

Article

Monitoring Characteristics and Environmental Field Analysis of Low-Level Wind Shear Induced by “Easterly Backflow” at Xining Airport

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Abstract

A significant low-level wind shear event that occurred at Xining Caojiabu Airport on 10 April 2019 was comprehensively analyzed. The analysis utilized data from the airport's ground automatic weather observation system (AWOS), lidar detection data, ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), and ETOPO2v2 topographic data from the National Oceanic and Atmospheric Administration (NOAA). The analysis focused on the evolution of meteorological elements during the wind shear, lidar characteristics, large-scale environmental features, and the main influencing systems. The results indicate that this was a typical “easterly backflow” low-level wind shear event, representing a special type of cold-frontal low-level wind shear, with the wind shear occurring in the prefrontal area as the cold front approached the airport. During the passage of the wind shear, the AWOS stations at Runways 29 and 11 sequentially recorded pressure increases and temperature decreases, reflecting the gradual intrusion of cold air from east to west into the airport. Lidar Plan Position Indicator (PPI), Range-Height Indicator (RHI), and Doppler Beam Swinging (DBS) modes revealed that the wind shear appeared as convergence between southeast and northwest winds, with an impact on the airport that moved from east to west and from bottom to top, belonging to a meso- γ -scale system. The evolution of the sea-level pressure field, pressure-change field, frontogenesis function, and temperature advection indicated that cold air first moved eastward along the Hexi Corridor and then poured back into the Huangshui River Valley through the topographic gap at the eastern end of the Qilian Mountains. The easterly wind converged with the westerly wind, and the topographic funneling effect strengthened the easterly backflow and promoted its westward advance, leading to the occurrence of low-level wind shear. The large-scale influencing systems of this event included a transverse trough over Mongolia at 500 hPa, an upper-level frontal zone, an upper-level jet stream, and a surface cold front. The favorable conditions for the formation of this “easterly backflow” low-level wind shear were the strengthening of baroclinicity in the upper-level frontal zone, intensified cold advection, momentum downward transport induced by the upper-level jet and ageostrophic secondary circulation, and the easterly backflow and wind speed enhancement caused by the special topography.

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1. Introduction

In recent years, rapid development has been achieved in global and Chinese civil aviation. General aviation, a vital component of civil aviation, has been rapidly expanding. Consequently, meteorological support demands for safe aviation operations have drastically increased, particularly in low-altitude airspace [1]. Low-level wind shear is defined by the International Civil Aviation Organization (ICAO) as a significant wind vector variation. This variation occurs between two spatial points below 600 m (2000 ft). The types mainly include tailwind, headwind, crosswind, and vertical wind shears [2]. Based on numerous pilot reports (PIREPs) and observational data, a statistical analysis was conducted by Belo-Pereira [3]. It was found that most wind shear events posing substantial threats to aviation are concentrated in extremely low-altitude regions. Accidents such as turbulence, runway excursion, and even stall can be caused by low-level wind shear. These accidents occur during aircraft takeoff and landing phases, severely threatening flight safety [1]. Low-level wind shear is characterized by short duration, small spatial scale, and high-frequency variations. Therefore, its real-time prediction and early warning are made highly challenging.

It is pointed out by the aviation hazard report of the National Research Council (NRC) that initial takeoff and approach-landing phases are the riskiest periods. Low-level wind shear is widely recognized as an “invisible killer” during these aircraft takeoff and landing phases [4]. It is statistically shown that about 15% of global approach-landing and runway safety accidents are directly correlated with low-level wind shear. The occurrence frequency and hazard intensity are remarkably enhanced at airports characterized by complex terrain and variable meteorological conditions [4]. In terms of dynamical responses, it is noted by Etkin and Reid [5] that aircraft aerodynamic balance can be broken by strong vertical shears of horizontal winds. Consequently, severe oscillations in pitch attitude are induced, and significant longitudinal position deviations are triggered. Therefore, important practical significance is attached to the research on airport low-level wind shear for ensuring flight safety. This is especially true when novel remote sensing detection methods are introduced.

The microburst phenomenon and its fatal threats to aviation safety were first systematically described by Fujita [6]. Thus, the foundation of modern wind shear research was established. Aviation-related wind shear and turbulence types were comprehensively reviewed by Sharman and Lane [7]. Based on meteorological causes, they were classified into convective wind shear, non-convective wind shear, and boundary layer turbulence induced by complex terrain. Classification guidance was thus provided for the identification and prediction of wind shear. Combined with long-term observational data, it was further summarized by Chan [8] that low-level wind shear is mainly caused by three factors. The first is severe convective weather (such as downbursts). The second is frontal systems, which are the primary meteorological conditions for non-convective wind shear generation. The third is the influence of topography and surface objects. When surrounding mountains are numerous or the terrain is complex, topographic wind shear is easily generated. This is caused by the blocking and perturbing effects of obstacles on the airflow. The early warning of such wind shear is extremely difficult.

A cold front is a frontal system formed by a cold air mass moving toward a warm air mass. The warm air is simultaneously forced to be lifted. Due to its higher density, the cold air mass is wedged into the bottom of the warm air mass. Consequently, the warm

air is forced upward, and an inclined interface is formed [9]. Global frontal climatology research [10] based on high-resolution reanalysis data indicates that cold fronts are active throughout the year in East Asia. The occurrence frequency is highest in spring, followed by winter, and lowest in summer. However, the dynamical and thermal intensities of cold fronts are the most severe in winter. Cold-frontal low-level wind shear is an atmospheric phenomenon characterized by sudden and significant variations in low-level wind vectors. It is directly caused by cold fronts and is recognized as an important type of non-convective low-level wind shear [8]. Its core characteristics are directly associated with the thermal and dynamical processes during cold frontal passages. A diagnosis of cold-frontal low-level wind shear was conducted by Hon [11] based on high-resolution numerical models. It was found that the wind speed difference is significantly enlarged by the distribution characteristics of cold and warm advection on both sides of the frontal zone. During frontal passages, drastic variations in wind fields are caused by strong pressure and temperature gradients within the narrow transition zone. Consequently, severe low-level wind shear is easily induced.

Xining Airport is located in the northeastern Qinghai–Tibet Plateau, in the Huangshui River Basin on the southeastern side of the Qilian Mountains, and belongs to the category of plateau airports. After cold air moves eastward along the Hexi Corridor in Gansu Province and reaches the eastern end of the Qilian Mountains, it pours back into Qinghai Province, triggering cold-frontal low-level wind shear at Xining Airport. Unlike most cold fronts that move from west to east, this type of low-level wind shear has a cold front moving from east to west, and its formation mechanism exhibits obvious particularities; however, related research remains insufficient. This paper focuses on a typical “east-erly backflow” low-level wind shear event at Xining Airport on 10 April 2019, with emphasis on its actual characteristics, lidar features, circulation background, momentum downward transport, and baroclinicity, aiming to provide more scientific basis for improving the early warning of low-level wind shear at plateau airports.

2. Data and Methods

2.1. Data

The observation data from the ground automatic weather observing system (AWOS) at Xining Caojiabu Airport (hereinafter referred to as Xining Airport) on 10 April 2019 were used. These included temperature, pressure, relative humidity (time resolution: 1 min), wind direction, and wind speed (time resolution: 30 s).

Observation data from the FC-III wind lidar at Xining Airport were used. The lidar adopted a combined scanning strategy, specifically including four combined modes: the PPI mode (plan position indicator scanning at 3°/6° elevation), the RHI mode (range-height indicator scanning at 110°/290° azimuth), the DBS mode (wind profile detection), and the GP mode (110°/290° glide path wind field monitoring). The core detection data included radial wind speed, horizontal wind direction and speed, and vertical wind direction and speed.

The retrospective ERA5 reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) was employed. It should be noted that ERA5 is not real-time data; it is a historical reanalysis product with a preliminary data delay of 5 days (ERA5T) and a final consolidated release delay of 2–3 months. The dataset utilized in this study features a spatial resolution of $0.25^\circ \times 0.25^\circ$ and a temporal resolution of 1 h. This dataset includes geopotential height, temperature, meridional wind, zonal wind, vertical velocity, and other fields, and it was mainly used for the retrospective diagnostic analysis of the large-scale circulation background and surface weather systems during the selected cases.

Global digital elevation model data, Earth Topography 2 min Version 2 (ETOPO2v2), developed by the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA), were used to characterize the topographic relief of the study area.

2.2. Some Calculation Formulas

2.2.1. Introduction to Lidar Scanning Modes

PPI Mode

The PPI (Plan Position Indicator) mode, also known as the plan scanning mode, performs circular scans at a fixed elevation angle. Its purpose is to obtain the evolution of the wind field around the instrument. Its data products include radial velocity, horizontal wind, and wind shear. The temporal resolution is a few minutes. The relationship between the radial wind speed measured in a single observation and the actual atmospheric wind (u, v, w) is given by:

$$V_r = u \sin \gamma \cos \theta + v \cos \gamma \sin \theta + w \sin \theta$$

where V_r is the measured radial velocity; u, v , and w represent the three-dimensional atmospheric wind components in the zonal (east–west), meridional (north–south), and vertical (up–down) directions, respectively; θ is the fixed elevation angle of the lidar beam from the horizontal plane; and γ is the azimuth angle measured clockwise from the geographic north. By scanning the surrounding area with multiple beams at different azimuth angles, the following system of equations is obtained:

$$V_{ri} = u \sin \gamma_i \cos \theta + v \cos \gamma_i \sin \theta + w \sin \theta$$

$$(i = 1, 2, 3 \dots)$$

Solving this overdetermined system by the least-squares method yields the best estimates of (u, v, w), providing the complete horizontal wind field information. The horizontal wind speed V_H and wind direction α are:

$$V_H = \sqrt{u^2 + v^2}$$

$$\alpha = \arctan(v/u)$$

RHI Mode

The RHI (Range-Height Indicator) mode performs a vertical cross-section scan by fixing the azimuth and varying the elevation angle from 0° to 90° . The radial wind speed from a single measurement and the actual wind components (u, v, w) are related by:

$$V_r(\phi) = u \cos \alpha \cos \phi + v \sin \alpha \cos \phi + w \sin \phi$$

where $V_r(\phi)$ is the lidar-measured radial wind speed; u, v, w are the east–west, north–south, and vertical wind components; α is the fixed azimuth during the scan; and ϕ is the continuously varying elevation angle (0° – 90°).

