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Characteristics and Establishment of Objective Identification Criteria and Predictors for Foehn Winds in Urumqi, China

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Abstract: The special terrain of Urumqi (in the valley area) often triggers strong foehn winds, causing huge losses to local people's lives and social economies. By using the surface observation data of the hourly temperature, pressure, humidity, and wind from the downwind Urumqi Meteorological Station and the upwind Dabancheng Meteorological Station in the Middle Tianshan Canyon and the NCEP/NCAR reanalysis data during 2008–2022, this paper establishes the dataset of foehn processes at Urumqi Station in the past 15 years and analyzes the variation rules of the associated meteorological variables during the foehn processes. In addition, based on the physical mechanism of the occurrence of foehn, a three-element identification criterion (i.e., $94° \leq$ 2 min average wind direction $\leq 168°$, 2 min average wind speed ≥ 2.0 m/s, and $\Delta\theta$ between Urumqi station and Dabancheng station ≥ 0.29 K) for foehn in Urumqi is established by comparing and analyzing the variations of wind direction (WD), wind speed (WS), and the potential temperature difference ($\Delta\theta$) between the two weather stations during the periods of foehn and non-foehn winds from 2013 to 2022. In addition, the performance of the three-element identification criterion is verified, and the results suggest that this criterion has an accuracy of 82.96% and a hit rate of 89.50% for the 2008–2012 foehn events in Urumqi. Moreover, the hit rate of this criterion for foehn wind of gale or above level (i.e., a 2 min wind ≥ 10.8 m/s on average) is 100%. In addition, combined with two predictors of sea-level pressure difference (ΔP) and $\Delta\theta$ between downwind stations and upwind stations, the foehn forecast can be more accurate than that provided by a single predictor. With $\Delta P \leq -12$ hPa and $\Delta\theta \geq 5$ K, the chances for foehn to occur are over 90%. This finding would have some reference and application values for the foehn forecasting.

Keywords: foehn; wind direction and speed; potential temperature difference; identification criterion

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Citation: Ayitikan, M.; Li, X.; He, Q.; Musha, Y.; Tang, H.; Li, S.; Zhong, Y.; Ren, G. Characteristics and Establishment of Objective Identification Criteria and Predictors for Foehn Winds in Urumqi, China. *Atmosphere* **2023**, *14*, 1206. https://doi.org/10.3390/atmos14081206

Academic Editor: Richard Turner

Received: 20 June 2023
Revised: 19 July 2023
Accepted: 25 July 2023
Published: 27 July 2023

1. Introduction

Foehn wind is a type of downhill wind with high temperatures and low humidity and often occurs on the lee slope of mountain ranges due to the terrain forcing when airflow passes through a valley or mountain pass [1]. Foehn is very strong, seriously affecting the local weather and climate [2–4], as well as the local people's daily lives, transportation, agriculture, air quality, etc. In addition, the hot and dry foehn can also influence people's physical and mental health, which has attracted widespread attention [5–12]. Foehn occurs in many mountainous areas of the world, such as the Alps in Europe, the Rocky Mountains in America, and the Caucasus Mountains on the border of Russia and Georgia. Between Bogda Mountain and Tianger Mountain on the northern slope of Tianshan Mountains in

China, i.e., in the canyon area near Urumqi, the large topographical difference often incurs foehn (southeast winds) to this region, and the most known is the foehn wind blowing from Dabancheng to Urumqi [13–16].

The research on foehn has a history of more than 150 years [17–22]. Over the years, the most basic research on foehn, such as its identification method, has been under exploration. Scholars from around the world have proposed different methods to identify Foehn. The most common identification method for foehn is that the temperature and relative humidity change suddenly at the same time, and the wind comes from the direction of the mountain ranges [19]. However, this method has certain shortcomings. When the temperature is high, this method is likely to misidentify the local winds caused by other weather phenomena, such as foehn [18]. Atkinson [17] used a two-element identification method to analyze the foehn that occurred in the east of the Rocky Mountains in America: One is that the upper-air wind must have a larger component perpendicular to the mountains, and the other is that the windward side of the mountain shows a high-pressure ridge and the lee side has a low-pressure trough in the surface synoptic chart. Schuetz et al. [19] only used potential temperature as the identification criterion, ignoring the element of wind, and, as a result, various wind directions appeared. Therefore, only considering potential temperature when identifying foehn can result in apparent deviations. In addition, many scholars have trained machine learning models to predict and identify foehn, but it is difficult to select effective predictors [23,24].

The most common method to identify foehn in China is to consider the changes in temperature, humidity, and wind over time. Zhao et al. [25] considered the criterion that the airflow is perpendicular to the mountain range when studying the foehn in the Taihang Mountains region. They defined the foehn as that the airflow was perpendicular to the mountain range, with wind speed (WS) $\geq$ 2.0 m/s and a rise in temperature of 3 °C in 10 min or 5 °C in 30 min, which ignored the weak foehn processes. Wang and Li [26,27] used the four-element criterion method (temperature, humidity, wind direction, and wind speed) to statistically analyze the characteristics of foehn in the eastern foothills of the Taihang Mountains and Xingtai City. Zhao et al. [28] analyzed the foehn in the Taihang Mountains, and their screening criteria were that the wind direction (WD) ranged from 225°–315°, wind speed $\geq$ 2 m/s, relative humidity decrease $\geq$ 20% at two adjacent moments, or relative humidity value $\leq$ 35% at the next moment. Xiong et al. [29] statistically compared the hourly temperature changes with the hourly average temperature in various months for the foehn process in the mid-section of the Taihang Mountains. Some scholars only considered the elements of WD and WS and only selected the foehn processes with winds stronger than gales (average wind $\geq$ 10.8 m/s or instantaneous wind $\geq$ 17.2 m/s) when diagnosing and analyzing the cases of foehn in Urumqi [30–34]. The above-mentioned manual identification methods based on different parameters are not only a heavy workload for the study of long-term climatic activity patterns of foehn but also prone to being affected by subjective elements and causing errors.

In the Alpine Mesoscale Programme, an objective identification method based on the physical mechanism of the foehn occurrence was established. This method mainly considered three meteorological elements: The potential temperature difference ($\Delta\theta$) between downwind mountain pass stations and upwind valley stations, WD and WS. Compared to temperature, potential temperature is a stable tracer, which is convenient for tracing the source and evolution characteristics of air particles or airflow [20,35–37]. Vergeiner et al. [36] confirmed that this method has a low misjudgment rate and can greatly reduce the workload.

For the northern slope of the Middle Tianshan Mountains, foehn sets out from the southern suburbs of Urumqi, sweeping across the urban area and even spreading to the downwind area in the northwest direction. The wind blows very fast, with the maximum speed even exceeding 40 m/s [14]. On 24 November 2004, foehn wind occurred in Urumqi, with instantaneous wind reaching 46 m/s. It broke the power transmission line towers in the southern suburbs, overturning the roofs of factories and blowing down trees and billboards on the roofs of buildings in urban areas. The city suffered heavy losses [19]. On 30 March 2012, foehn in Urumqi lasted for nearly 20 h, with average wind being Scale 8–9 and instantaneous wind reaching Scale 10–12 in the urban area. The powerful winds blew off walls and billboards, knocked down power poles, delayed flights, and caused traffic jams on urban roads. Three people were killed by falling objects, and more than 80 people were injured, causing huge economic losses. During December 22–26 of the same year, the foehn wind in the southern suburbs of Urumqi reached Scale 8–11, and dozens of cars were buried by the wind and snow. In addition, foehn occurs in the spring and summer as well. The strong winds can also transport soil and dust particles along the canyon downwind to Urumqi City, forming sandstorm weather. For example, observation records showed that on 3 April 2014, the 10 min average wind speed in the urban area of Urumqi and its southern suburbs reached 14.6 m/s from 15:00 to 16:00 (Beijing time, same below), and the concentration of PM_{10} in the southern part of the urban area reached as high as 3720 $\mu g/m^3$ at 15:00. Studies have shown that 71% of heavy pollution events in Urumqi are related to foehn [6–8]. In summary, foehn, which originated from the northern slope of the Middle Tianshan Mountains, has brought a lot of disastrous damage to Urumqi, causing huge losses to local people's lives and economic development. However, foehn forecasting has always been the difficulty and focus of weather forecasting. In order to gain a deeper understanding of the climatic activity laws of the foehn in Urumqi, we are to construct a three-element method with the consideration of potential temperature in addition to wind speed and direction to identify foehn, which is very necessary for basic research work.

