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Analysis of Near-Surface Atmospheric Turbulence and Its Intermittency in the Hinterland of the Gurbantunggut Desert in Winter

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Key Points

Strong stability shifted velocity spectra toward slower motions and suppressed high frequency vertical fluctuations

Turbulent bursts occupied little time but produced much stronger kinematic heat exchange than nonburst periods

Burst duration changed little with stability while its relative contribution to heat exchange increased

Abstract: Winter snow-covered deserts favor weak and intermittent near-surface turbulence because of high albedo, low temperatures, weak winds, smooth surfaces, and frequent stable stratification. This study examined turbulence structure, burst occurrence, and burst-related kinematic heat exchange at the KLML station in the Gurbantunggut Desert from 1 December 2023 to 29 February 2024 using gradient-tower and 10-m eddy-covariance observations. Among 3,944 valid half-hourly records, strongly stable conditions accounted for 46.3%, and stable conditions collectively accounted for 72.7%. Friction velocity generally decreased with increasing stability, whereas turbulent kinetic energy varied nonmonotonically and remained broadly distributed under strongly stable conditions. Normalized premultiplied spectra showed a shallow scale-transition depression and a frequency-dependent crossover, with higher low-frequency but lower principal-turbulent and high-frequency spectral levels under strong stability, especially for vertical velocity. Across 4,322 unique valid 30-min segments, the mean and median burst fractions were 5.15% and 5.12%, respectively. Across 4,307 segments with valid intensity ratios, the mean absolute kinematic heat-exchange intensity during bursts was 2.58 times that during non-burst periods. Stability had little systematic effect on burst time fraction but generally increased the burst contribution to absolute heat exchange and the burst-to-non-burst intensity ratio. Representative cases showed that threshold exceedances were embedded in continuous turbulence under weak stability but occurred in separated short intervals under strong stability. In one strongly stable event, enhanced turbulence coincided with stronger winds, increased 2–10 m vector shear, and pronounced heat-flux fluctuations while stable thermal stratification persisted, indicating a favorable dynamical background rather than a confirmed triggering mechanism.

Keywords: stable boundary layer; intermittent turbulence; turbulent bursts; turbulent heat exchange; snow-covered desert; gradient Richardson number

1 Introduction

The stable boundary layer (SBL) is one of the most complex and least ful

ly understood regimes of the atmospheric boundary layer. Unlike the daytime convective boundary layer, in which strong mixing is mainly driven by buoyancy, the SBL usually forms under nocturnal surface radiative cooling, cold underlying surfaces, or persistent surface cooling. It is characterized by an increase in potential temperature with height, suppressed vertical mixing, weak turbulence intensity, and pronounced nonstationarity and intermittency (Stull, 1988; Mahrt, 1999, 2014). The SBL controls the exchange of momentum, heat, water vapor, and trace substances between the land surface and the atmosphere, and is closely related to near-surface pollutant dispersion, low-visibility weather, wind-energy development, aviation safety, and boundary-layer parameterization in numerical models (Mahrt, 2014; Ren et al., 2025). However, under stable stratification, turbulence signals are often weak, scale separation is unclear, and turbulence is strongly affected by non-turbulent motions, which makes its observation, identification, and parameterization difficult. In recent years, increasing attention has been paid to weak turbulence, turbulence intermittency, and the role of submesoscale motions in stable-boundary-layer transport, indicating that the SBL remains an important frontier in international boundary-layer meteorology and land-atmosphere interaction research (Mahrt & Acevedo, 2023; Mahrt, 2024; Boyko & Vercauteren, 2024; Ren et al., 2025; Xu et al., 2026).

Within the classical framework of Monin–Obukhov similarity theory, turbulent fluxes in the surface layer are generally assumed to be related to local mean gradients and time-averaged turbulence statistics (Monin & Obukhov, 1954; Foken, 2006). This theory performs well under stationary, horizontally homogeneous, and fully developed turbulent conditions, but it is often challenged under strongly stable stratification. In strongly stable boundary layers, turbulence is frequently spatially heterogeneous, temporally intermittent, and locally enhanced in short bursts, so conventional 30-min mean fluxes may mask the actual instantaneous exchange processes. Here, a turbulent burst (hereafter, burst) refers to a short-lived interval during which turbulence intensity increases distinctly above the local background level and may be accompanied by

enhanced instantaneous momentum or heat exchange (Mahrt, 1999; Vickers & Mahrt, 2003; Sun et al., 2004; Mortarini et al., 2018). In addition, turbulence under strong stability may become decoupled from surface fluxes, and near-surface transport is no longer controlled only by local surface gradients, but can also be modulated by low-level jets, gravity waves, density currents, drainage flows, and other submesoscale motions (Banta et al., 2006, 2007; Sun et al., 2012; Vercauteren & Klein, 2015; Ding et al., 2025). Therefore, a key issue in SBL research is not only to determine whether turbulence is weak or strong, but also to identify its intermittent temporal organization and to quantify the actual contribution of short-lived enhanced turbulent motions to heat exchange.

Intermittent turbulence is one of the most representative dynamical phenomena in stable boundary layers. Previous studies have shown that even when background turbulence is weak, short periods of enhanced turbulence can occur abruptly and contribute substantially to local mixing and turbulent transport (van de Wiel et al., 2002; Sun et al., 2012). These events are commonly associated with enhanced local wind shear, downward influence of low-level jets, gravity-wave breaking, density-current intrusion, or submesoscale wind disturbances (Ohya et al., 2008; Vercauteren & Klein, 2015; Cava et al., 2019; Ding et al., 2025; Mahrt, 2024). Recent studies also suggest that turbulence intermittency can exhibit scale-dependent characteristics and that nonstationary turbulence under submesoscale disturbances may not be adequately captured by conventional stationarity diagnostics (Gencarelli et al., 2026; Xu et al., 2026). From the perspective of the turbulent kinetic energy budget, buoyancy suppresses vertical motions under stable stratification, while mechanical shear can still convert mean kinetic energy into turbulent kinetic energy. When local wind shear becomes sufficiently strong, turbulence suppressed by stable stratification may re-intensify during short-lived turbulent episodes (Stull, 1988; Banta et al., 2007). Although burst events usually last for only a short time, their instantaneous turbulence intensity and unit-time exchange intensity can be substantially greater than those during non-burst periods, making them potentially important contributors to nonstationary heat

exchange in strongly stable boundary layers.