DBS Mode

The DBS (Doppler Beam Swinging) mode is a wind profile detection mode that transmits beams at a fixed elevation toward four azimuths (east, south, west, north). Radial velocities are used to retrieve the horizontal wind components (east–west u , north–south v). The radial velocity equation is:

$$\begin{cases} V_{rE} = u \sin \gamma + w \cos \gamma \\ V_{rW} = -u \sin \gamma + w \cos \gamma \\ V_{rN} = v \sin \gamma + w \cos \gamma \\ V_{rS} = -v \sin \gamma + w \cos \gamma \end{cases}$$

(with corresponding equations for other directions). The horizontal wind retrieval formulas are:

$$u = \frac{V_{rE} - V_{rW}}{2\sin\gamma}$$

$$v = \frac{V_{rN} - V_{rS}}{2\sin\gamma}$$

where γ is the zenith angle of the beam, and V_{rE} , V_{rW} , V_{rN} , V_{rS} are the radial velocities in the east, west, north, and south directions, respectively.

2.2.2. Calculation of Frontogenesis Function

The classical two-dimensional frontogenesis function was used for horizontal frontogenesis analysis in low-level wind shear research. The frontogenesis function F is defined as the rate of change in the horizontal potential temperature gradient, expressed as:

$$F = \frac{d}{dt} |\nabla_h \theta| = \frac{1}{|\nabla_h \theta|} \left[\frac{\partial \theta}{\partial x} \left(-\frac{\partial u}{\partial x} \frac{\partial \theta}{\partial x} - \frac{\partial v}{\partial x} \frac{\partial \theta}{\partial y} \right) + \frac{\partial \theta}{\partial y} \left(-\frac{\partial u}{\partial y} \frac{\partial \theta}{\partial x} - \frac{\partial v}{\partial y} \frac{\partial \theta}{\partial y} \right) \right]$$

where $|\nabla_h \theta|$ is the magnitude of the horizontal potential temperature gradient, defined as $|\nabla_h \theta| = \sqrt{\left(\frac{\partial \theta}{\partial x}\right)^2 + \left(\frac{\partial \theta}{\partial y}\right)^2}$; θ is the potential temperature; u and v are the zonal (x -direction) and meridional (y -direction) wind components, respectively; and d/dt is the total derivative operator. In this explicitly expanded form, the equation captures the combined effects of the local change, advection, and the kinematic effects of horizontal wind gradients (stretching and shearing) on the potential temperature field.

2.2.3. Calculation of Temperature Advection

The horizontal temperature advection was calculated as follows:

$$ADVT = -V_h \cdot \nabla_h T = -\left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right)$$

where V_h is the horizontal wind vector; u and v are the zonal and meridional wind components, respectively; T is the air temperature. and x and y represent the horizontal coordinates. The horizontal temperature gradients $\left(\frac{\partial T}{\partial x}\right)$ and $\left(\frac{\partial T}{\partial y}\right)$ were computed using central differences. Where $ADVT > 0$, warm advection is present, representing the transport of warm air into the study area; where $ADVT < 0$, cold advection is present, representing the transport of cold air.

3. Topographic Characteristics and Airport Overview

3.1. Topographic Features

Xining Airport (102°02'35" E, 36°31'39" N) is located in Gaozhai Subdistrict, Huzhu Tu Autonomous County, Haidong City, Qinghai Province, approximately 28 km from the city center of Xining. Situated at an elevation of approximately 2184.2 m, the airport is surrounded by mountains that are generally 300–800 m higher than the airfield. Thus, it is classified as a typical plateau complex mountainous airport (Figure 1) [12].

Located in the northeastern part of the Qinghai–Tibet Plateau, the airport is bordered by the Qilian Mountains to the north and the Laji Mountains to the south, nesting within the narrow valley of the Huangshui River. This typical canyon topography exerts significant dynamical amplification and physical constraint effects on boundary-layer cold air activities and low-level wind shear development. Consequently, it is highly prone to inducing a pressure-driven channeling effect [13,14]. Under specific synoptic backgrounds, the southward-moving northern cold air is blocked by the Qilian Mountains, making it difficult for the air mass to directly cross the terrain. Instead, its main body advects south-

eastward along the lower-elevation Hexi Corridor. After bypassing the eastern end of the Qilian Mountains, the topography forces a backflow intrusion, causing the cold air to intrude into the Huangshui Valley from east to west. Superimposed with the channeling effect inside the valley, the low-level wind speed of the intruding cold air is sharply enhanced. This process is recognized as a core mechanism fundamentally responsible for inducing low-level wind shear at Xining Airport [15].

Topography of Xining Airport and Surrounding Areas

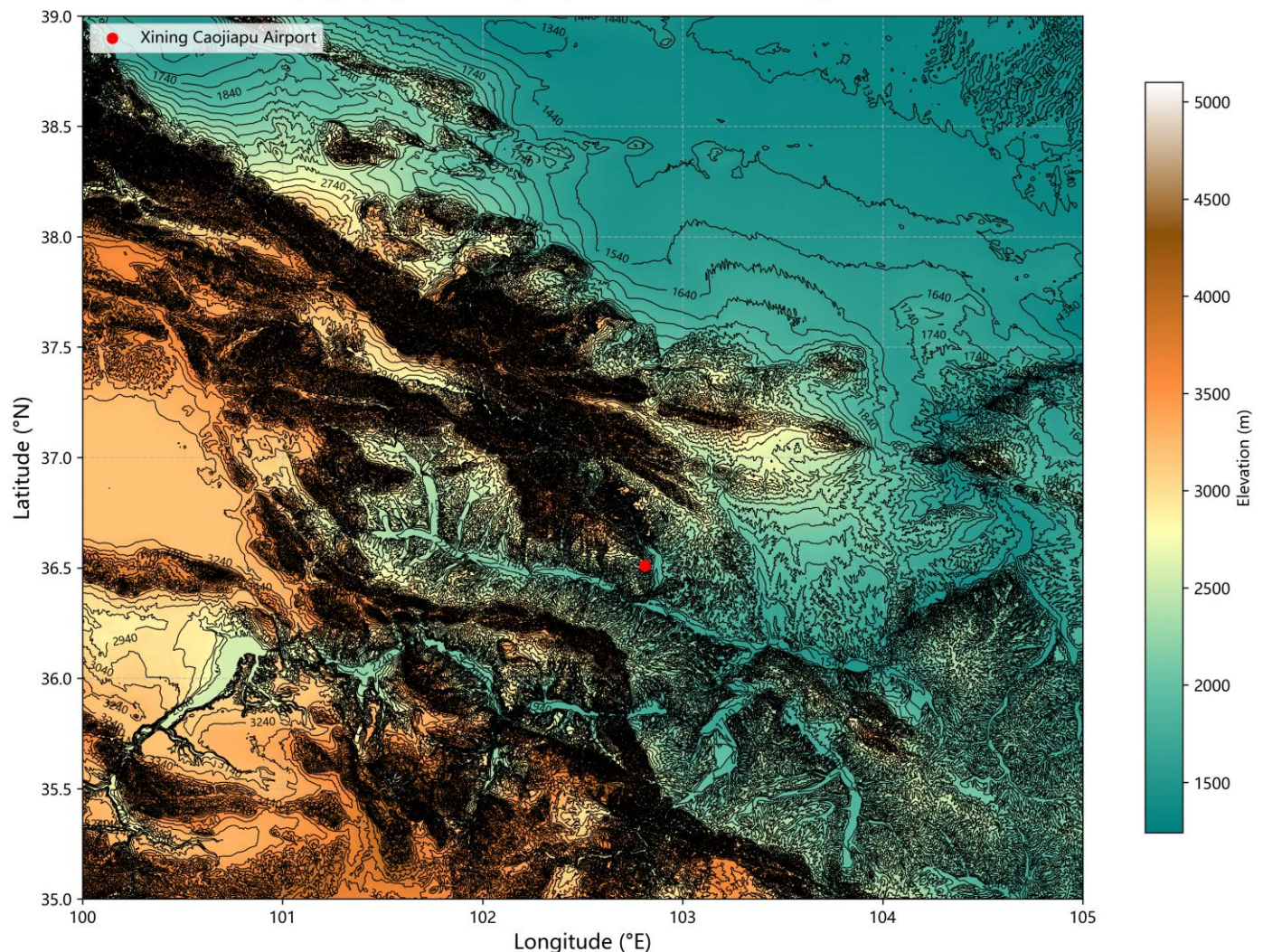


Figure 1. Topographic Map of Xining Caojiabao Airport and Surrounding Area (The red dot in the image represents Xining Airport).

3.2. Airport Introduction

Xining Airport has one runway oriented southeast–northwest (Figure 2) with a total length of 3800 m and a width of 50 m. The western end is Runway 11 with an azimuth of 110°, and the eastern end is Runway 29 with an azimuth of 290°. The runway azimuth indicates that aircraft approaching from that angle will land on the correspondingly numbered runway. Automatic weather observation stations (AWOS) are deployed at the thresholds of both runways. The Doppler Wind Lidar (DWL) is installed in the middle portion of the runway, 1153 m from the threshold of Runway 11 and 316 m from the runway centerline.