2. Study Area, Data and Methods

2.1. Study Area

The Tianshan Mountains are located in the central part of Xinjiang, China, with an average elevation of over 4000 m and stretching for more than 2000 km from east to west. Xinjiang is divided into two different climatic zones: Northern Xinjiang and Southern Xinjiang. The Middle Tianshan Canyon (MTC) from Dabancheng to Urumqi runs through the Tianshan Mountains in a southeast-northwest direction. The narrowest part of the MTC is about 15 km wide, and both ends are very prone to mountain pass winds or downhill storms. Urumqi is located at the opening of the northern end of the MTC. The urban area is surrounded by mountains with a height of 1300–5000 m on three sides, and the northern opening faces the Junggar Basin, which is roughly shaped like a trumpet (Figure 1). The terrain of urban areas slopes from southeast to northwest, with an average elevation of 800 m and a drop of 300–400 m. When the cold air mass in the periphery of the Mongolian high-pressure system flows back to the southern slope of the Tianshan Mountains, a pressure gradient across the Tianshan Mountains is easily formed at both ends of the MTC, which in turn leads to airflow passing through the MTC, invading Urumqi and its downwind regions and generating foehn wind. The geographical location and elevation information of meteorological stations are presented in Figure 1 and Table 1.

2.2. Data

This paper uses the observation data of meteorological elements, including hourly 2 min average wind speed and direction, 10 min average wind speed and direction, atmospheric pressure, sea level pressure, temperature, relative humidity, etc., from the Urumqi station (downwind station) and Dabancheng (upwind station) in the canyon from 2008 to 2022. Due to the lack of maximum and instantaneous wind speed and direction data before 2016, we only use the maximum and instantaneous wind speed and direction data from 2016 to 2022.

The NCEP/NCAR reanalysis data are from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) of the United States. In this study, when analyzing the upper-air and surface weather conditions during the foehn period, we adopt the NCEP/NCAR reanalysis data of temperature, pressure, wind speed, etc., four times a day with a spatial resolution of 2.5° × 2.5°.

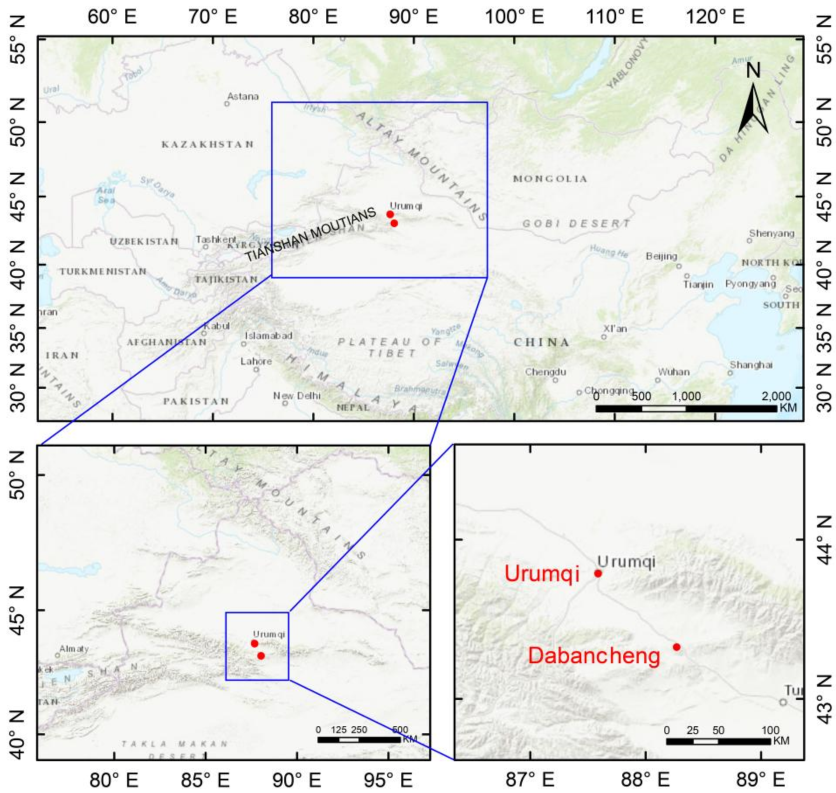

Figure 1. Distribution of topography around Urumqi.

Table 1. Elevation information (above sea level) of Urumqi and Dabancheng.

Station	Longitude/°	Latitude/°	Elevation/m
Dabancheng Station (upwind)	88.32	43.35	1105.3
Urumqi Station (downwind)	87.65	43.78	935.9

2.3. Artificial Screening Method for Foehn Weather Processes

Based on the 2008–2022 hourly data of WD and WS, temperature, pressure, and relative humidity in the upper air and on the surface, as well as the occurrence frequency of foehn in Urumqi, the distribution of various meteorological elements over time is plotted, and the onset time and end time of foehn in Urumqi are further determined. At the same time, the upper-air circulation, the surface pressure of "high in the south and low in the north", and the abrupt rise (drop) in temperature (humidity) during the foehn period are adopted as well. In addition, the dataset of foehn processes in Urumqi in 2008–2022 is counted.

When selecting cases of foehn in Urumqi, we analyzed the upper-air and surface conditions of each case. For example, on 30 March 2017, a very strong foehn occurred in Urumqi. The 500 hPa circulation at 14:00 showed that Xinjiang was under the control of a strong high ridge and the synoptic situation was relatively stable (Figure 2). Meanwhile, the 850 hPa circulation was controlled by a warm high, and there was a warm tongue near Urumqi in the temperature field. On the surface synoptic chart, from the Ural Mountains to West Siberia in the north were the low-pressure areas, while the Mongolian high in the south was strong and stable, forming a pressure pattern of "high in the south and low in the north". Under such a situation, Urumqi lay in the southwestern section of the Mongolian high, and as a result, the foehn occurred in the canyon area from Dabancheng to Urumqi.

This case reflects the typical upper-air circulation and surface synoptic situation during the process of foehn in Urumqi.