Snow-covered desert surfaces provide a unique environment for studying stable-boundary-layer turbulence and burst events. On the one hand, snow cover substantially increases surface albedo, reduces daytime absorption of incoming shortwave radiation, and promotes near-surface cooling and temperature-inversion development under nocturnal radiative cooling (Armstrong & Brun, 2008; Anderson & Neff, 2008). On the other hand, desert surfaces generally have low aerodynamic roughness, and snow cover can further smooth the surface, thereby weakening the generation of mechanically produced turbulence near the ground (Stull, 1988; Mamtimin et al., 2020). Recent studies over polar snow surfaces, patchy snow in mountain terrain, and snow-covered complex terrain have also shown that snow processes can significantly modify the surface energy balance, stable stratification, near-surface coupling state, and turbulent exchange structure (Adler et al., 2023; Haugeneder et al., 2024; Hong & Jiang, 2024; Engbers et al., 2025). Compared with polar snow surfaces, mountain snow, grasslands, croplands, urban surfaces, the Tibetan Plateau, and bare deserts, snow-covered deserts combine high albedo, strong radiative cooling, weak winds, low roughness, and persistent stable stratification, representing a land-surface type with distinct coupled snow–desert characteristics. Under such conditions, continuous turbulence is likely to be suppressed, whereas short-lived burst events may make a more pronounced relative contribution within weak background turbulence.

The Gurbantunggut Desert, located in the arid region of northwestern China, is a typical temperate desert and one of the desert regions in China with relatively persistent winter snow cover. Previous studies have shown that winter snow cover in this region can significantly affect the surface radiation budget, near-surface thermal structure, and boundary-layer height (Mamtimin et al., 2020; Zhang et al., 2022; Wang et al., 2023). Meanwhile, the surface heat source and land–atmosphere interaction in the Gurbantunggut Desert exhibit marked seasonal and spatial variations, which are important for understanding desert boundary-layer structure and turbulent exchange processes (Aihaiti et al., 2023; Li et al., 2023). Comparative studies over the Tibetan

Plateau, urban areas, and semi-arid or desert ecosystems further show that boundary-layer turbulence varies strongly with surface forcing, thermal conditions, and aerodynamic roughness (Wang et al., 2015; Liu et al., 2017; Che & Zhao, 2021; Pan et al., 2022). Compared with strongly thermally forced deserts such as the Taklimakan Desert, the winter boundary layer over the snow-covered Gurbantunggut Desert is more likely to be jointly controlled by stable stratification and weak mechanical turbulence production. Recent studies over the Taklimakan Desert have shown that turbulence intermittency and submesoscale motions can substantially affect flux estimation, similarity relationships, and land–atmosphere exchange under desert conditions (Wei et al., 2019; Zhang et al., 2024; Kang et al., 2026). However, observational studies on the occurrence characteristics of burst events and their contribution to heat exchange in the near-surface layer over winter snow-covered deserts remain limited.

Based on these considerations, this study uses gradient tower observations and 10-m eddy-covariance observations collected at KLML Station in the Gurbantunggut Desert from 1 December 2023 to 29 February 2024. The gradient tower data are used to characterize the winter near-surface meteorological background, radiation conditions, and stability structure. The 10-m eddy-covariance data include both EddyPro-derived 30-min turbulence statistics and the original 20-Hz high-frequency wind–temperature time series, which are used to analyze overall turbulence characteristics, wind-component spectral structures, and burst-event identification. This study focuses on three questions: (1) What are the basic stability conditions, turbulence statistics, and spectral characteristics of the near-surface layer over a winter snow-covered desert? (2) What fraction of each 30-min period is occupied by burst events, and how much do these events contribute to absolute heat exchange? (3) How do burst duration, heat-exchange contribution, and the burst-to-non-burst exchange intensity ratio vary with stability, and can low-level wind enhancement and near-surface vertical wind shear provide a favorable dynamical background for burst occurrence? By addressing these questions, this study aims to improve understanding of nonstationary turbulent heat exchange in the stable boundary layer over snow-covered deserts and to provide

observational evidence for winter land–atmosphere interaction and stable-boundary-layer parameterization in arid regions.

2 Site, Data, and Methods

2.1 Site Description

The study site is located in the Gurbantunggut Desert, Xinjiang, northwestern China, which is a typical temperate desert surface. In contrast to bare desert surfaces during the warm season, the study period was in winter, when the surface was frequently covered by snow. This produced a coupled snow-desert surface with both high snow albedo and low desert aerodynamic roughness. Snow cover reduces the absorption of incoming shortwave radiation during the day, while radiative cooling, low temperatures, and weak winds at night favor near-surface cooling and the maintenance of stable stratification. Meanwhile, the low roughness of the desert surface, further smoothed by snow cover, limits the generation of mechanically produced turbulence near the ground. Therefore, the winter surface layer at the site is characterized by the combined effects of thermal stabilization and dynamically weak turbulence production. These conditions provide a suitable environment for examining weak background turbulence, strong stable stratification, and intermittent turbulent bursts over a snow-covered desert surface.

The observation period extended from 1 December 2023 to 29 February 2024. During this period, the study area was generally characterized by high surface albedo, low air temperature, weak wind, and persistent stable stratification. These conditions make the site suitable for investigating winter near-surface turbulence structure and

intermittent turbulent exchange over a snow-covered desert.