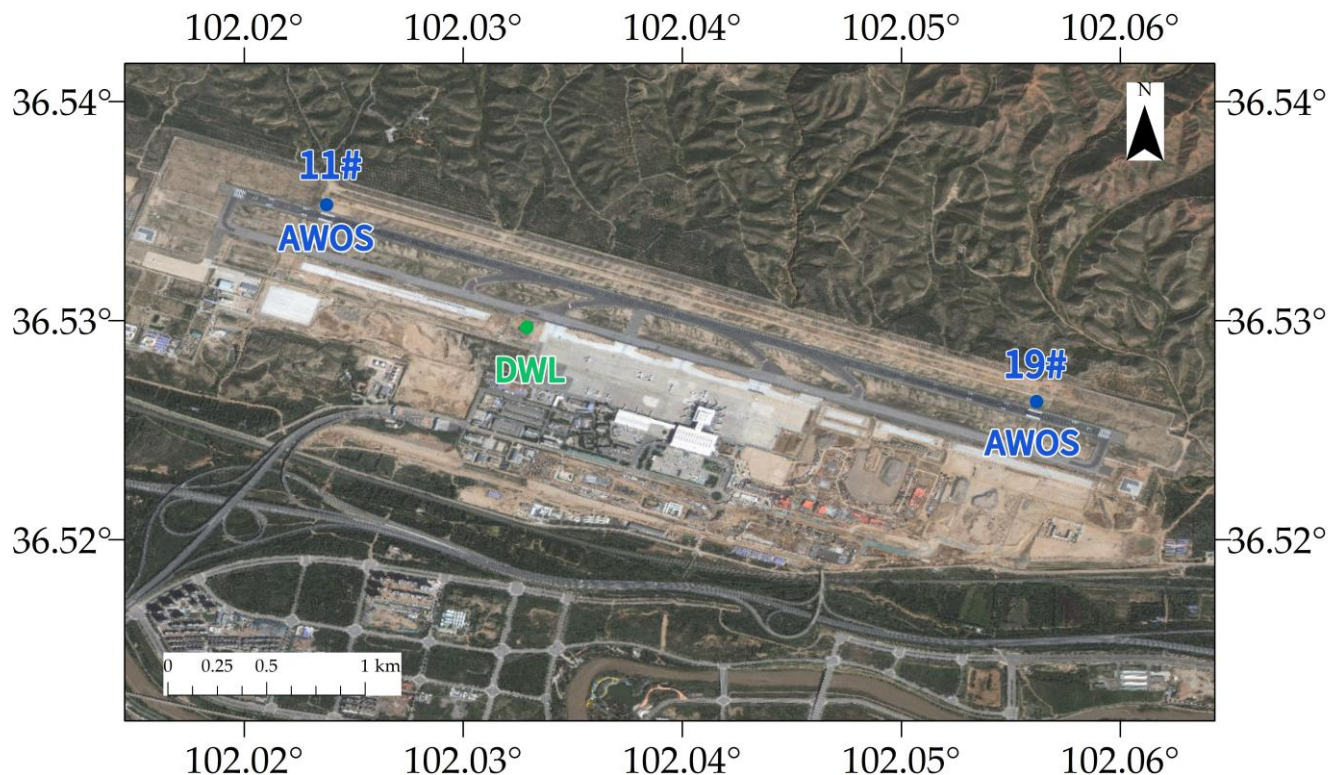


Figure 2. Top view of Xining Airport and the distribution of main observation equipment.

4. Observational Characteristics of Low-Level Wind Shear

4.1. Awos Observations

The period from afternoon to evening in April–June is the high-incidence period for low-level wind shear at Xining Airport [16], and the low-level wind shear on the afternoon of 10 April 2019 occurred exactly within this period. Around the evening of 10 April, both runways experienced significant changes in wind direction and speed, with the change in wind direction being more pronounced than that in wind speed (Figure 3). Before 18:02 (local time, same below), the wind direction at both Runway 29 and Runway 11 was northwest. At 18:02, the northwest wind at Runway 29 began to veer; within one minute the direction shifted from 310° to 234° (southwest), and the speed decreased to 5 m s^{-1} . From 18:03 to 18:04, the wind continued to veer to 131° (southeast), and the speed dropped to 3.4 m s^{-1} . Thereafter, the direction remained between 110° and 130° (southeast). For Runway 11, before 18:12 it was completely controlled by westerly wind, with the direction near 280° . At 18:12, the direction shifted markedly from 263° (westerly) to 136° (southeast) within one minute, and the speed fell to 2.1 m s^{-1} . Thereafter, the direction stayed between 110° and 130° , and the speed gradually increased to 10 m s^{-1} . The wind-direction and wind-speed changes at Runway 11 were similar to those at Runway 29 but occurred with a time lag. Thus, the airport runway area was affected by a low-level wind shear event from 18:00 to 18:30 on 10 April 2019. The wind shear first appeared at Runway 29 and later affected Runway 11; it was a wind shear process characterized by the convergence of easterly and westerly winds.

From Figure 4, the pressure values at both runways changed consistently and both showed a clear increase during the wind shear, indicating that the backflow cold air from the east gradually affected the airport. The temperatures at Runways 29 and 11 dropped abruptly at 18:06 and 18:15, respectively, and relative humidity rose abruptly at 18:05 and 18:14, respectively, the occurrence times of abrupt changes in relative humidity and tem-

perature are almost identical. It can be seen that Xining Airport was controlled by relatively dry and warm air before the low-level wind shear and by relatively moist and cold air afterward.

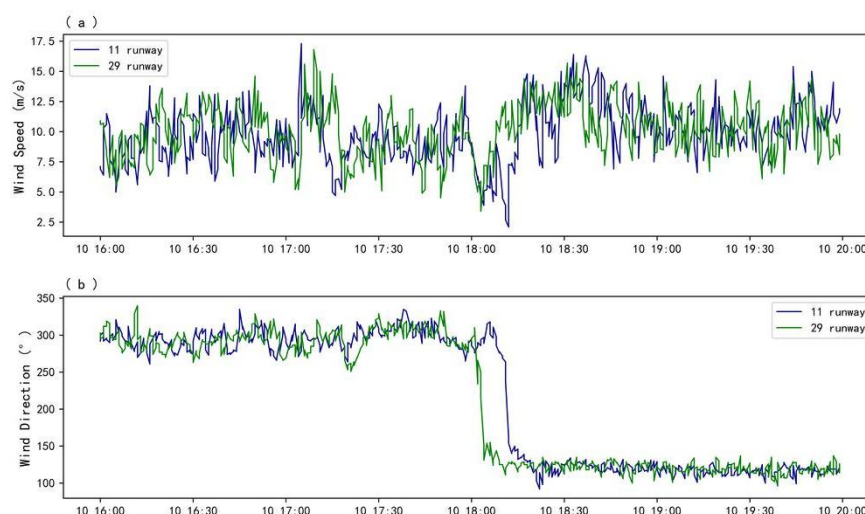


Figure 3. Time series of wind speed (a) and wind direction (b) at Runways 29 and 11 of Xining Airport from 16:00 to 20:00 on 10 April 2019.

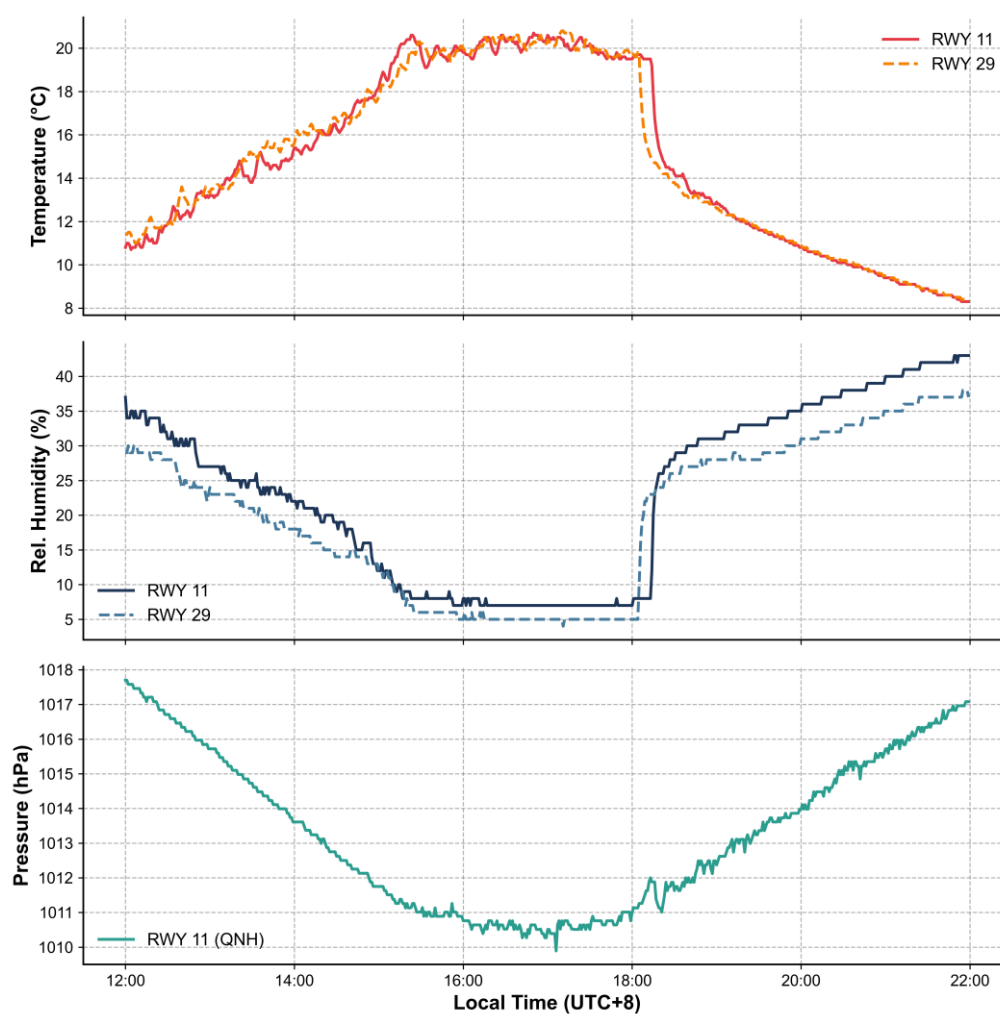


Figure 4. Time series of temperature, relative humidity, and pressure at Runways 29 and 11 of Xining Airport on 10 April 2019.