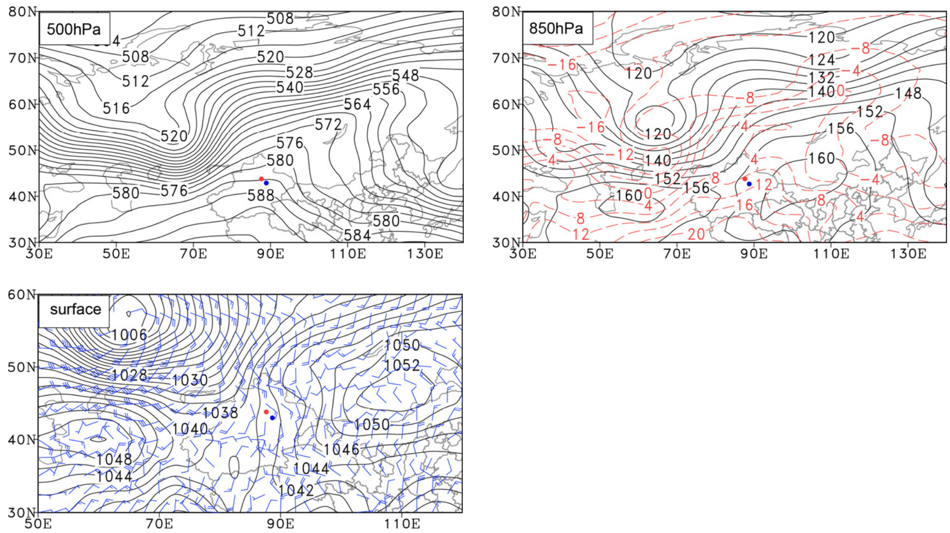

Figure 2. Upper-air and surface synoptic situation at 14:00 on 30 March 2017 (the 500 hPa and 850 hPa black solid lines represent the geopotential height with an interval of 40 dagpm; the red dashed line represents temperature with an interval of 4 °C; the black solid line represents sea level pressure with an interval of 2 hPa; the blue wind barb represents surface wind with the long rod indicating 4 m/s and the half rod 2 m/s; the red dot is Urumqi Station; and the blue dot is Dabancheng Station.

Figure 3 shows the changes of various meteorological elements during the foehn process on 30 March 2017. At 08:00, the wind turned to the southeast; at 09:00, it was affected by northeast airflow; and at 10:00, it turned to the southeast again. At the same time, the weather elements were all rapidly varying. The wind kept strengthening, with the average speed at 14:00 reaching 10.9 m/s and the peak speed reaching 18.5 m/s. Simultaneously, relative humidity dropped sharply from 82% at 9:00 to 29% at 10:00 and maintained around 20% from 10:00 to 16:00. Conversely, temperatures rose sharply from 6.2 °C to 14.8 °C, with an hourly temperature change of 8.6 °C from 9:00 to 10:00. At 16:00, the temperature reached its highest point of 20.3 °C. It can be seen from Figure 3 that the temperature rise caused by the foehn was much greater than that caused by the radiation heating at the same time the previous day (the temperature was 15.1 °C at 18:00 on the 29th). Air pressure in Urumqi was on a downward trend during the foehn period. At 17:00 on the 30th, the wind turned northwest, with the average speed slowing down to 1.6 m/s. Correspondingly, temperature dropped, humidity increased, and pressure gradually increased, and the foehn process ended. In summary, it is determined that the duration of the foehn weather was from 10:00 to 16:00 on 30 March, a total of 6 h. Based on the weather situations and changes in meteorological elements, a total of 3110 h of foehn weather during 2008–2022 were selected. The rest hours were non-foehn weather.

2.4. Selection of Three-Element Threshold Method

In the Alps, Drechsel et al. [18] utilized the law that the potential temperature satisfies the dry adiabatic conservation during the sinking motion of air mass on leeward slopes and took the potential temperature as a tracer. The mountain-climbing airflow sinks on the leeward slope, and when the potential temperature at the downwind station is equal to or higher than that at the upwind station, a foehn will occur in the downwind region. In addition to the potential temperature, it is also necessary to define the range of wind directions and the minimum wind speed of the foehn. This identification method uses the physical mechanism of the occurrence of foehn, and its applicability has been recognized [36].

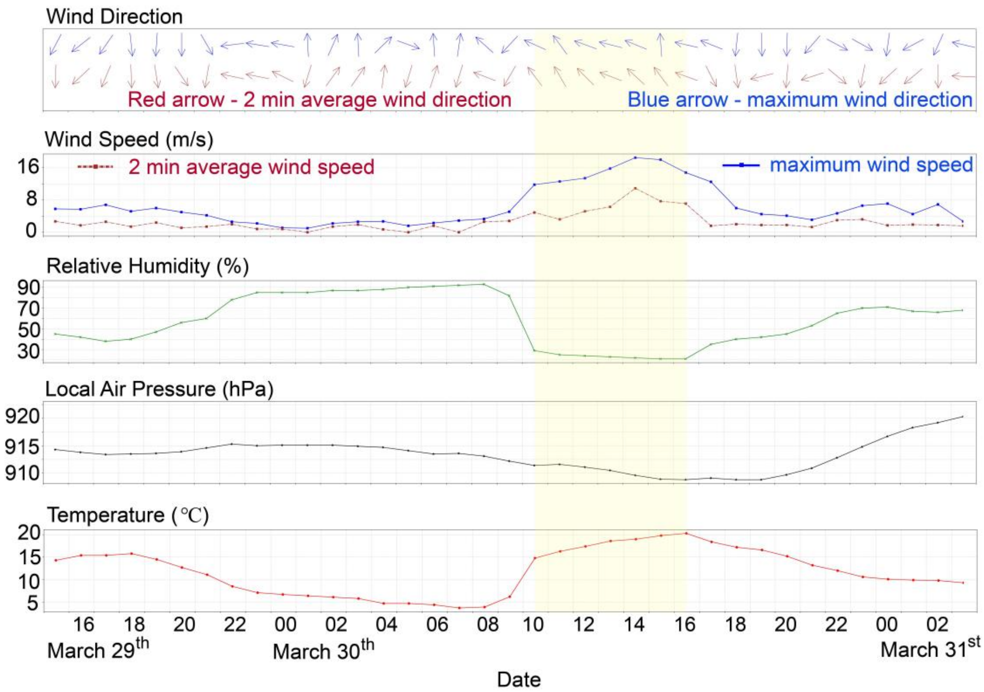

Figure 3. Changes in surface meteorological elements in Urumqi from 15:00 on 29 March to 03:00 on 31 March 2017 (yellow shaded area represents the foehn period).

This paper selects Urumqi Station as the downwind station and Dabancheng Station as the upwind station for reference. In addition, a comparative analysis of the sea-level pressure difference (ΔP) and the potential temperature difference ($\Delta\theta$) between the two stations during periods of foehn and non-foehn weather is conducted. Based on this, the occurrence probability of foehn under different ΔP and $\Delta\theta$ is obtained statistically.

Potential temperature:

$$\theta = T\left(\frac{P_0}{P_1}\right)^{\frac{Rd}{C_pd}} \tag{1}$$

Potential temperature difference ($\Delta\theta$):

$$\begin{aligned}\Delta\theta &= \Delta\theta_{\text{Downwind station}} - \Delta\theta_{\text{Upwind station}} \\ &= \Delta\theta_{\text{Urumqi Station}} - \Delta\theta_{\text{Dabancheng Station}}\end{aligned} \tag{2}$$

Sea-level pressure difference (ΔP):

$$\begin{aligned}\Delta P &= \Delta P_{\text{Downwind station}} - \Delta P_{\text{Upwind station}} \\ &= \Delta P_{\text{Urumqi Station}} - \Delta P_{\text{Dabancheng Station}}\end{aligned} \tag{3}$$

where T is temperature, P_1 is air pressure, P_0 is the standard air pressure, i.e., P_0 = 1000 hPa, C_pd represents the specific heat at constant pressure, Rd represents the gas constant for dry air, $Rd/C_pd = 0.286$, and P is for sea-level pressure.

2.5. Verification Methods

To test the reliability of the identification criterion of foehn weather in Urumqi, this paper evaluates the identification effect of foehn weather in five years from 2008 to 2012 based on the identification criterion of foehn. The accuracy rate, hit rate, false-alarm rate, and missing rate are taken as verification indicators. Through comprehensive judgment, the optimal three-element identification criterion for foehn in Urumqi is determined.