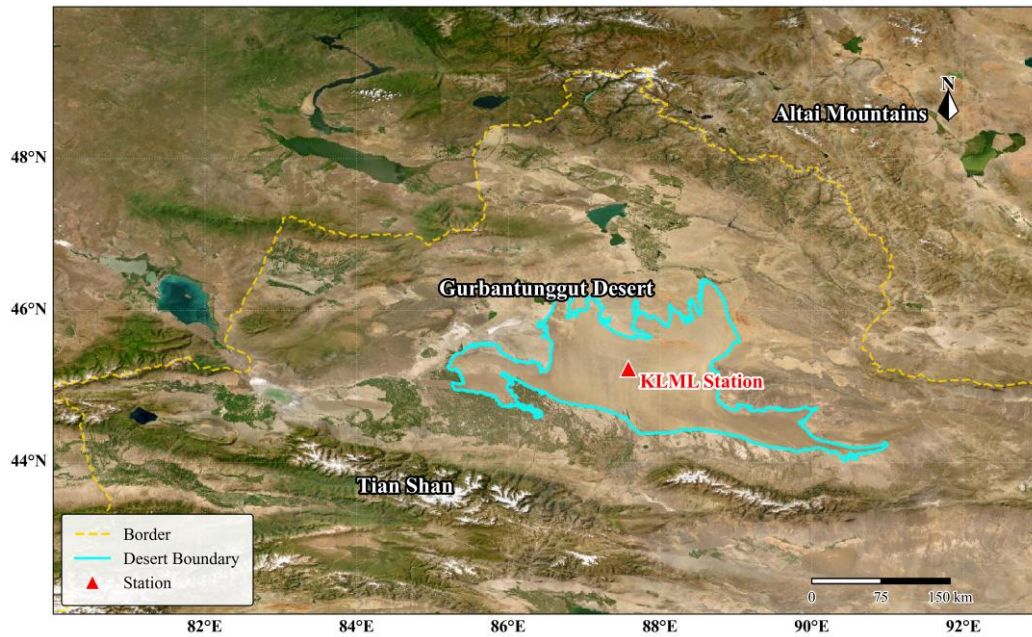


Figure 1 Map of the study area

2.2 Observations and Data

The site-based observations used in this study were collected at the Kelameili Land–Atmosphere Interaction Observation Station (KLML Station; 45°14' N, 87°35' E; 531 m above sea level), which was established in 2012 by the Institute of Desert Meteorology, China Meteorological Administration. The station is located in the hinterland of the Gurbantunggut Desert, where the surrounding terrain is flat and open and the surface is frequently covered by snow during winter. The study period extended from 1 December 2023 to 29 February 2024. The site-based datasets mainly consisted of routine meteorological and radiation observations from a gradient-tower system and turbulence observations from a 10-m eddy-covariance system.

The 32-m meteorological gradient tower was located on the northwestern side of the observation field. East–west-oriented horizontal booms were installed at 0.5, 1, 2, 4, 10, 20, and 32 m above ground level. Cup anemometers (Model 010C, Met One Instruments, USA), wind-direction sensors (Model 020C, Met One Instruments, USA), and temperature–relative humidity probes (Model HMP45C, Vaisala, Finland) were installed at these levels to measure wind speed, wind direction, air temperature, and

relative humidity. An atmospheric pressure sensor (Model PTB220, Vaisala, Finland) was installed at 1 m, and an ultrasonic snow-depth sensor (Model SR50A-L, Campbell Scientific, USA) was installed at 2 m. The gradient-tower measurements were sampled at 1 Hz using a CR1000 data logger (Campbell Scientific, USA), which generated 10-s, 1-min, 30-min, and 1-h data products. The 30-min data were primarily used in this study.

The radiation observation system was located to the south of the gradient tower. A four-component net radiometer (Model NR01, Hukseflux, the Netherlands) was mounted approximately 1.5 m above the ground to measure incoming and reflected shortwave radiation and downward and upward longwave radiation, from which net radiation was calculated. The radiation measurements were sampled at 1 Hz using a CR3000 data logger (Campbell Scientific, USA), with 10-s, 1-min, 30-min, and 1-h products generated. The 30-min radiation data were used in the analysis. Surface albedo was calculated as the ratio of reflected shortwave radiation to incoming shortwave radiation. To avoid unrealistic albedo values during nighttime and very-low-radiation conditions, only periods with incoming shortwave radiation greater than 100 W m^{-2} were retained, and at least eight valid half-hourly samples were required for the calculation of daily albedo.

The 10-m eddy-covariance system was mounted at the outer end of a horizontal boom on the gradient tower and consisted of a three-dimensional sonic anemometer (WindMaster Pro, Gill Instruments, UK) and an open-path infrared gas analyzer (LI-7500A, LI-COR Biosciences, USA). The sonic anemometer measured the three wind components and sonic temperature, whereas the open-path infrared gas analyzer measured high-frequency fluctuations in CO_2 and H_2O densities. Signals from the system were synchronously recorded at 20 Hz using a CR3000 data logger (Campbell Scientific, USA), corresponding to a sampling interval of 0.05 s. Each complete 30-min period nominally contained approximately 36,000 high-frequency samples. The 30-min turbulence statistics and wind-component spectral data used in this study were processed using EddyPro, whereas the original 20-Hz wind and sonic-temperature time

series were used for subsequent turbulent-burst identification. Detailed processing procedures are described in Section 2.3.

All site-based data-acquisition systems were equipped with GPS time-synchronization modules and were automatically synchronized at 00:00 local time each day. The original observations were recorded in local Urumqi time (UTC+6), which is 2 h behind Beijing Standard Time. To ensure temporal consistency among the different datasets, all observation times were converted to and analyzed in Beijing Standard Time (UTC+8).