4.2. Lidar Characteristics of Low-Level Wind Shear

4.2.1. Ppi Characteristics

Figure 5 presents the radial wind speed and retrieved horizontal wind fields from lidar PPI scans, capturing the spatial evolution of the wind shear. Initially (17:49–17:52, Figure 5a,b), the airport was dominated by uniform northwest winds. However, at 17:52, a southeast wind emerged 6–8 km southeast of the lidar (at ~500 m AGL), creating a positive–negative velocity convergence. By 17:58 (Figure 5c), this convergence formed a distinct headwind convergence line (wind-direction shear) 4 km into the eastern glide path, marking the onset of the low-level wind shear event.

As this easterly flow advanced westward, it systematically altered the wind field. It triggered wind-direction changes at the Runway 29 AWOS at 18:02 and subsequently at the Runway 11 AWOS at 18:12 (Figure 5d–f), eventually dominating the entire eastern side of the lidar. The shear's influence ended around 18:33 when the easterly wind pushed beyond the western end of the western glide path (Figure 5g).

Integrating the AWOS and lidar PPI data, this event was primarily a directional low-level wind shear lasting from 17:58 to 18:33. The headwind convergence line spanned 6–8 km, identifying it as a meso- γ -scale weather system that progressively swept across the airport area below 500 m.

4.2.2. Rhi Characteristics

Figure 6 presents the vertical distribution of radial wind from RHI scans along the runway. Prior to the frontal arrival (17:51, Figure 6a), the boundary layer was uniformly dominated by westerlies. The onset of the shear event was captured at 18:01 (Figure 6b) when a near-surface cold front emerged approximately 4 km east of the lidar, generating an initial easterly–westerly horizontal shear line below 500 m.

Crucially, the RHI data visually captured the main body of cold air intruding westward in a distinct wedge shape. This near-surface intrusion forced the pre-existing westerlies to retreat aloft, causing wind speeds to drop significantly ($<10 \text{ m s}^{-1}$) within the convergence zone. As the easterly flow systematically advanced across the lidar location (18:10–18:19, Figure 6c,d), it deepened to occupy the lowest 1 km layer by 18:27 (Figure 6e). Ultimately, this process established a stable and strong vertical wind shear between 500 and 1000 m, clearly demonstrating the vertical dynamic structure of the cold front.

In summary, the multi-time RHI observations clearly revealed the evolution of this low-level wind shear process. Negative velocity first appeared in the near-surface layer 4 km east of the runway, producing the initial vertical stratification of westerly and easterly winds. As the easterly wind strengthened and advanced westward, the vertical stratification also moved westward, successively affecting the eastern and western sides of the runway and ultimately establishing a stable wind-field structure with easterly wind in the near-surface layer and significant vertical wind shear at middle–low levels.

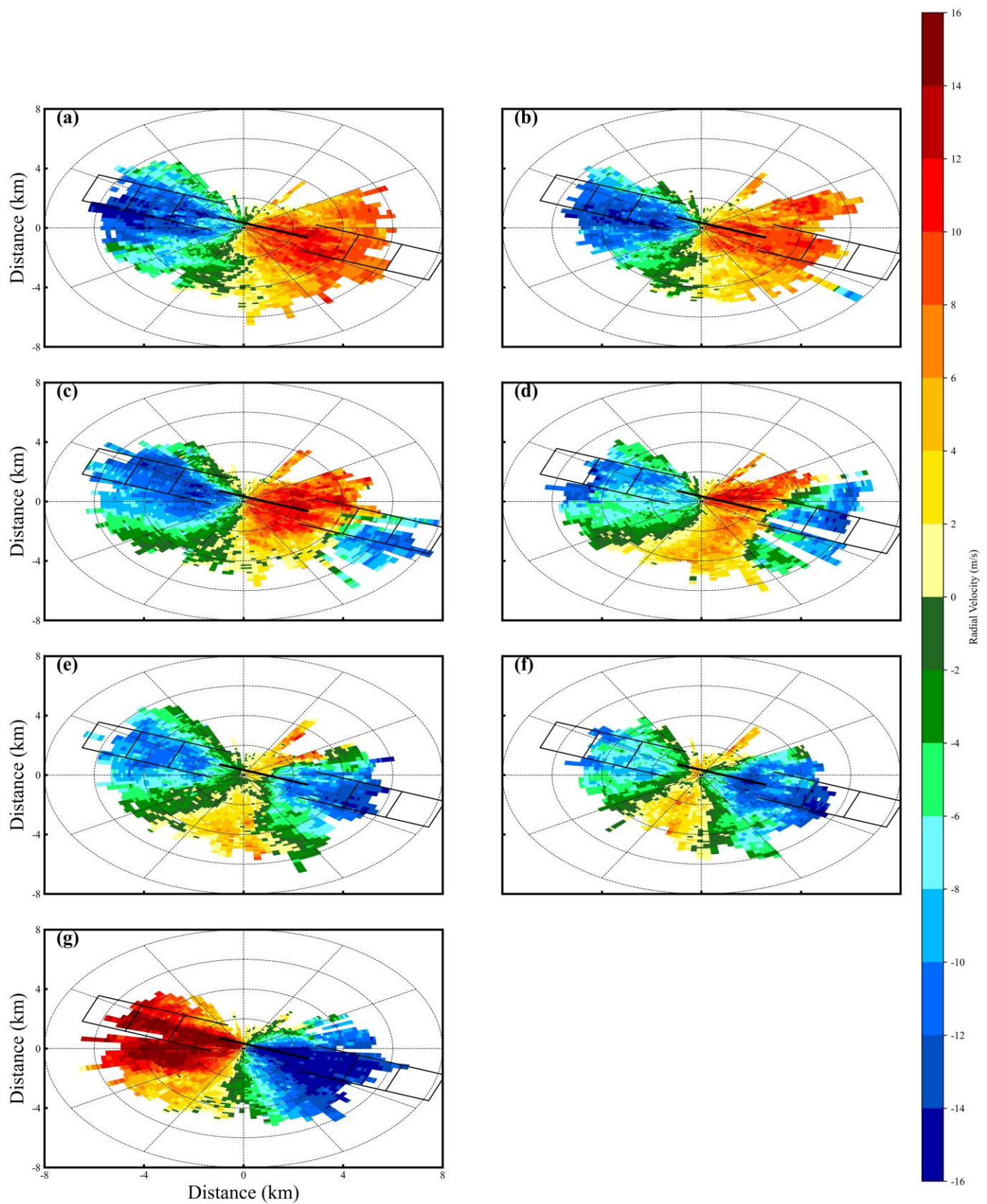


Figure 5. Lidar PPI images (3° elevation) at Xining Airport from 17:49 to 18:33 on 10 April 2019. The lidar is at the coordinate origin. (The black narrow rectangle denotes the runway; the black wide rectangle denotes the glide path. Runway 11 is on the west side; Runway 29 is on the east side. Shading: radial wind speed [m s^{-1}]. Warm colors represent positive velocities (away from lidar); cool

colors represent negative velocities (toward lidar). Vectors denote the retrieved horizontal wind [m s^{-1}].) (a) 17:49 (b) 17:52 (c) 17:58 (d) 18:03 (e) 18:08 (f) 18:11 (g) 18:33.

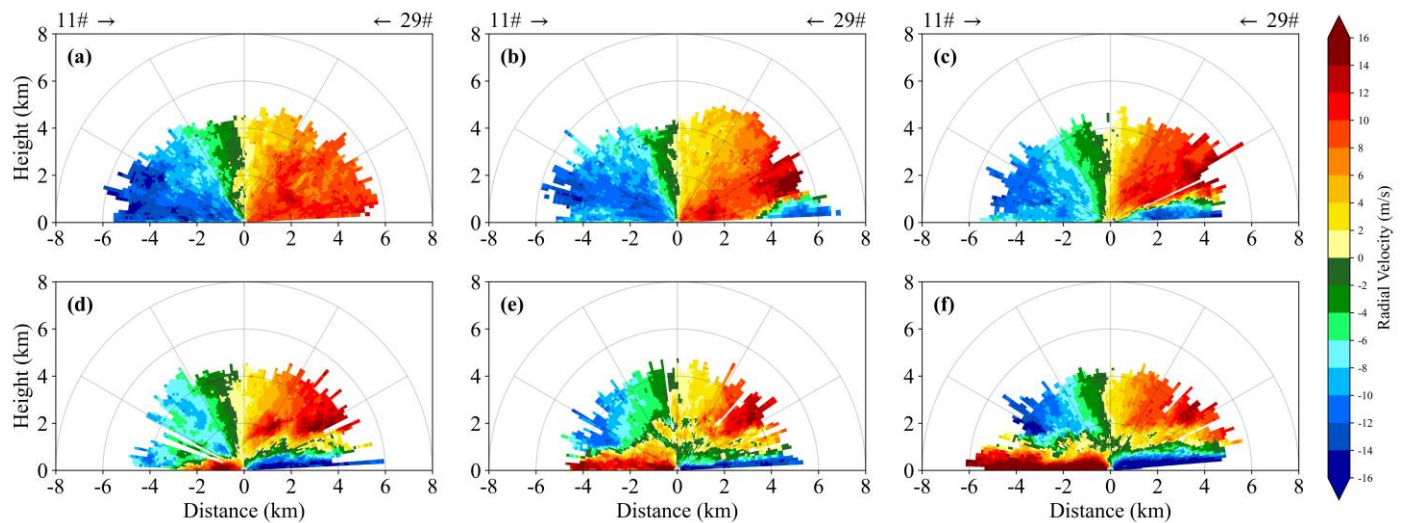


Figure 6. Lidar RHI images (110° azimuth) at Xining Airport from 17:51 to 18:36 on 10 April 2019. Shading: radial wind speed [m s^{-1}]. (a) 17:51 (b) 18:01 (c) 18:10 (d) 18:19 (e) 18:27 (f) 18:36.