Accuracy rate:

$$PC = \frac{NA}{NA + NB + NC} \times 100\% \tag{4}$$

Hit rate:

$$\mathrm{POH} = \frac{\mathrm{NA}}{\mathrm{NA} + \mathrm{NC}} \times 100\% \tag{5}$$

False-alarm rate:

$$\mathrm{PAR} = \frac{\mathrm{NB}}{\mathrm{NA} + \mathrm{NB}} \times 100\% \tag{6}$$

Missing rate:

$$\mathrm{PO} = \frac{\mathrm{NC}}{\mathrm{NA} + \mathrm{NC}} \times 100\% \tag{7}$$

where NA is a three-element identification criterion, based on which the correct time of foehn occurrence in Urumqi is identified; NB is the false-alarm time, i.e., the misjudgment time; and NC is the missing time. If the accuracy and hit rates are higher and the false-alarm and missing rates are lower, the identification effect will be better. Otherwise, the identification effect will be worse.

3. Results

3.1. Climatic Characteristics of Foehn in Urumqi

According to the hourly 2 min average WD and WS at Urumqi Station in the past 15 years (2018–2022) and the hourly maximum WD and WS in the past 5 years, the wind rose diagram was drawn (Figure 4). It can be seen that most of the strong winds blowing in Urumqi are SSE winds. The maximum average wind in the past 15 years occurred at 06:00 on 22 November 2007, with a speed of 20.1 m/s and a direction of 120°. The maximum WS in the past 5 years appeared at 12:00 on 21 March 2021, reaching 28.2 m/s in the direction of 94°. The occurrence frequency of strong northwesterly winds is much smaller than that of strong southeasterly winds (foehn). Similarly, the wind speed value of strong northwesterly winds is also much smaller than that of strong southeasterly winds (foehn).

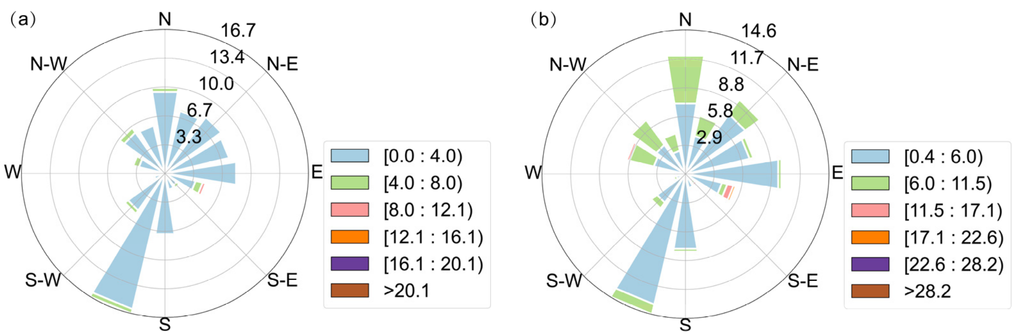

Figure 4. Wind rose diagrams of Urumqi. ((**a**) The 2 min average WD and WS in the past 15 years; (**b**) the maximum wind speed and direction in the past 5 years).

Time Characteristics of Foehn Processes

In the past 15 years, a total of 3110 h of foehn weather occurred in Urumqi, in which the daytime foehn took 1816 h and the nighttime foehn took 1294 h. The frequency of foehn weather in Urumqi during the day was about 1.4 times that of at night, which was the consequence of the favorable thermal conditions provided by solar radiation during the day.

The occurrence of foehn was different in four seasons, with the peak number (1527 h) in spring, followed by 1020 h in autumn, 411 h in summer, and the lowest (152 h) in winter. Affected by the changes in atmospheric circulation, there are periodic strong winds in Northern and Southern Xinjiang in spring and autumn every year. Comparatively, cold air is very active and temperatures are relatively high in spring and autumn, so the pressure difference of "high in the south and low in the north" is very easy to form when the cold and warm alternate. Therefore, the better thermal conditions and the special terrain effect jointly contribute to more foehn events in the spring and autumn [34]. In addition, in the past 15 years, there have been 182 h of strong foehn with the 2 min average wind speed exceeding 10.8 m/s in Urumqi, accounting for 5.85% of the total hours of foehn in Urumqi.

As shown in Figure 5, the occurrence times of foehn present the seasonal variation. Generally, the hours of foehn in spring at each time are all higher than in other seasons. The spring foehn often occurs between 10:00 and 12:00, with the highest frequency at 11:00. In autumn, summer, and winter, foehn often occurs during the periods of 13:00–15:00, 11:00–13:00, and 11:00–13:00, respectively, and the highest foehn frequency in each season is at 14:00, 12:00, and 13:00, respectively. Foehn wind mostly breaks out in the morning in spring, at noon in summer, and in the afternoon in autumn and winter. Relative to summer and winter, foehn occurs more frequently in the early morning hours in spring and autumn. The lowest occurrence times of foehn are at 21:00 (spring), 19:00 (autumn), 01:00 (summer), and 05:00 (winter).

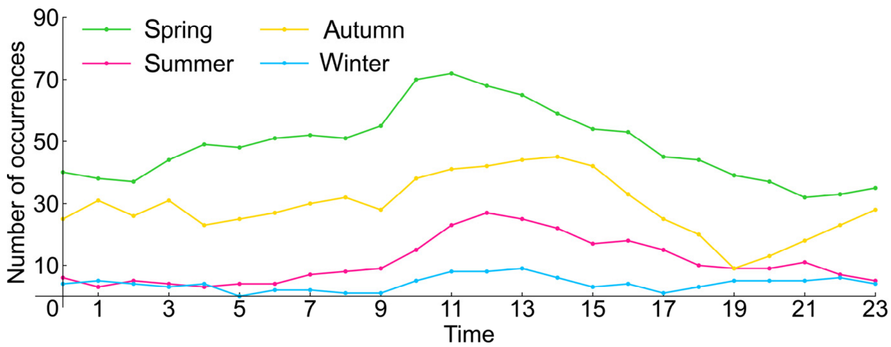

Figure 5. Time distribution of the occurrence time of foehn in the four seasons.

From the distribution of the WS spectrum of foehn (Figure 6), it can be seen that the average wind speed of foehn in spring, autumn, and summer ranges mainly within 2–8 m/s. In winter, it varies within 0–6 m/s in most cases, which indicates the foehn WS in winter is relatively lower. In the four seasons, the strongest foehn is found in the spring, with an average speed faster than 4 m/s, accounting for 74.82%. Among them, the frequency of foehn WS faster than 10 m/s is higher than in other seasons and takes up a rate of 6.99%.

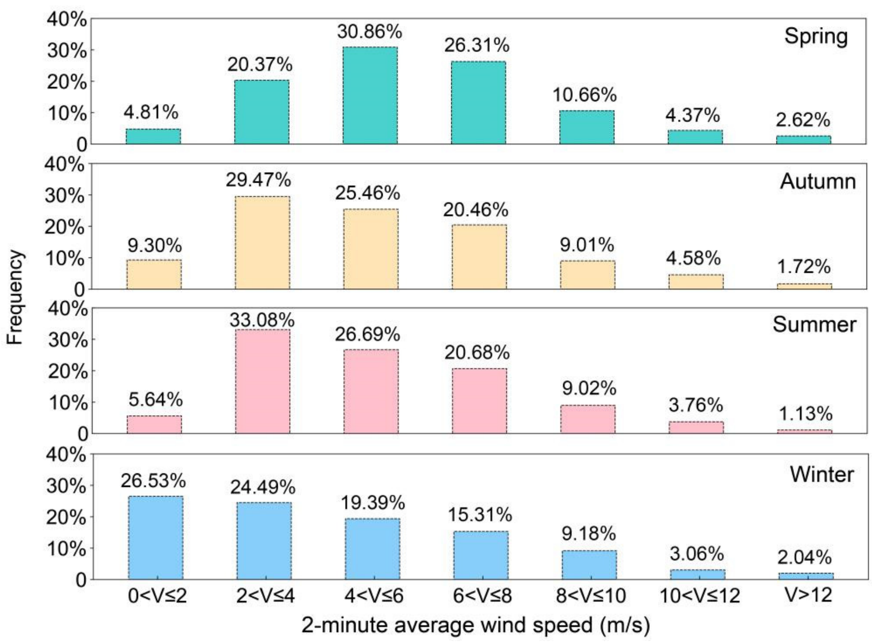

Figure 6. Spectral distribution of average wind speed of foehn in the four seasons.