ERA5 reanalysis data were used to characterize the winter-mean regional circulation and boundary-layer background. The variables included 850-hPa geopotential height and horizontal winds, 10-m horizontal winds, and planetary boundary-layer height.

2.3 Data Preprocessing and Burst Detection

2.3.1 Eddy-Covariance Data Processing and Turbulence Variables

The 30-min eddy-covariance statistics used in this study were obtained directly from EddyPro processing. The raw high-frequency data were processed in EddyPro with standard procedures, including coordinate rotation, detrending, frequency-response correction, and quality control. The EddyPro outputs include momentum flux, sensible heat flux, latent heat flux, friction velocity, turbulence kinetic energy, and related stability parameters. After the EddyPro processing, missing values and invalid records were further removed before the data were used to examine the overall turbulence characteristics under different stability regimes.

To identify intermittent turbulent bursts, the original 20-Hz wind-temperature data from the same 10-m eddy-covariance system were further analyzed. The sampling interval of the 20-Hz data was 0.05 s, and each 30-min segment contained approximately 36,000 samples. The raw TOB3 files were converted to TOA5 text files using LoggerNet, with each TOA5 file corresponding to one 30-min segment. For each

segment, the time stamp, three-dimensional wind components, and sonic temperature were extracted. Missing values and physically unrealistic outliers were removed, and a moving-window despiking procedure was applied to reduce the influence of abnormal spikes on subsequent statistics.

The three-dimensional wind components were then rotated using a double-rotation method so that the mean lateral and vertical wind components were approximately zero within each 30-min segment. The 30-min mean values were treated as the background state, and turbulent fluctuations were calculated as

$$u'(t) = U_x(t) - \overline{U_x}$$

$$v'(t) = U_y(t) - \overline{U_y}$$

$$w'(t) = U_z(t) - \overline{U_z}$$

$$T'(t) = T_s(t) - \overline{T_s}$$

where (U_x) , (U_y) , and (U_z) are the three wind components after rotation, (T_s) is sonic temperature, and the overbar denotes the 30-min mean. The instantaneous turbulence kinetic energy was then calculated as

$$e(t) = \frac{u'^2(t) + v'^2(t) + w'^2(t)}{2}$$

The instantaneous kinematic heat-flux term was calculated as

$$w'T'(t) = w'(t)T'(t)$$

Here, $(e(t))$ was used to describe high-frequency variations in turbulence intensity, while $(w'T'(t))$ was used to compare heat-exchange characteristics between burst and non-burst periods. Because these variables were calculated point by point from the original 20-Hz data, their native temporal resolution was 0.05 s.

2.3.2 Burst Detection and Heat-Exchange Metrics

Because instantaneous turbulent kinetic energy may be affected by small-scale fluctuations and instrumental noise, a 5-s moving window was applied to $e(t)$ to obtain a smoothed turbulent kinetic energy series, denoted as $TKE_{\text{smooth}}(t)$. For each 30-min segment, the mean and standard deviation of $TKE_{\text{smooth}}(t)$ were denoted as μ and σ , respectively. Periods satisfying

$$TKE_{\text{smooth}}(t) > \mu + 2\sigma$$

were identified as burst periods. Threshold-based and event-detection methods have been widely used to identify intermittent turbulence and burst-like turbulent motions in stable boundary layers (Nappo, 1991; Mahrt, 1999; Sun et al., 2004; Vercauteren & Klein, 2015). In this study, the 2σ threshold was used as an empirical criterion to reduce the influence of background random fluctuations while retaining sufficient burst samples for stability-dependent statistics. Sensitivity tests using $\mu + 1\sigma$ and $\mu + 3\sigma$ thresholds changed the absolute values of burst-related statistics but did not alter the main stability-dependent patterns.

Based on this criterion, each 30-min segment was divided into burst and non-burst periods. The burst time fraction was defined as

$$B_f = \frac{N_{\text{burst}}}{N_{\text{all}}} \times 100\%$$

where (N_{burst}) is the number of burst samples and (N_{all}) is the total number of samples in the 30-min segment. This metric represents the relative duration of burst periods within each segment.

To quantify the contribution of burst events to turbulent heat exchange, the absolute value of the instantaneous kinematic heat-flux term was used to avoid cancellation between positive and negative fluctuations. The burst contribution to absolute heat exchange was defined as

$$C_{\text{abs}} = \frac{\sum_{\text{burst}} |w'T'|}{\sum_{\text{all}} |w'T'|} \times 100\%$$

This metric represents the fraction of total absolute heat exchange contributed by burst periods. To compare the exchange efficiency between burst and non-burst periods, the burst-to-non-burst absolute heat-exchange intensity ratio was defined as

$$R_{\text{abs}} = \frac{\overline{|w'T'|}_{\text{burst}}}{\overline{|w'T'|}_{\text{non - burst}}}$$

When ($R_{\text{abs}} > 1$), the unit-time exchange intensity during burst periods is greater than that during non-burst periods. It should be noted that burst detection was based on the smoothed turbulence kinetic energy series, whereas the heat-exchange statistics were calculated from the original high-frequency, double-rotated turbulence signals.

2.4 Stability Metric and Statistical Analysis

2.4.1 Gradient Richardson Number and Stability Classification

To independently characterize near-surface atmospheric stability, a finite-difference estimate of the gradient Richardson number, Ri_g , was calculated from the 2- and 10-m gradient-tower observations:

$$Ri_g = \frac{\frac{g}{\bar{\theta}_v} \frac{\theta_{v,10} - \theta_{v,2}}{\Delta z}}{\left(\frac{u_{10} - u_2}{\Delta z}\right)^2 + \left(\frac{v_{10} - v_2}{\Delta z}\right)^2}$$

where g is the gravitational acceleration, $\bar{\theta}_v$ is the layer-mean virtual potential temperature between 2 and 10 m, $\theta_{v,10} - \theta_{v,2}$ is the virtual potential-temperature difference between the two levels, u and v are the two orthogonal horizontal wind components, and $\Delta z = 8\text{m}$ is the vertical separation. Virtual potential temperature was derived from air temperature, vapor pressure, and atmospheric pressure at each level, whereas the horizontal wind components were calculated from the observed wind speed and direction. To avoid unrealistically large Ri_g values under near-zero shear, periods with a vector wind shear smaller than 0.005s^{-1} were excluded from the subsequent

stability-stratified analysis.

