 hPa). This pressure reduction results from warming and sinking of foehn air creating low pressure.

2.3.2 Temperature Characteristics Pre-foehn, regional temperature averages -8.7 to -13.3 ℃. During development, most stations cool (0.2–0.5 ℃) except Wulabo and Hongyanchi (high-altitude stations at ~1000 m) which warm slightly (0.3-0.4 ℃) as they lie near the foehn base. In the vigorous period, Wulabo and Hongyanchi continue warming (0.8 ℃ and 2.4 ℃ respectively) while other stations cool more significantly (0.3-0.8 ℃), with Urumqi station showing maximum cooling. During decline, all stations show slight warming (0.1–0.3 ℃), and post-foehn, gradual warming continues (0.3 ℃). The near-surface cooling during foehn development and vigorous periods enhances inversion strength, consistent with earlier analysis.

2.3.3 Wind Speed Variations Wind transports and dilutes pollutants—higher speeds mean lower concentrations. Pre-foehn, regional average wind speed is 0.5–2.2 $m \cdot s^{-1}$, with only Wulabo, Hongyanchi, Bagang, and Urumqi stations exceeding 1.0 $m \cdot s^{-1}$. During development, high-altitude stations (Wulabo, Hongyanchi, Bagang) show increased wind speeds (0.2–0.4 $m \cdot s^{-1}$), while low-altitude stations show little change or slight decreases. In the vigorous period, most stations except southeastern and central urban stations show increased speeds, with Wulabo, Hongyanchi, and Bagang increasing significantly (2.8, 1.3, and 0.4 $m \cdot s^{-1}$ respectively). During decline, wind speeds change little, and post-foehn, speeds decrease. This pattern shows that foehn enhances horizontal diffusion capacity at high-altitude locations while weakening it in low-altitude urban areas.

3. Discussion

This study uses 2013–2017 hourly surface data, second-level radiosonde data, and wind profile radar data to identify and analyze low-altitude foehn evolution in Urumqi. Statistical analysis of monthly and seasonal diffusion conditions reveals that Urumqi's atmospheric diffusion capacity is poor in winter, especially in December–January, ranking poorly nationwide. This enhances understanding of regional winter atmospheric diffusion capacity and pollution levels.

Statistical analysis of 8 typical foehn cases demonstrates that foehn development weakens boundary layer horizontal diffusion and vertical exchange capacity, with diffusion parameters reaching extreme values (minimum or maximum) during the vigorous period when conditions are worst. This aligns with varying element changes across stages, providing crucial insights for judging foehn impacts on diffusion conditions and surface elements, and offering references for air pollution forecasting and control in the Urumqi urban agglomeration.

4. Conclusions

1. **Seasonal and Monthly Variations:** Among the three atmospheric diffusion conditions in Urumqi, mixed layer thickness and ventilation coefficient are largest in summer (2.61×10^{3} m and 14.49×10^{3} $m^2 \cdot s^{-1}$) and smallest in winter (0.44×10^{3} m and 1.52×10^{3} $m^2 \cdot s^{-1}$). Inversion layer thickness, temperature difference, and static stability index are largest in winter (768 m, 4.82 ℃, 6.36) and smallest in summer (113 m, 0.48 ℃, 0.37). Overall conditions are worst in winter and best in summer, with December–January being extremely unfavorable for pollutant diffusion.

2. **Foehn Stage Evolution:** During the five stages of low-altitude foehn, atmospheric mixed layer thickness and ventilation coefficient show decreasing-increasing patterns, reaching minimum values during the vigorous period (0.30×10^{3} m and 0.62×10^{3} $m^2 \cdot s^{-1}$). Inversion layer thickness/intensity and static stability index show opposite increasing-decreasing trends, peaking during the vigorous period (inversion thickness = 808 m, temperature difference = 10.9 ℃, static stability index = 0.99×10^{1}). Foehn development weakens boundary layer diffusion capacity, with worst conditions during the vigorous period when parameters reach extremes.

3. **Surface Element Evolution:** During foehn development and vigorous periods, station pressure decreases, high-altitude stations show temperature increases and wind speed enhancement, while low-altitude areas below the foehn layer experience temperature decreases and wind speed reduction—most pronounced during the vigorous period. This demonstrates that foehn stabilizes the atmosphere below the foehn layer, inhibiting pollutant diffusion more clearly than single-station studies previously showed.

4. **Operational Application:** Foehn development trends can be used to predict boundary layer diffusion conditions and surface meteorological element evolution, providing valuable references for air pollution forecasting and control in the Urumqi urban agglomeration.

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