3.2. Establishment of Three-Element Identification Criterion for Foehn in Urumqi

3.2.1. Characteristics of WD and WS during Foehn and Non-Foehn Processes

Figure 7 shows the distribution of the 2 min average WD and WS during the periods with foehn and non-foehn in Urumqi. In Figure 7a, the WD is mostly concentrated around 90°–170° in the foehn period, and the westerly airflow occasionally interrupts the foehn process. However, the westerly airflow is too weak and transient to affect the temperature and humidity, and the surface pressure pattern of "high in the south and low in the north" remains unchanged. Therefore, the westerly airflow was not removed from the foehn weather process. In addition, the WD of foehn at night is more chaotic than that during the daytime, which is mainly because the mixed airflow of mountain wind and foehn wind generates a wider spread of winds. During the foehn process, the WS is felt prominently, and the average wind speed is mostly in the range of 4–8 m/s. The WS of foehn at night is smaller than that during the day, and the night speed is mostly around 2–4 m/s.

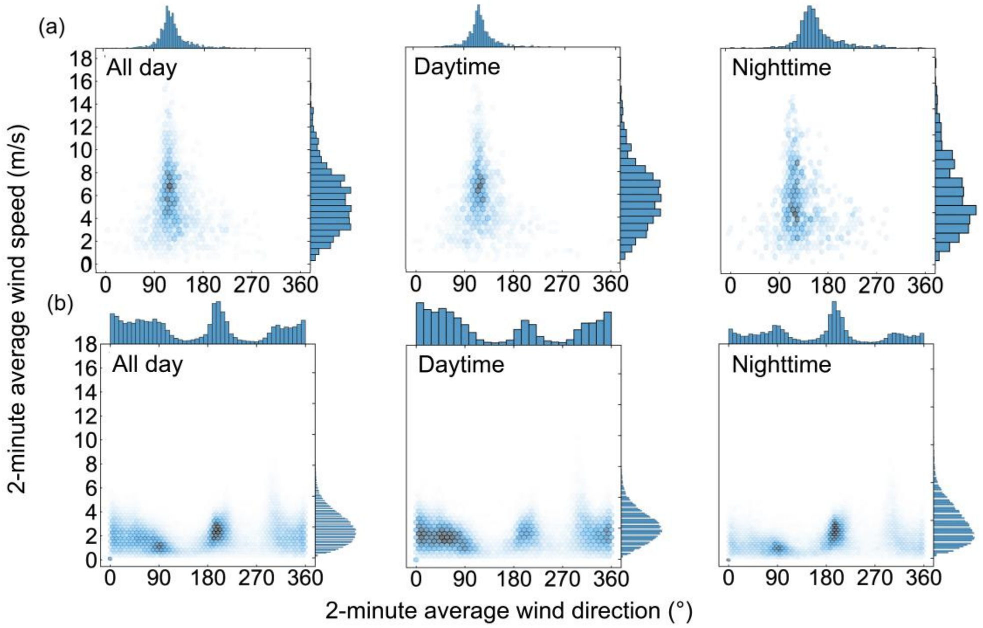

Figure 7. Distribution of wind speed and direction during foehn and non-foehn periods in Urumqi. ((**a**) Foehn; (**b**) non-foehn).

Figure 7b illustrates that during non-foehn periods, the WD is widely distributed. However, between 180° and 225°, there exists a distinct southwest wind, which is a mountain wind with a speed of around 2 m/s and mostly occurs from 22:00 to the next day's 10:00. During non-foehn periods, the WS distribution is significantly smaller than the WS of foehn, and mostly concentrated in the range of 0–4 m/s.

3.2.2. Characteristics of Δθ and ΔP between Downwind Station and Upwind Station during Foehn and Non-Foehn Periods

Figure 8 shows the Δθ and ΔP between the downwind station (Urumqi Station) and the upwind station (Dabancheng Station) during the periods of foehn and non-foehn. We can see that during the foehn period, the Δθ (ΔP) is mostly positive (negative), which is concentrated within 0–15 K (−10 hPa to 0 hPa). The average value of Δθ for foehn is 4.92 K. During the non-foehn period, however, the Δθ is mostly negative in the range from −5 to 5 K and the ΔP from −5 hPa to 5 hPa. Overall, there are some differences in the distributions of Δθ and ΔP between the downwind station and the upwind station. All of the above have passed the significance test at the 0.01 level. The variations of Δθ and ΔP over time during the foehn and non-foehn periods at Urumqi Station are given in Figure 9, which reveals that during the foehn, the Δθ in the daytime (08:00–20:00) is mostly in the range of 0–5 K, much smaller than the Δθ (5 K–5 K) at night (20:00–08:00 the next day). In the non-foehn period, the $\Delta\theta$ during the day (night) is mainly concentrated between −5 K and 0 K (−5 K to 5 K). There are also positive values for the $\Delta\theta$ at night during non-foehn periods because of the mixed airflow of mountain wind and foehn wind, but the WD of mountain winds is different from that of the foehn. Consequently, by defining the scopes of WD, WS, and $\Delta\theta$, foehn can be distinguished from other wind types. In addition, during the foehn period, the ΔP is negative, varying within −10 hPa to 0 hPa, while during the non-foehn period, the ΔP also has a negative value, which is between −5 hPa and 5 hPa. Meng et al. [16] pointed out that before the occurrence of foehn in Urumqi, the pressure decrease occurs first in Northern Xinjiang and later in Southern Xinjiang. The pressure is reduced quickly in Urumqi, which is more than twice as fast as that in Dabancheng, forming a "high in the south and low in the north" pressure gradient. Hence, the foehn weather occurs. When the foehn blows in Urumqi, air pressure is lowered in both Northern and Southern Xinjiang. Once the pressure in Urumqi rises but the pressure to the south of Dabancheng continues to decline, the foehn will stop in a very short period of time. Therefore, when the sea level pressure in Dabancheng is greater than that in Urumqi, the foehn may not happen in Urumqi.

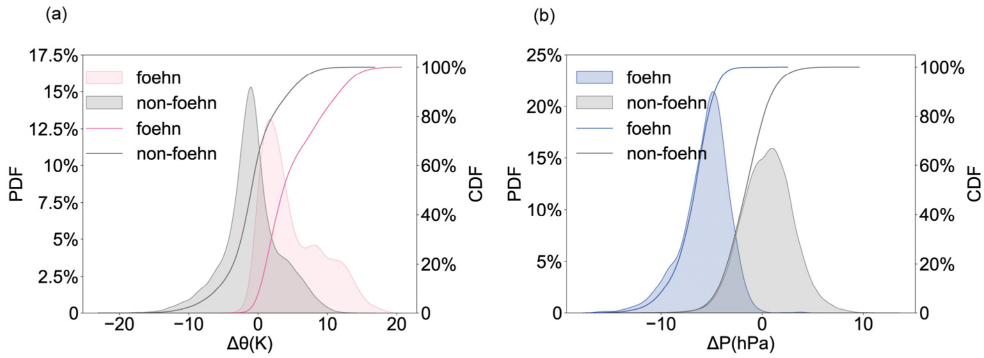

Figure 8. Probability density distribution of $\Delta\theta$ and ΔP during foehn and non-foehn processes in Urumqi ((**a**) $\Delta\theta$; (**b**) ΔP).