Unlike flux-based stability parameters, Ri_g was derived entirely from independent gradient observations and did not directly include eddy-covariance quantities such as friction velocity or sensible heat flux. This approach reduces the possibility of artificial mathematical coupling between the stability parameter and the turbulence statistics, making Ri_g suitable for examining burst activity and associated heat exchange under different background stability regimes.

Following classical stability theory and previous observational studies, the samples were divided into four stability regimes: ($Ri_g < 0$), ($0 \leq Ri_g < 0.1$), ($0.1 \leq Ri_g < 0.25$), and ($Ri_g \geq 0.25$). The ($Ri_g < 0$) regime represents unstable stratification, in which buoyancy promotes turbulence. The ($Ri_g > 0$) regimes represent stable stratification. Based on the Miles-Howard stability criterion, a critical Richardson number of approximately 0.25 is commonly regarded as the upper limit for shear instability in stratified flows (Miles, 1961; Howard, 1961; Stull, 1988). Therefore, ($Ri_g \geq 0.25$) was defined as the strongly stable regime, in which turbulence is strongly suppressed by buoyancy.

In practice, the transition in turbulence characteristics does not occur abruptly at ($Ri_g = 0.25$), but usually involves a transition zone (Mahrt, 1999). The range ($0 \leq Ri_g < 0.1$) was treated as a weakly stable regime, where mechanical shear can still maintain relatively continuous background turbulence. The range ($0.1 \leq Ri_g < 0.25$) was treated as a transitionally stable regime, where continuous turbulence is increasingly suppressed and intermittent turbulent motions become more evident (Sun et al., 2012). This classification allows the response of burst occurrence and heat-exchange contribution to be examined along a stability sequence from unstable to strongly stable conditions.

2. 4. 2 Matching Burst Statistics With Stability Conditions

After the burst statistics were obtained for each 30-min segment, they were matched with the corresponding (Ri_g) values by time. This procedure produced a joint

dataset containing burst time fraction, burst contribution to absolute heat exchange, burst-to-non-burst exchange intensity ratio, and stability parameters for each valid 30-min segment.

The analysis proceeded in three steps. First, the seasonal distribution of burst time fraction was examined to characterize the overall occurrence of intermittent turbulent bursts. Second, the burst contribution to absolute heat exchange and the burst-to-non-burst exchange intensity ratio were calculated to quantify the heat-exchange effect of burst periods. Third, the above burst statistics were compared among the four (Ri_g)-based stability regimes to assess the modulation of burst characteristics by stability.

To further illustrate the temporal structure of burst events under different stability regimes, representative 30-min cases were selected from the (Ri_g) groups. For each stability group, the case with (R_{abs}) closest to the group median was selected as the representative case. This selection strategy avoids using only extreme events to represent each stability regime and provides a more typical view of intermittent turbulence under different stability backgrounds.

3 Results

3.1 General Characteristics of Near-Surface Turbulence Under Winter Snow Cover

3.1.1 Winter Circulation Background and Local Micrometeorological Conditions

The winter near-surface environment at the study site was characterized by the combined effects of weak dynamic forcing and strong thermal stabilization. The ERA5 reanalysis fields show that both the 850-hPa wind and the near-surface 10-m wind over the basin interior, where the KLML station is located, were generally weak during winter (Figures 2a and 2b). The winter mean planetary boundary-layer height was also relatively low, indicating limited mechanical turbulence production in the lower atmosphere. These large-scale and regional conditions provided a weak-wind background for the development of a stable surface layer.

The local micrometeorological observations further confirm the cold and weak-wind conditions during the observation period (Figures 2c and 2d). The mean 2-m air temperature was approximately -15.8°C , with a minimum of about -33°C , and the mean 10-m wind speed was only about $0.72\text{ m}\cdot\text{s}^{-1}$. To characterize the radiative properties of the winter snow-covered surface, daily albedo was calculated only when the downward shortwave radiation exceeded 100 W m^{-2} , thereby avoiding undefined or unrealistic values during nighttime and very low-radiation periods. The daily albedo was then estimated as the ratio of accumulated outgoing to incoming shortwave radiation, and days with fewer than eight valid half-hourly samples were excluded. The results show that the effective daily mean albedo increased and remained near 0.71 during the persistent snow-cover period. The high-albedo snow surface reduced daytime absorption of solar radiation, while nocturnal radiative cooling under weak-wind and low-temperature conditions favored near-surface cooling and the maintenance of stable stratification. The mean nighttime net radiation loss was approximately 22 W m^{-2} .

Overall, the combination of weak background winds and strong snow-surface radiative cooling favored the development of a cold and stable near-surface layer. Such conditions suppressed continuous mechanically generated turbulence, but they also made the surface layer sensitive to changes in vertical wind shear. When wind speed increases occur above the near-surface layer, the resulting enhancement of vertical wind-speed differences may provide a favorable dynamic background for short-lived turbulent bursts. Therefore, the winter snow-covered desert surface represents a suitable environment for examining weak background turbulence, stable stratification, and intermittent turbulent heat exchange.