4.2.3. Dbs Characteristics

From Figure 7, a clear horizontal wind vertical shear existed above the lidar at Xining Airport, and its evolution exhibited distinct phases. Before the shear, the airspace above the lidar was controlled by northwest wind with speeds at various heights mainly $12\text{--}16 \text{ m s}^{-1}$. At 18:07, the wind direction remained northwest, but wind speeds generally decreased to $4\text{--}8 \text{ m s}^{-1}$, significantly lower than the previous moment. At 18:15, the near-surface wind direction first turned easterly, forming an initial horizontal wind vertical shear layer with the overlying westerly wind; the overall wind speed changed little compared with the previous time. After the initial shear formed, the influence range of the low-level easterly wind continuously expanded upward, the controlled thickness gradually increased, pushing the shear layer upward, and the wind speed in that layer also gradually increased.

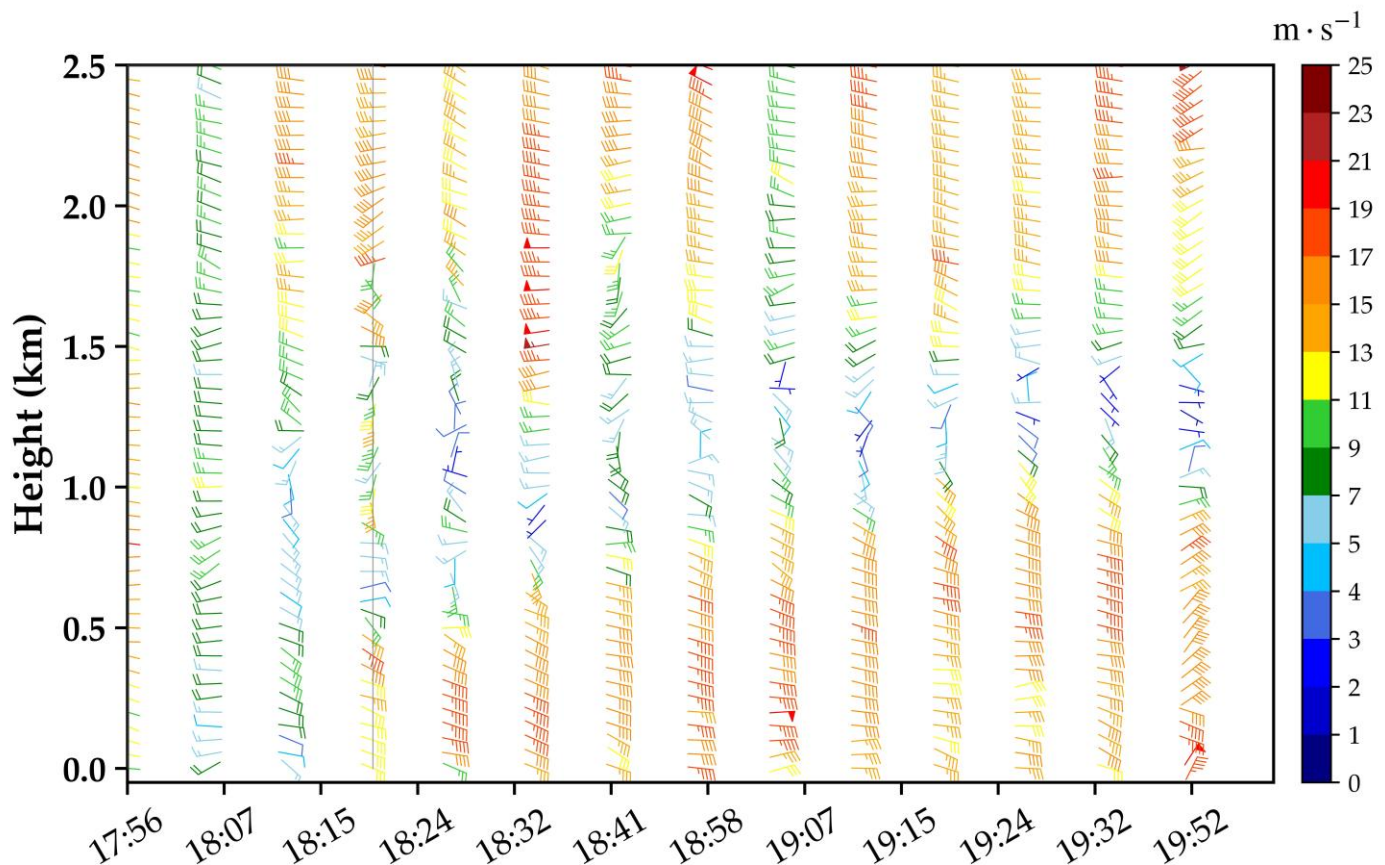


Figure 7. Lidar DBS horizontal wind barbs at Xining Airport from 17:00 to 20:00 on 10 April 2019.

5. Synoptic-Scale Analysis of the Low-Level Wind Shear

5.1. Surface Pattern Characteristics

At 18:00 on 10 April (Figure 8), the sea-level pressure field showed an east–west-oriented low-pressure belt west of Xining Airport (approximately 90° E–100° E, 34° N–38° N), and the airport lay within this low-pressure system. At the same time, the area north of the Qilian Mountains was controlled by a high-pressure system. Blocked by the Qilian Mountains, an area of dense isobars formed at the base of the high, with a strong horizontal pressure gradient force that constituted the cold-frontal zone. The divergent flow behind the high formed northwest winds behind the cold front, pushing the front southeastward. After the front moved eastward out of the Hexi Corridor, part of the cold air poured back into the Huangshui Valley through the topographic gap at the eastern end of the Qilian Mountains, and the wind direction behind the cold front also changed from northwest to northeast. Therefore, during this low-level wind shear event, the overall surface pressure field was characterized by “high in the north and low in the south.” The eastward-moving, southward-propagating cold air and the terrain-forced easterly wind backflow provided favorable synoptic-scale background and dynamic conditions for the occurrence of low-level wind shear at Xining Airport. The wind shear occurred in the pre-frontal area as the cold front approached the airport.

On the surface 3 h pressure-change field (Figure 9), at 17:00 on 10 April (Figure 9a), Xining Airport was located in a strong negative pressure-change area, while the area to its north was a positive pressure-change area. A dense zone of isallobars between them again confirmed the existence of the cold-frontal zone. At 18:00 (Figure 9b), the negative pressure-change area at the airport weakened, and the northern positive pressure-change area moved southward to central Gansu; the 0 hPa isallobar approached Xining Airport,

and the pressure-change gradient increased, indicating that cold air was pouring back from northeast to southwest into Qinghai. The upper-level jet stream serves as a primary dynamical driver for the middle and lower troposphere, typically corresponding to regions with strong atmospheric baroclinity. Based on the jet streak secondary circulation theory, the divergence and convergence fields in different quadrants of the upper-level jet force significant ascending or descending motions below. This dynamical mechanism not only modulates the cyclogenesis and evolution of surface weather systems but also triggers strong downward momentum transfer, which rapidly intensifies the low-level wind fields and contributes to the generation of severe wind shear [17–19].

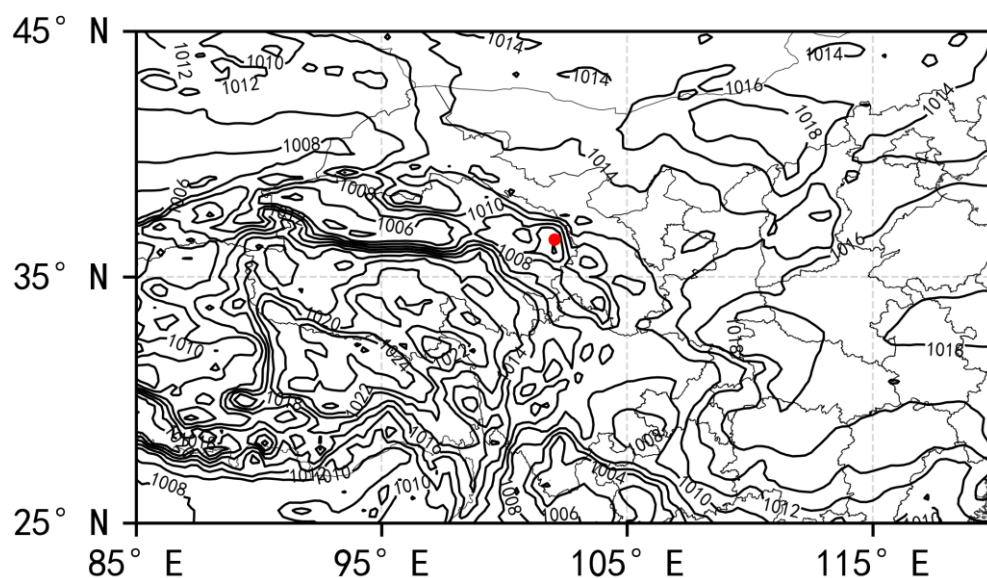


Figure 8. Sea-level pressure field at 18:00 on 10 April 2019 (black contours, hPa) Red dot: Xining Airport.