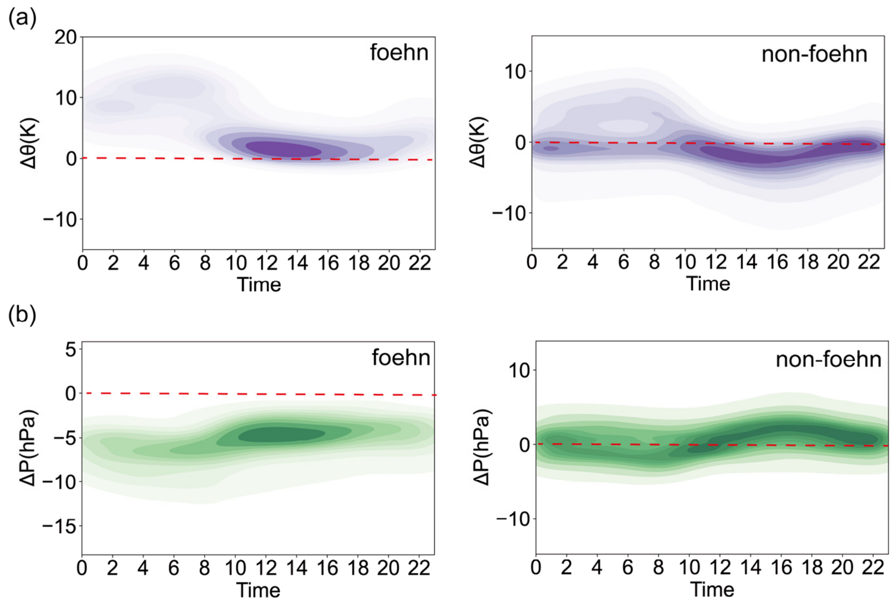

Figure 9. Distribution of $\Delta\theta$ and ΔP over time during the processes of foehn and non-foehn in Urumqi ((**a**) $\Delta\theta$; (**b**) ΔP).

3.3. Establishment of Identification Criterion for Foehn in Urumqi

Based on the 10-year feohn data from 2013 to 2023, including the 2 min average wind speed and direction, the $\Delta\theta$ between downwind statin (Urumqi) and upwind statin

(Dabancheng), and the threshold of ΔP, the three-element identification criteria for different schemes are established. The values of WD, WS, Δθ, and ΔP are sorted in ascending order. The 5th (95th) percentile is used as the minimum (maximum) value for the selection of the wind speed threshold. For the WS, Δθ, and ΔP, their numerical values can be infinite in theory. Thus, the thresholds of WS and Δθ only need to be greater than or equal to the 5th percentile, while ΔP only needs to be smaller than or equal to the 95th percentile. The identification criteria of three elements of different schemes are designed (Table 2), and the optimal identification criterion is obtained by testing and evaluating the performance of different criteria in the foehn cases in the five years 2008–2012.

Table 2. Accuracy, hit rate, false-alarm rate, and missing rate of the three-element identification criterion for different schemes.

	Three-Element Threshold	Accuracy	Hit Rate	False-Alarm Rate	Missing Rate
All day	$94^\circ \leq WD \leq 168^\circ$, $WS \geq 2.0$ m/s, $\Delta P \leq -0.28$ hPa	67.97%	69.44%	3.03%	30.56%
All day	$94^\circ \leq WD \leq 168^\circ$, $WS \geq 2.0$ m/s, $\Delta\theta \geq 0.29$ K	82.96%	89.50%	8.09%	10.50%
Daytime	$91^\circ \leq WD \leq 157^\circ$, $WS \geq 2.2$ m/s, $\Delta\theta \geq 0.05$ K	83.63%	85.51%	2.56%	14.49%
Nighttime	$101^\circ \leq WD \leq 176^\circ$, $WS \geq 2.0$ m/s, $\Delta\theta \geq 2.29$ K	73.27%	73.53%	9.71%	20.47%

Firstly, the three-element identification criterion for the 2 min average WD, WS, and ΔP ($94^\circ \leq WD \leq 168^\circ$, $WS \geq 2.0$ m/s, $\Delta P \leq -2.8$ K) is established, and the accuracy rate, hit rate, false-alarm rate, and missing rate of the identification criterion are 67.97%, 69.44%, 3.03%, and 30.56%, respectively. That demonstrates that the accuracy rate and hit rate of the identification criterion considering WD, WS, and ΔP are relatively low.

Then, combined with the above-analyzed characteristics of WD, WS, and Δθ between daytime and nighttime during the period of foehn and non-foehn, the three-element identification criteria for the whole day (24 h), daytime, and nighttime are established. The threshold values of WD, WS, and Δθ under different identification schemes are different, as illustrated in Table 2. The results show the identification criteria for the whole day ($94^\circ \leq WD \leq 168^\circ$, $WS \geq 2.0$ m/s, $\Delta\theta \geq 0.29$ K) and daytime ($91^\circ \leq WD \leq 157^\circ$, $WS \geq 2.2$ m/s, $\Delta\theta \geq 0.05$ K) have the highest accuracies of 82.96% and 83.63%, respectively, and their hit rate, false-alarm rate, and missing rate throughout the day are 89.50%, 8.09%, and 10.50%, and those in the daytime are 85.51%, 2.56%, and 14.49%, respectively.

Owing to the more concentrated WD and significant WS during the daytime foehn (Section 3.2.1), the accuracy of the identification criterion for the daytime feohn is relatively high. In addition, the identification criterion for the nighttime feohn with $101^\circ \leq WD \leq 176^\circ$, $WS \geq 2.0$ m/s, and $\Delta\theta \geq 2.29$ K presents an accuracy rate of 73.27%, a hit rate of 73.53%, a false-alarm rate of 9.71%, and a missing rate of 20.47%. The mixture of nighttime foehn wind and mountain wind often causes chaotic wind directions in the false-alarm and missing events, so the WD between 180° and 220° may also lead to a significant rise in temperature and drop in humidity. In addition, when the foehn process lasts from daytime to nighttime, different wind directions are also possible, which can result in false-alarm results. Sometimes, when the wind direction at night is around 100° and meets the range of the three-element identification criterion, the relative humidity does not decrease but increases, which disagrees with the characteristics of foehn, leading to the missing results. Therefore, when there are mixed airflows of foehn wind and mountain wind at night, it is easy to produce false-alarm and missing results, resulting in low accuracy of the identification criterion at night.

Comparing different identification criteria for the whole day, daytime, and nighttime, we can see that if the identification criteria for the daytime and nighttime events are established separately, the accuracy of nighttime identification will be lower. In addition, despite the higher accuracy rate of the identification criterion for the daytime, its hit rate is lower than that of all days, which is as high as 89.50%. In summary, in our establishment of foehn identification criteria in Urumqi, the daytime and nighttime criteria are no longer established separately. We adopt the uniform identification criterion, namely: $94° \leq 2$ min average WD $\leq 168°$, 2 min average WS ≥ 2.0 m/s, and $\Delta\theta \geq 0.29$ K between upwind station and downwind station (Table 3). This criterion has a 100% hit rate for the identification of foehn at the gale level with a 2 min average WS ≥ 10.8 m/s.

Table 3. The three-element identification criterion for foehn in Urumqi.