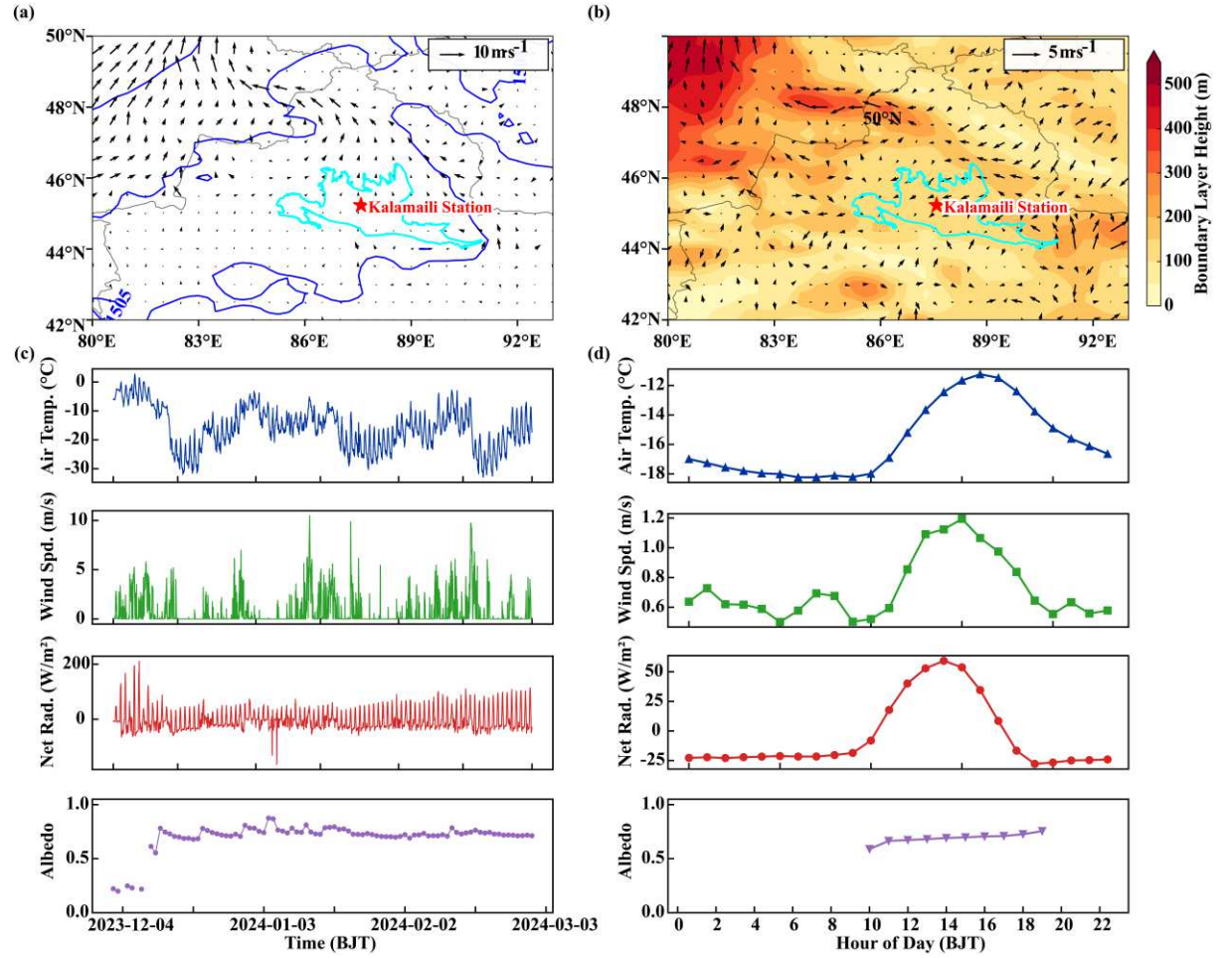


Figure 2 Winter synoptic circulation background and local micrometeorological features in the Gurbantunggut Desert hinterland (a) 850-hPa mean geopotential height and wind fields; (b) 10-m wind field and boundary layer height distribution; (c) winter time series of near-surface meteorological variables at KLML Station; (d) diurnal variations of major meteorological elements at KLML Station. The green line and red star represent the desert boundary and KLML Station, respectively.

3.1.2 Near-Surface Turbulence Statistics Under Different Stability Regimes

Figure 3 presents the diurnal variations in friction velocity (u_*), turbulent kinetic energy (TKE), and sensible heat flux (H), together with their statistical distributions under different stability regimes during winter. As shown in Figure 3a, the hourly sample sizes were generally between approximately 150 and 175, indicating a relatively even temporal distribution of the observations. Both u_* and TKE remained relatively low, with substantial overlap among the hourly boxplots, suggesting comparatively weak diurnal variability. Friction velocity was relatively high from daytime to early afternoon and decreased during the evening, whereas TKE tended to be higher during the early morning and morning and weakened toward the afternoon and evening. In

contrast, H exhibited a much clearer diurnal cycle. Its median remained close to zero or slightly negative at night, increased markedly after 12:00 BJT, and reached relatively high values around 14:00 BJT. The broader boxes and whiskers during the afternoon indicate both enhanced sensible heat exchange and greater variability. The peak periods of u_* , TKE, and H did not coincide completely, suggesting that the evolution of near-surface turbulence was not controlled solely by surface thermal forcing but was also influenced by dynamical processes.

Among the 3944 common valid records used in Figure 3b, strongly stable conditions accounted for the largest proportion, 46.3% ($n = 1828$), while stable conditions collectively represented approximately 72.7% of the observations. The median u_* decreased progressively from 0.1304 m s^{-1} under unstable conditions to 0.1188, 0.1097, and 0.1049 m s^{-1} with increasing stability. The strongly stable median was approximately 19.6% lower than the unstable value, indicating that stable stratification generally suppressed near-surface momentum exchange. In contrast, TKE did not decrease monotonically with increasing stability. The median values for the four regimes were 0.2044, 0.1869, 0.2129, and $0.1958 \text{ m}^2 \text{ s}^{-2}$, respectively. Moreover, the upper quartile under strongly stable conditions reached $0.4167 \text{ m}^2 \text{ s}^{-2}$, exceeding those of the other regimes. This indicates that although the typical turbulence intensity remained relatively weak, energetic turbulent events still occurred under strongly stable conditions.