5.2. 500 hPa Circulation Characteristics

At 500 hPa on 10 April 2019 (Figure 10), north of 35° N, the airspace over Xinjiang was under the control of a high-pressure ridge, and a transverse trough was located over Mongolia in front of the ridge. At the base of the transverse trough, northwest flow was present, along which cold air continuously split off and moved eastward and southward. Over the Hexi Corridor, contours and isotherms were dense, and wind speeds were relatively high, with the maximum exceeding 30 m s^{-1} , indicating the existence of an upper-level frontal zone. South of 35° N, from southern Shaanxi to the Sichuan Basin, there was a northeast–southwest-oriented low trough. Xining Airport was situated in the rear of this southern low trough and within the northwest flow at the base of the Mongolian transverse trough, in the influence area of the upper-level frontal zone where strong baroclinity existed.

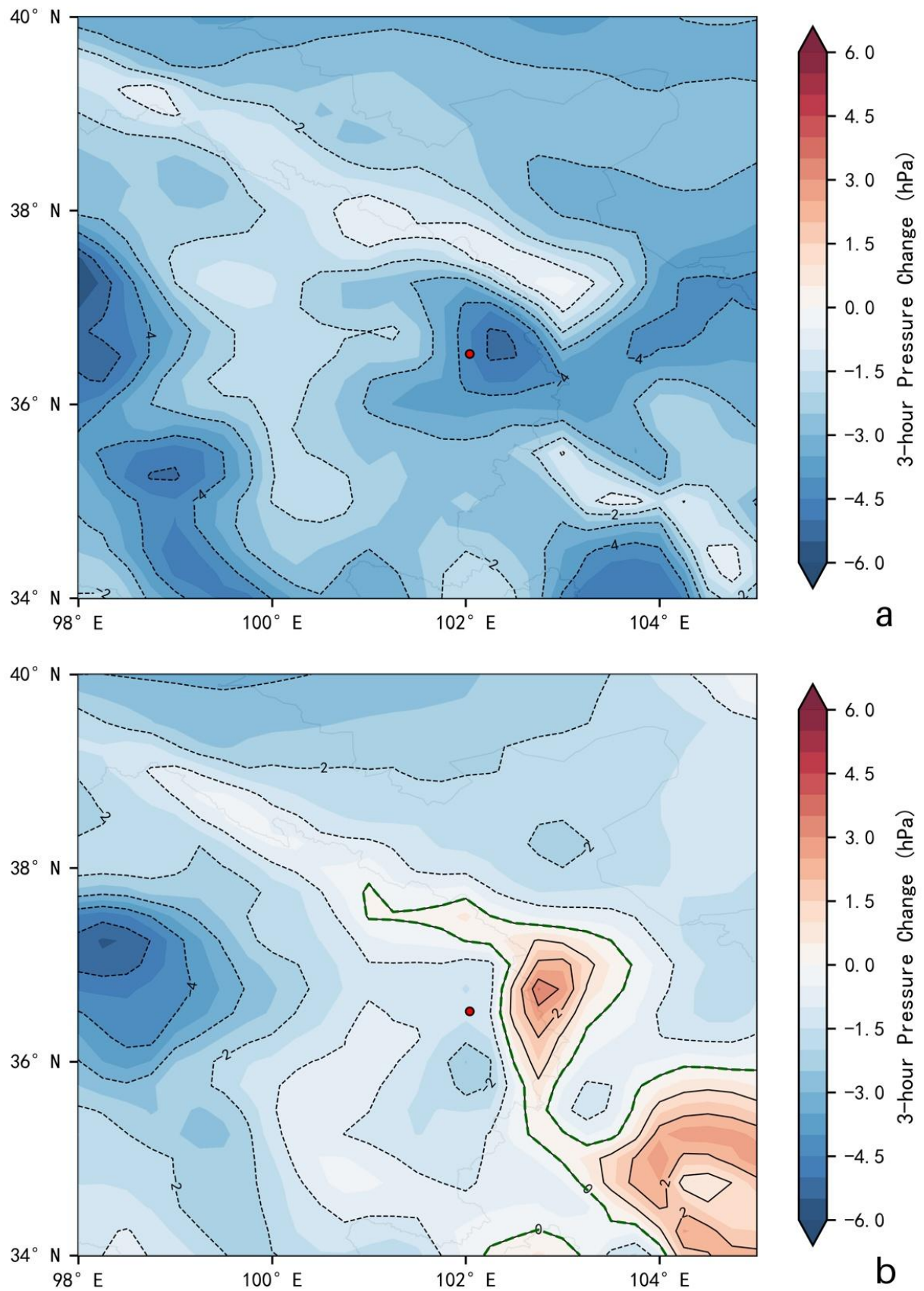


Figure 9. Surface 3 h pressure-change field (a) 16:00, (b) 18:00 on 10 April 2019 (Red dot: Xining Airport).

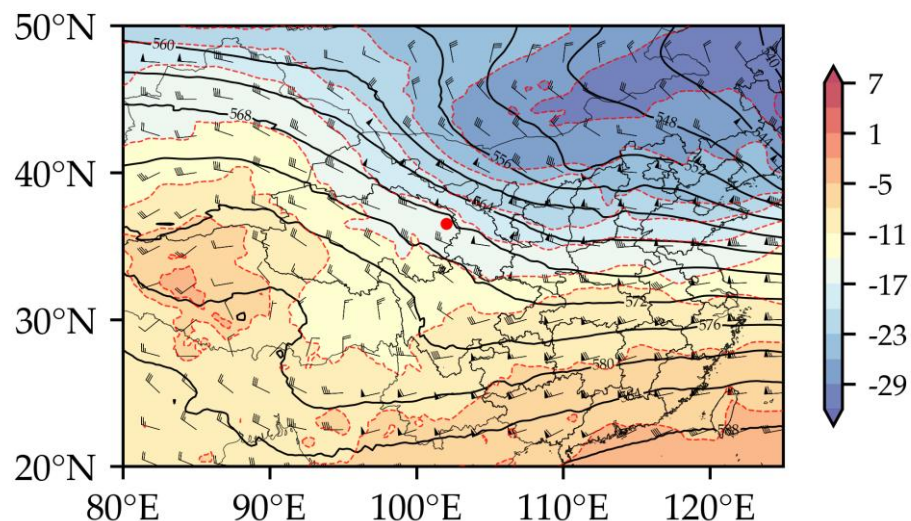


Figure 10. Geopotential height at 500 hPa (black contours, dagpm), temperature (shaded, °C), isotherms (red dashed, °C), and wind field (m s^{-1}) at 18:00 on 10 April 2019 (Red dot: Xining Airport).

5.3. 300 hPa Upper-Level Jet Stream Characteristics

The 300 hPa circulation clearly showed the coordinated configuration of the polar-front jet and the subtropical jet. As seen in Figure 11, over Eurasia, a relatively straight polar-front jet was present near 60° N, while the subtropical jet was mainly located between 30° N and 50° N with large meanders. The two jets tended to merge near 90° E, where each formed a distinct jet core. East of 90° E, a deep trough existed, with a subtropical westerly jet core ahead of and behind the trough. The pre-trough jet core was mainly westerly, with a maximum speed exceeding 72.5 m s^{-1} ; the post-trough jet core was mainly northwest, with a maximum speed reaching 45.0 m s^{-1} . Xining Airport was located near the exit region of the post-trough jet core. The upper-level jet stream serves as a primary dynamical driver for the middle and lower troposphere, typically corresponding to regions with strong atmospheric baroclinity. Based on the jet streak secondary circulation theory, the divergence and convergence fields in different quadrants of the upper-level jet force significant ascending or descending motions below. This dynamical mechanism not only modulates the cyclogenesis and evolution of surface weather systems but also triggers strong downward momentum transfer, which rapidly intensifies the low-level wind fields and contributes to the generation of severe wind shear [19–21].

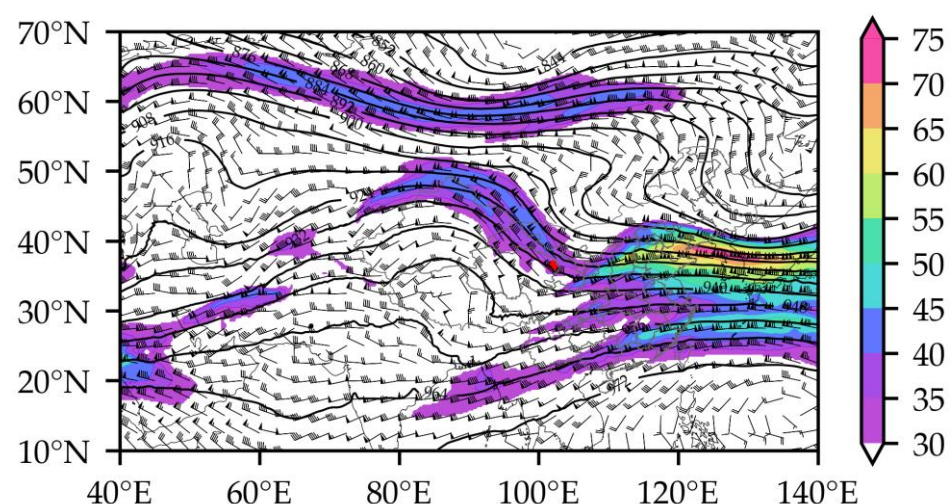


Figure 11. Geopotential height at 300 hPa (black contours, dagpm) and wind (wind barbs and shade, m s^{-1}) at 18:00 on 10 April 2019 (Red dot: Xining Airport).