	2 min Average WD (°)	2 min Average WS (m/s)	$\Delta\theta$ (K)
Foehn	$94 \leq$ WD ≤ 168	WS ≥ 2.0	$\Delta\theta \geq 0.29$

3.4. Construction of Probability Predictors for Foehn in Urumqi

During the foehn period, the ΔP and $\Delta\theta$ between Urumqi and Dabancheng stations are different from the ΔP and $\Delta\theta$ of other wind types. Thus, we calculate the chances of foehn occurrence in Urumqi by combining the two predictors ΔP and $\Delta\theta$, as shown in Figure 10. One can see from the figure that the chance of foehn occurrence is significantly negatively correlated to the magnitude of ΔP but positively to $\Delta\theta$. When one predictor is fixed, changes in the other predictor will cause significant changes in the occurrence probability of foehn. For example, when $\Delta P = -7.5$ hPa, the probability of foehn occurrence varies from less than 40% ($\Delta\theta = 0$ K) to more than or equal to 80% ($\Delta\theta = 10$ K); when $\Delta\theta = 7.5$ K, the probability alters from less than 20% ($\Delta P = -2.5$ hPa) to more than or equal to 80% ($\Delta P = -10$ hPa). In addition, when $\Delta P \leq -12$ hPa and $\Delta\theta \geq 5$ K, the chance of foehn occurrence is as high as 90%. Therefore, considering the two predictors ΔP and $\Delta\theta$ simultaneously can greatly improve the forecast accuracy of foehn weather in Urumqi.

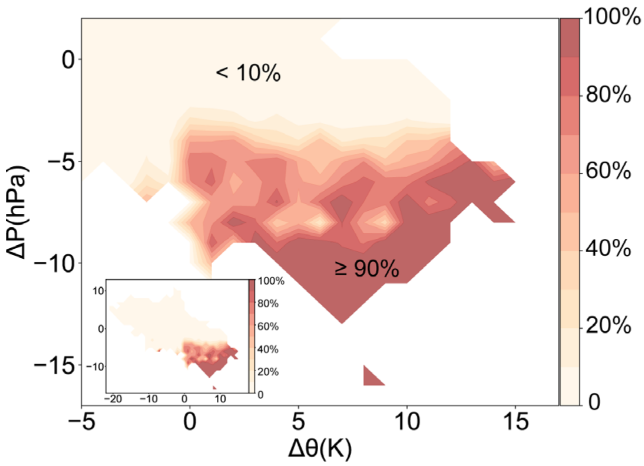

Figure 10. Probability of foehn occurrence in Urumqi under different values of ΔP and $\Delta\theta$.

4. Conclusions

Based on the hourly surface meteorological data and NCEP/NCAR reanalysis data from 2008 to 2022, we have established a time series of foehn occurrence in Urumqi in the past 15 years and analyzed the characteristics of WD, WS, ΔP, and $\Delta\theta$ between the downwind Urumqi Station and the upwind Dabancheng Station during the periods with foehn and non-foehn in Urumqi. Based on the data of foehn cases from 2013 to 2022, the three-element identification criteria with different thresholds for the whole day, daytime, and nighttime have been established. By analyzing and discussing the statistical indicators of accuracy, hit rate, false-alarm rate, and missing rate of the different identification criteria of foehn from 2008 to 2012, the three-element identification criterion for foehn in Urumqi has been further established. We have also calculated the chances of foehn occurrence in Urumqi under different values of ΔP and $\Delta\theta$. The detailed conclusions are as follows:

When strong winds blow in Urumqi, the southeast winds are much stronger than the northwest winds. The max 2 min average WS reached 20.1 m/s in 2008–2022, and the peak value of the extreme WS even reached 28.2 m/s in the late five years, and all these winds were from the southeast direction. In the past 15 years, there have been a total of 3110 h of foehn wind in Urumqi, of which the frequency of foehn during the daytime (1816 h) was about 1.4 times that of the nighttime (1294 h). There were 182 h of strong foehn with the 2 min average WS exceeding 10.8 m/s. Overall, the foehn hours of the whole day (24 h) in spring are longer than in other seasons. Among the four seasons of the year, the foehn wind is strongest in the spring, while the foehn in the winter blows at the lowest speed.

During the foehn period, the wind direction is mostly between 90° and 170°, with the average speed mainly in the range of 4–8 m/s. The WD of foehn is concentrated (scattering), and the WS is relatively high (low) during the daytime (nighttime). During the non-foehn period, there are distinct mountain winds in the direction from 180° to 225° at a speed of around 2–4 m/s, mostly from 22:00 to 10:00 the next day. The ΔP value between the downwind station and the upwind station is mainly positive (negative) during the foehn (non-foehn), but there is also a certain probability of a positive value of ΔP at night during the non-foehn, which is mainly caused by the mountain winds. Since the wind direction of mountain wind is different from that of foehn wind, when the WD and WS ranges of foehn are defined, foehn can be distinguished from the non-foehn winds by setting the threshold of $\Delta\theta$ used in foehn weather.

The three-element identification criterion for foehn in Urumqi includes $94° \leq$ 2 min average WD $\leq 168°$, 2 min average WS ≥ 2.0 m/s, and $\Delta\theta \geq 0.29$ K between downwind station and upwind station. The identification accuracy and hit rate of this criterion for the 5-year foehn cases (2008–2012) in Urumqi are 82.96% and 89.50%, respectively. In particular, its hit rate for the foehn winds that are stronger than the level of gale (i.e., 2 min average WS ≥ 10.8 m/s) is 100%. The verification results indicate that this method has a better performance in identifying foehn winds in Urumqi.

The ΔP and $\Delta\theta$ between Urumqi Station and Dabancheng Station have certain indicative significance for predicting foehn in Urumqi. The combination of ΔP with $\Delta\theta$ is more accurate in diagnosing foehn than only using a single predictor. The greater the ΔP and $\Delta\theta$, the higher the probability of the occurrence of foehn. With $\Delta P \leq -12$ hPa and $\Delta\theta \geq 5$ K, the probability of foehn occurrence is higher than 90%.

Author Contributions: Conceptualization, M.A., X.L. and Q.H.; data curation, M.A., Y.M. and S.L.; formal analysis, M.A., X.L. and Q.H.; funding acquisition, S.L. and Y.Z.; investigation, M.A., S.L. and Y.Z.; methodology, M.A. and X.L.; project administration, M.A.; resources, M.A., X.L. and G.R.; software, M.A., Y.M. and H.T.; supervision, X.L. and Q.H.; validation, M.A. and X.L.; visualization, M.A., X.L., Q.H., Y.M. and H.T.; writing—original draft, M.A., X.L. and H.T.; writing—review and editing, M.A. and X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the National Natural Science Foundation of China (Grant No. 42205010, Grant No.42165002), and Xinjiang Meteorological Bureau Science and Technology Innovation Development Fund Project (MS202303).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this paper can be provided by M.A. (maoln@idm.cn) upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Brinkmann, W. What is a foehn? *Weather* **1971**, *26*, 230–239. [CrossRef]
2. Seibert, R. South foehn studies since the ALPEX experiment. *Meteorol. Atmos. Phys.* **1990**, *43*, 91–103. [CrossRef]
3. Nishi, A.; Kusaka, H. Future changes of the extreme high-temperature events influenced by foehns in Niigata, Japan. *Atmos. Sci. Lett.* **2023**, *24*, e1137. [CrossRef]