Sensible heat flux showed the clearest response to atmospheric stability. Under unstable conditions, the median H was 8.53 W m^{-2} , with an interquartile range of $0.89\text{--}23.20 \text{ W m}^{-2}$, indicating predominantly positive sensible heat transport. The medians decreased to -0.55 and -0.79 W m^{-2} in the two intermediate stable regimes, demonstrating a marked suppression of the typical heat exchange. Under strongly stable conditions, the median H was 1.96 W m^{-2} , whereas the mean reached 18.58 W m^{-2} , with an interquartile range of $-2.52\text{--}14.38 \text{ W m}^{-2}$. The large difference between the mean and median indicates a strongly right-skewed distribution in which a limited number of intense positive heat-flux events elevated the mean. Overall, increasing

stability reduced the typical momentum and heat exchange, whereas the broad TKE and H distributions under strongly stable conditions indicate that relatively energetic turbulence and heat-transfer events could still occur intermittently within an otherwise weak turbulent background.

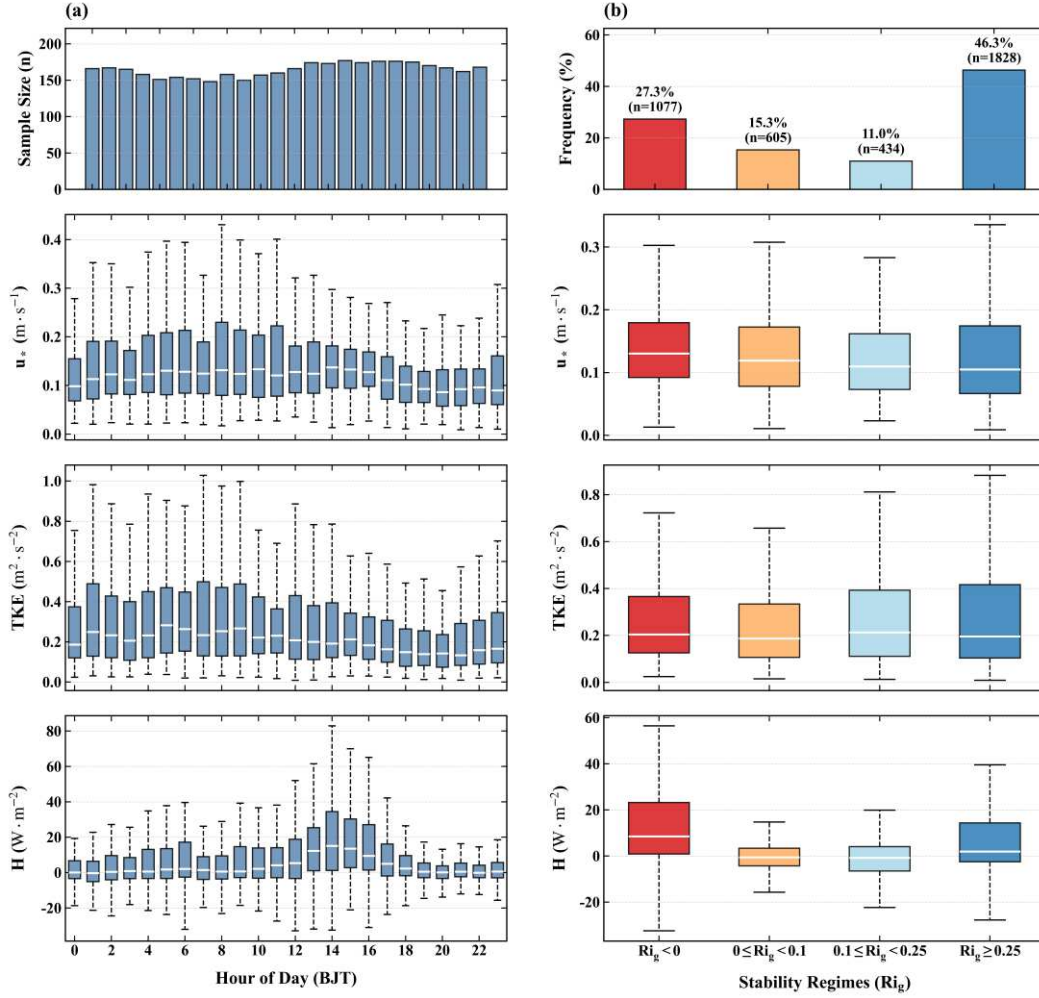


Figure 3. Diurnal variations in key near-surface turbulence variables and their statistical characteristics under different stability regimes during winter. (a) Hourly sample sizes and boxplot distributions of friction velocity (u_*), turbulent kinetic energy (TKE), and sensible heat flux (H); (b) sample frequencies and statistical distributions of u_* , TKE, and H under different stability regimes. A total of 3944 common valid half-hourly records were included. Boxes denote the 25th–75th percentiles, white lines indicate medians, and whiskers represent non-outlying values within 1.5 times the interquartile range.