5.4. Momentum Downward Transport Characteristics

To further investigate the momentum downward transport associated with the upper-level jet, the spatial configuration of vertical velocity and zonal wind along 103° E (east of Xining Airport) was analyzed (Figure 12). From Figure 12, a large westerly wind speed center was observed at 200 hPa, with the maximum exceeding 34 m s^{-1} . Combined with Figure 11, this area was the exit region of the subtropical jet, and Xining Airport lay on the southern side of this exit region. In the vertical velocity field, north of the jet (approximately $37\text{--}38^\circ \text{ N}$), a clear negative-velocity area corresponded to deep ascending motion; south of the jet (approximately $35\text{--}36^\circ \text{ N}$), a clear positive-velocity area corresponded to deep descending motion. Together, these formed a complete ageostrophic secondary circulation cell in the vertical. The vertical motion centers of this secondary circulation were both located at the 400–500 hPa level, and the maximum vertical velocity of the descending branch exceeded 1.2 Pa s^{-1} , indicating strong descending motion. This dynamic structure allowed the strong westerly momentum carried by the subtropical jet to be efficiently transported downward from the upper to the lower troposphere.

In summary, the upper-level jet stream significantly intensifies the deep vertical wind shear from the middle and upper troposphere to the near-surface layer. Based on jet streak dynamics, the pronounced ageostrophic secondary circulation in the jet exit region, along with its associated subsidence, triggers substantial downward momentum transfer. This dynamical process ultimately leads to a rapid enhancement of the post-frontal northwest winds at the surface [22,23], thereby intensifying the east wind backflow caused by cold air at the eastern end of the Qilian Mountains and ultimately leading to the formation of low-level wind shear at the airport. Therefore, this low-level wind shear at Xining Airport was the result of the combined effects of momentum downward transport induced by the secondary circulation in the jet-exit region and the dynamic forcing of the cold front.

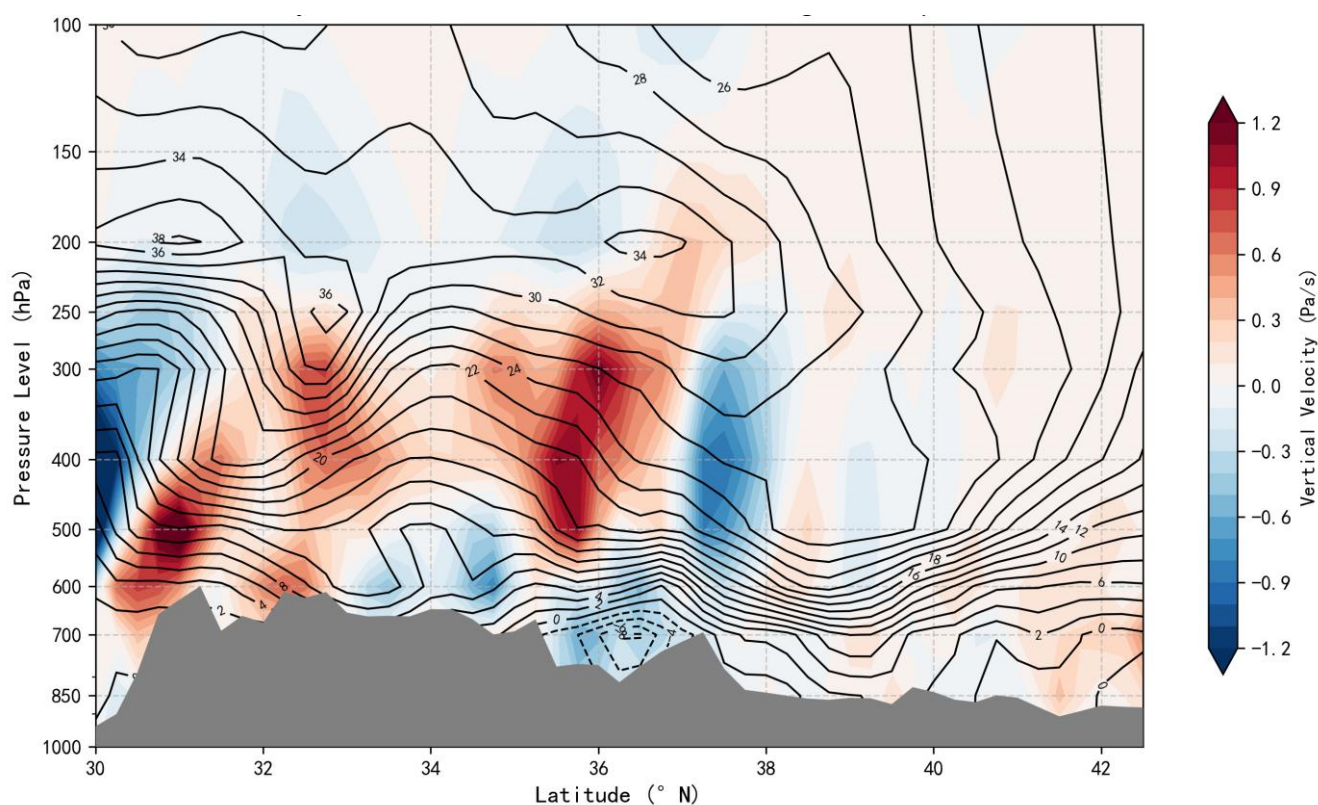


Figure 12. Vertical cross-section of vertical velocity (shaded, Pa s^{-1}) and zonal wind speed (contours, m s^{-1}) along 103°E at 18:00 on 10 April 2019.

5.5. Frontogenesis Function Characteristics

The distribution of the frontogenesis function indicated that at 14:00 on 10 April, the 500 hPa frontogenesis function over Xining Airport and its surroundings was weakly positive (Figure 13a), with no obvious frontogenesis. To the north of Xining, a strong frontogenesis zone existed, with its strongest center located north of 40°N and between $105\text{--}110^\circ \text{E}$, oriented northeast–southwest. A secondary strong center, similar in orientation to the Qilian Mountains, was oriented northwest–southeast. This frontogenesis zone corresponded to the eastward-moving cold front. At 16:00 (Figure 13b), the frontogenesis zone gradually moved southward, and the northwest–southeast frontogenesis center strengthened. Xining Airport was located on the southern edge of this zone, where frontogenesis began to intensify. By 18:00 (Figure 13c), accompanying the east wind backflow of part of the cold air, a strong frontogenesis center with intensity exceeding $4.5 \times 10^{-9} \text{ K m}^{-1} \text{ s}^{-1}$ quickly formed in the range $37\text{--}38^\circ \text{N}$, $102\text{--}104^\circ \text{E}$, signifying strong convergence of cold and warm air and the strengthening of horizontal temperature gradient and wind-field horizontal convergence, providing thermal and dynamic conditions for the outbreak of cold-frontal low-level wind shear. At this time, the low-level wind shear occurred at Xining Airport. By 20:00 (Figure 13d), as the main body of cold air further moved eastward and southward, the frontogenesis zone that had previously affected Xining Airport gradually weakened, the horizontal temperature gradient in the frontal zone decreased correspondingly, and the frontogenesis center northeast of the airport dropped below $2 \times 10^{-9} \text{ K m}^{-1} \text{ s}^{-1}$. Consequently, the turbulence in the mid-low level wind field tended to subside, and the low-level wind shear process ended completely.

In summary, the evolution of the 500 hPa frontogenesis function field clearly reflected the high synchronicity of this wind shear event with the dynamic forcing and life cycle of the front. The development and evolution of the strong frontogenesis center directly led to the outbreak and subsequent weakening of the low-level wind shear.

5.6. Temperature Advection Characteristics

At 14:00 on 10 April, the warm-advection center was located near the low-level 700 hPa west of Xining Airport (Figure 14a), with a central intensity exceeding $1.3 \times 10^{-4} \text{ K s}^{-1}$. At this time, the entire atmospheric column over the airport was almost controlled by weak warm advection, indicating that the station had not yet been affected by cold air and was in a relatively warm and dry air mass. At 16:00 (Figure 14b), due to afternoon surface heating, the warm advection west of the airport strengthened, with the center near 500 hPa. Simultaneously, as cold air poured back from east to west, the leading edge of cold advection began to affect Xining Airport, with its center located at around 500 hPa east of the airport. Cold and warm advection formed a clear confrontation, the isotherms became denser with time, baroclinicity over the airport increased, and the cold front gradually approached the airport. At 18:00, the layer below 500 hPa at Xining Airport was controlled by cold advection, and the cold-advection center had already moved west of the airport (Figure 14c). As discussed in Section 5.1, at this time the cold front arrived near the airport, forming a shear between easterly and westerly winds in the prefrontal zone. At 20:00, the area near the airport turned into a weak-advection zone, at which point the wind shear had completely ended (Figure 14d). The analysis of temperature-advection variation depicts a complete picture of this “east wind backflow” low-level wind shear process, from initial weak warm-advection control, through the cold–warm advection confrontation during the cold-front passage, to total cold-advection control, and finally to a weak-advection state.