4. Fanchao, K.; Zhiluan, L. Statistical Characteristics and Formation Mechanisms of Night Warming Events at Yunding Winter Olympic Stadium in Chongli. *Chin. J. Atmos. Sci.* **2022**, *46*, 191–205. (In Chinese) [CrossRef]
5. Luo, R.; Zheng, Y.G.; Chen, M. Mechanism of a rare night sudden intense warming event in Beijing and surrounding area. *Meteor Mon.* **2020**, *46*, 478–489. (In Chinese) [CrossRef]
6. Li, X.; Zhao, K.; Zhong, S.; Yu, X.; Feng, Z.; Zhong, Y.; Maulen, A.; Li, S. Evolution of Meteorological Conditions during a Heavy Air Pollution Event under the Influence of Shallow Foehn in Urumqi, China. *Adv. Atmos. Sci.* **2023**, *40*, 29–43. [CrossRef]
7. LI, X.; Xia, X.; Zhong, S. Shallow foehn on the northern leeside of Tianshan Mountains and its influence on atmospheric boundary layer over Urumqi, China—A climatological study. *Atmos. Res.* **2020**, *240*, 104940. [CrossRef]
8. Li, X.; Xia, X.; Wang, L.; Cai, R.; Zhao, L.; Feng, Z.; Ren, Q.; Zhao, K. The role of foehn in the formation of heavy air pollution events in Urumqi, China. *J. Geophys. Res. Atmos.* **2015**, *120*, 5371–5384. [CrossRef]
9. Dou, X.; Bin, J.; Jiang, J. The Meteorological Causes of the Collapse of Iron tower in Urumqi Electronic Network. *Xinjiang Meteorol.* **2005**, *28*, 32–34. [CrossRef]
10. Wang, N.; Yang, H.; Zhou, J.; Cao, D. Quantitative Study on Impact of Severe Weather on Flight Delay at Urumqi Airport. *J. Arid. Meteorol.* **2018**, *36*, 684–693.
11. Zhang, G.; Zhang, D.L.; Sun, S. On the Orographically Generated Low-Level Easterly Jet and Severe DownslopeStorms of March 2006 over the Tacheng Basin of Northwest China. *Mon. Weather. Rev.* **2018**, *146*, 1667–1682. [CrossRef]
12. Zhang, K.; Ma, Y.; Liu, Y.; Li, Y. Agricultural Significance of Incineration Effect in Ailao Mountain (Southwest Monsoon Mountain). *China Mt. Res.* **1993**, *11*, 81–87.
13. Mikutta, C.A.; Pervilhac, C.; Znoj, H.; Federspiel, A.; Müller, T.J. The Impact of FoehnWind on Mental Distress among Patients in a Swiss Psychiatric Hospital. *Int. J. Environ. Res. Public Health* **2022**, *19*, 10831. [CrossRef] [PubMed]
14. Zhang, J.; Su, Q.; Sun, S. *Xinjiang Short-Term Weather Forecast Guidebook*; Urumqi, Xinjiang People's Publishing House: Urumqi, China, 1986; pp. 341–347.
15. Diao, P. The statistical characteristics and forecast of southeast gale in Urumqi in spring. *Xinjiang Meteorol.* **1991**, *14*, 16–18.
16. Meng, Q.; Lyu, B.; Diao, P. Research on the Distribution Law of Southeast Gale in Urumqi Area. *Xinjiang Meteorol.* **1995**, *18*, 6–10.
17. Atkinson, B.W.; Wu Zhang, J. Mesoscale shallow convection in the atmosphere. *Rev. Geophys.* **1996**, *34*, 403–431. [CrossRef]
18. Drechsel, S.; Mayr, G.J. Objective Forecasting of Foehns for a Subgrid-Scale Alpine Valley. *Weather. Forecast.* **2008**, *23*, 205–218. [CrossRef]
19. Schultz, D.M.; Doswell, C.A. Analyzing and forecasting Rocky Mountain lee cyclogenesis often associated with strong winds. *Weather Forecast.* **2000**, *15*, 152–173. [CrossRef]
20. Lentink, H.S. Extreme Foehn in Switzerland: A Climatology and the Relation to Large Scale Flow. Master's Thesis, University Utrecht, Utrecht, Switzerland, 2012; pp. 1–65. Available online: https://studenttheses.uu.nl/handle/20.500.12932/15889 (accessed on 1 May 2023).
21. Richner, H.; Gutermann, T. Statistical analysis of foehn in Altdorf, Switzerland. *Int. Conf. Alpine Meteorol.* **2007**, *2*, 457–460.
22. Richner, H.; Hächler, P. Understanding and Forecasting Alpine Foehn. In *Mountain Weather Research and Forecasting: Recent Progress and Current Challenges*; Springer Atmospheric Sciences: Berlin, Germany, 2013; pp. 219–260.
23. Milz, T.; Hofsteenge, M.; Katurji, M.; Vetrova, V. Foehn Analysis using Unsupervised Deep Anomaly Detection. In Proceedings of the EGU General Assembly, Vienna, Austria, 23–28 April 2023. [CrossRef]
24. Sprenger, M.; Schemm, S.; Oechslin, R.; Jenkner, J. Nowcasting Foehn Events Using the AdaBoost Machine Learning Algorithm. *Weather Forecast.* **2017**, *32*, 1079–1099. [CrossRef]
25. Zhao, S.L.; Wang, R.K.; Guo, Y.B.; Tan, J.L.; Shi, Z.Z. The Foehn in the Middle Rang of Taihang Mountain. *Meteor Mon.* **1993**, *19*, 3–6.
26. Wang, Z.; Ding, Y.; Zhang, Y.; Fan, J.; Zhang, S.; Tian, L. Statistical Characteristics and Mechanism Analysis of Foehn Weather in the Eastern Foothills of Taihang MountainII:Case analysis of the influence of leeward wave on the generation and propagation of Foehn. *Plateau Meteorol.* **2012**, *31*, 555–561.
27. Li, D.; Zhang, Q.; He, K.; Sun, J.; Zhao, Z. Analysis of Temporal and Spatial Characteristics of Foehn in Xingtai City. *J. Agric. Catastrophol.* **2022**, *12*, 122–124. [CrossRef]
28. Zhao, Z.; Ma, H.; Ding, Z.; Xu, Y. The Influence of the Foehn on the Temperature of Baoding Area. *Shanxi Sci. Technol.* **2016**, *31*, 88–91. [CrossRef]
29. Xiong, X.; Wang, S.; Zhang, W. Analysis of Foehn Characteristics in Middle Section of Taihang Mountains Based on Background Method. *Meteorol. Sci. Technol.* **2020**, *48*, 433–437. [CrossRef]
30. Wan, Y.; Cao, X.; Dou, X.; Lu, H. The Application of ECMWF Refined Net Numerical Forecast Data in the Southeast Gale in Urumqi. *Desert Oasis Meteorol.* **2014**, *8*, 32–38. [CrossRef]
31. Tang, H.; Wang, X.; Chu, C.; Sun, M. Formation mechanism of a southeast gale event in Urumqi urban area: The coupling of gravity wave and ultra-low level jet. *Arid. Land Geogr.* **2019**, *42*, 1229–1238.
32. Sun, M.; Li, R.; Liu, J.; Aki, R. Analysis of Comparison Between the Two Kinds of the Southeasterly Gale Cases in Spring in Urumqi. *Desert Oasis Meteorol.* **2017**, *11*, 38–45.
33. Diao, X.; Feng, L.; Zhou, D.; Diao, P. Diagnostic analysis of southeast gale in Urumqi in March 2017. *Xinjiang Farm Res. Sci. Technol.* **2018**, *2*, 44–45.

34. Maulen, A.; Li, X.; Wang, S.; Mu, S.; Li, S.; Zhong, Y. Temporal and Spatial Characteristics of Foehn on the North Slope of the Tianshan Mountains of China and Prediction Ability of European Fine Grid Numerical Products. *Mt. Res.* **2022**, *40*, 823–834. [CrossRef]
35. Bougeault, P.; Binder, P.; Kuettner, J. (Eds.) *MAP Science Plan*; MeteoSwiss: Zurich, Switzerland, 1998; p. 64.
36. Vergeiner, J. South Foehn Studies and a New Foehn Classification Scheme in the Wipp and Inn Valley. Ph.D. Thesis, University of Innsbruck, Innsbruck, Austria, 2004; pp. 1–111.
37. Mayr, G.J.; Armi, L.; Arnold, S.; Banta, R.M.; Darby, L.S.; Durran, D.D.; Flamant, C.; Gaberšek, S.; Gohm, A.; Mayr, R.; et al. Gap flow measurements during the Mesoscale Alpine Programme. *Meteor. Atmos. Phys.* **2004**, *86*, 99–119. [CrossRef]