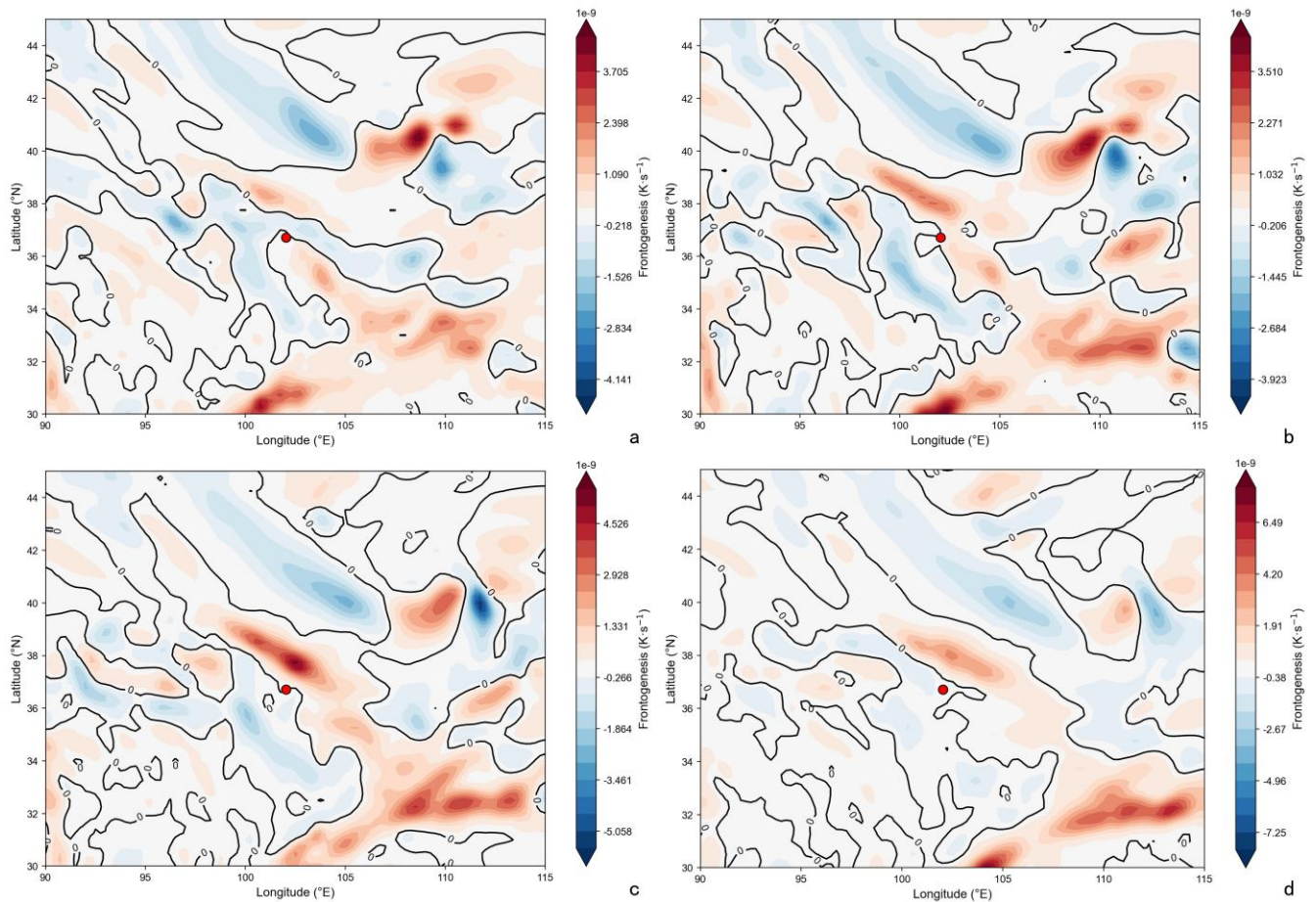


Figure 13. Horizontal distribution of 500 hPa frontogenesis function on 10 April 2019 (Red dot: Xining Airport) (a) 14:00 (b) 16:00 (c) 18:00 (d) 20:00.

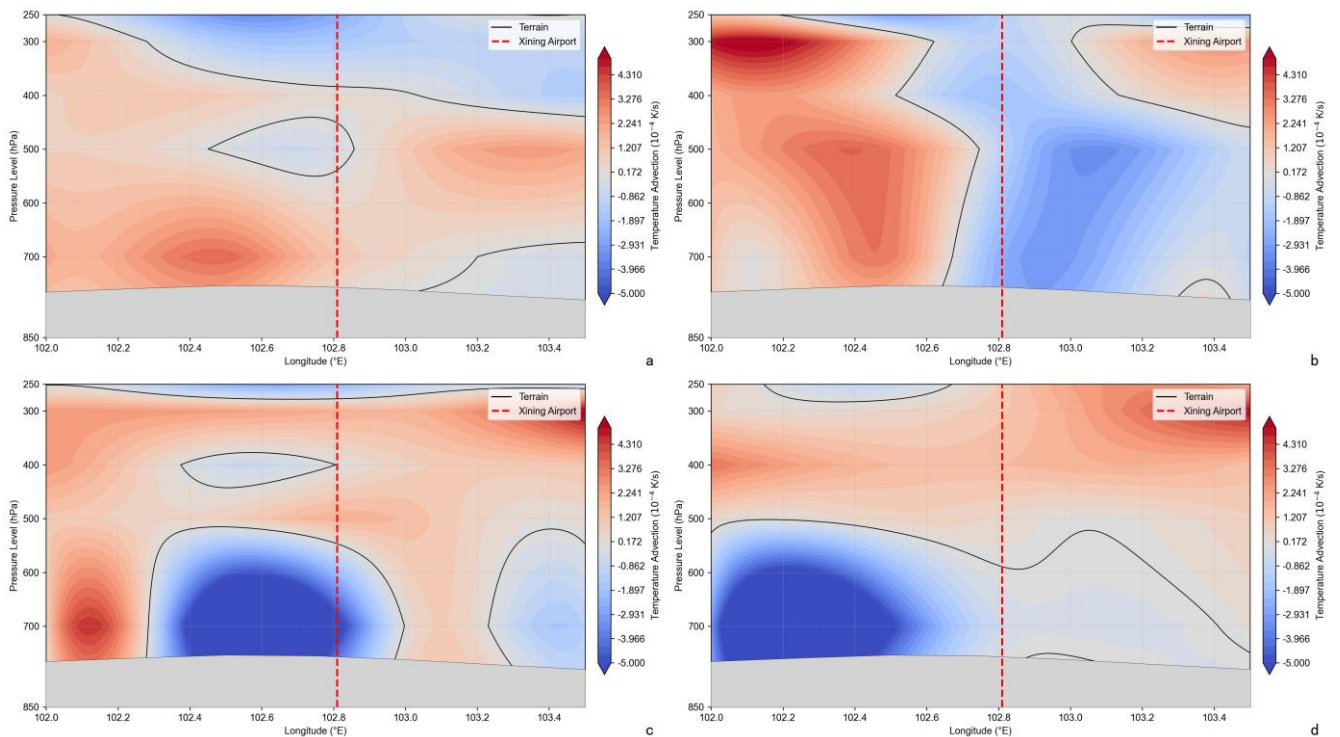


Figure 14. Zonal vertical cross-section of temperature advection across Xining Airport (102°02'35" E, 36°31'39" N) on 10 April 2019 (Red dashed line: longitude of Xining Airport) (a) 14:00 (b) 16:00 (c) 18:00 (d) 20:00.

6. Conclusions

Xining Caojiabu Airport is a typical plateau mountain airport, and its unique topographic conditions provide a favorable local environment for the occurrence of low-level wind shear. Cold air from the north is blocked by the Qilian Mountains and cannot easily move directly southward; it mainly moves eastward along the Hexi Corridor and then pours back at the eastern end of the Qilian Mountains. The easterly backflow converges with the westerly flow in the Huangshui Valley, forcing the front to move east–west along the valley, forming a narrower and stronger frontal zone, thereby triggering low-level wind shear. Ground AWOS data showed that the wind shear began to affect the airport at around 18:00, first impacting Runway 29 and then propagating from east to west along the runway to Runway 11. Accompanying the wind shear event, the runway area experienced a sudden temperature drop, a pressure rise, and a relative-humidity increase. Lidar PPI, RHI, and DBS observations further revealed that the wind shear appeared as wind-direction convergence between southeast and northwest winds, belonging to a meso- γ -scale system, with an impact on the airport that was “from east to west and from bottom to top.”

This low-level wind shear occurred under a favorable large-scale environmental background. At 500 hPa, Xining Airport was located in the influence area of the upper-level frontal zone at the base of the Mongolian transverse trough, with baroclinicity strengthening over time. At 300 hPa, the subtropical westerly jet provided an abundant momentum source, and an ageostrophic secondary circulation formed in the vertical, favoring momentum exchange between upper and lower layers and momentum downward transport. The evolution of the sea-level pressure field, pressure-change field, frontogenesis function, and temperature advection indicated that the occurrence of the wind shear was not the result of a single cold-front process but rather the product of the synergistic effects of multiple factors, including baroclinic development in the upper-level frontal zone, momentum downward transport from the upper-level jet, cold-frontal forcing, and topographic dynamic enhancement. The mechanism of cold front type wind shear belongs to the mixed influence of cold front system and terrain. Terrain always exists, and wind shear will occur only when a suitable weather system appears. This shows that the primary factor of cold front type wind shear is the cold front, followed by the influence of topography.

In this study, the monitoring characteristics and environmental field of the “easterly backflow” low-level wind shear at Xining Airport were analyzed, with a focus on the AWOS and lidar observations of the wind shear and the favorable large-scale environmental conditions. This has deepened the understanding of this type of low-level wind shear to some extent. However, owing to limitations in monitoring means and data, the meso- and micro-scale structure and causes of the low-level wind shear, as well as the amplifying effect of the valley topography, were less explored. In future work, new monitoring equipment such as wind-profiler radar and microwave radiometer will be combined to further reveal the meso- and micro-scale characteristics of wind shear and to advance in-depth investigations.

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