3.1.3 Spectral Characteristics and Similarity Under Different Stability Regimes

Figure 4 presents the normalized premultiplied power spectra of the longitudinal

(u), lateral (v), and vertical (w) velocity components under different stability regimes. All three components exhibit a shallow spectral depression between the low-frequency range and the principal turbulent spectral range, suggesting a transition between relatively slow submesoscale or nonstationary motions and higher-frequency local turbulence. Because this depression is relatively weak and the spectra were averaged and smoothed within each stability class, it is interpreted here as a scale-transition feature rather than definitive evidence of a well-defined spectral gap. The spectra also show a pronounced frequency-dependent ordering among the stability regimes. The $Ri_g \geq 0.25$ group generally occupies the upper part of the spectra at low frequencies but shifts toward the lowest spectral levels within the principal turbulent and high-frequency ranges. This crossover indicates that, with increasing stability, slow low-frequency motions make a larger relative contribution to the normalized spectral structure, whereas high-frequency local turbulent fluctuations are suppressed. Previous observations have associated enhanced low-frequency horizontal velocity spectra with quasi-horizontal submesoscale motions, including wind meandering and other nonstationary disturbances, while decreasing high-frequency spectral densities under strong stability have been related to weakening of the local turbulent energy cascade. For the u and v components, this behavior is expressed mainly as an elevated strongly stable spectrum at low frequencies, with comparatively modest differences at intermediate and high frequencies. The separation is clearer for w , for which the strongly stable group remains lowest around the principal spectral maximum and throughout the high-frequency range, indicating a stronger suppression of vertical velocity fluctuations. Overall, increasing stability does not weaken all scales of motion uniformly; instead, it modifies the relative spectral distribution by increasing the prominence of low-frequency nonstationary motions while reducing high-frequency local turbulence and vertical motions. Because the spectra are normalized, this result should be interpreted as a redistribution of relative spectral weight across scales rather than as evidence that the absolute low-frequency turbulent energy increases under strongly stable conditions.

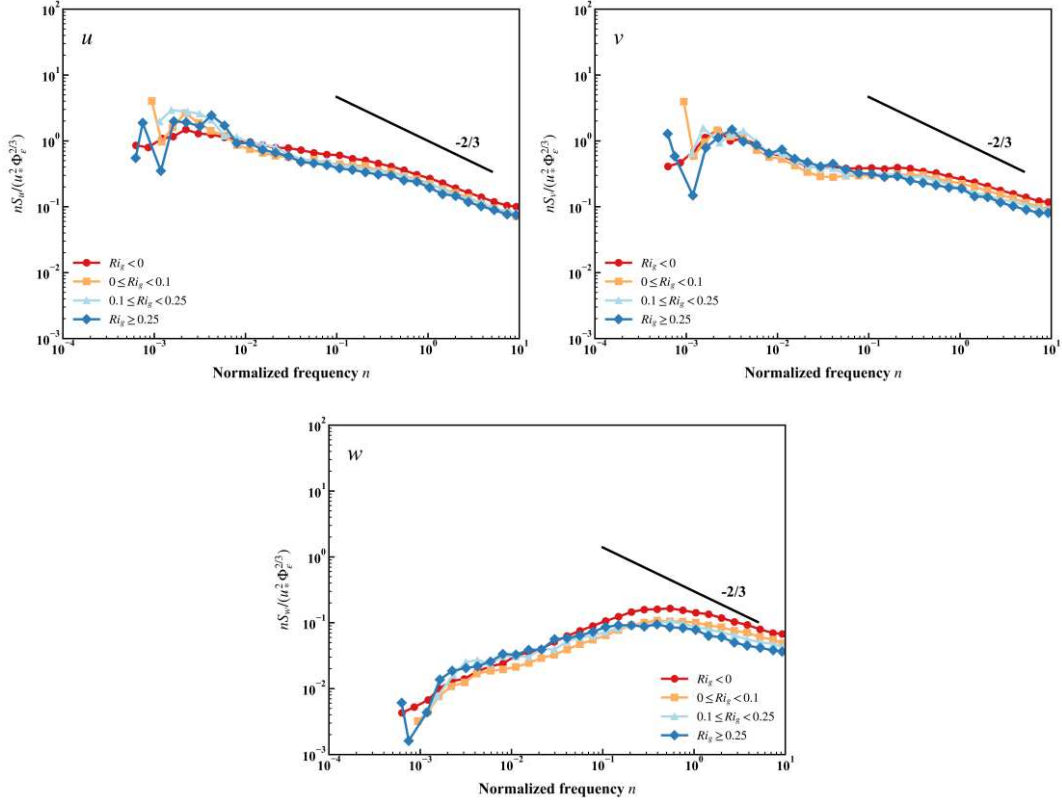


Figure 4. Normalized premultiplied power spectra of the U, V, and W wind-speed components under different stability regimes.

3. 2 Characteristics of Intermittent Turbulence and Its Heat-Exchange Effects

3. 2. 1 Seasonal Statistics of Burst Occurrence

A total of 4,322 valid 30-min segments derived from the 20-Hz wind-temperature observations were successfully matched with the corresponding stability records during 1 December 2023–29 February 2024. The seasonal time series shows that the burst time fraction remained generally low throughout the observation period (Figure5a). Most 30-min segments had burst fractions between approximately 3% and 7%, while only a small number exceeded 8%, with occasional values approaching or exceeding 10%. The burst fraction fluctuated continuously around a low background level, without extended periods of persistently high values. This pattern indicates that enhanced turbulence did not occur as a sustained state, but mainly appeared as short and temporally separated events.

The 3-day moving average included in Figure 5a remained close to 5% during

most of the winter. Although moderate variations occurred among different periods, no pronounced seasonal increase or prolonged high-value interval was observed. Thus, under the prevailing snow-covered and frequently stable conditions, weak background turbulence was repeatedly interrupted by short-lived turbulent enhancements. This temporal organization represents an important feature of winter near-surface exchange at the study site.

The frequency distribution further illustrates the overall occurrence characteristics of the burst events (Figure 5b). The 30-min burst fraction exhibited a unimodal distribution with a peak near 5%. The seasonal mean and median were 5.15% and 5.12%, respectively, indicating a relatively consistent characteristic burst fraction across the valid samples. Most values were concentrated between 4% and 6%, while the distribution extended toward higher fractions, showing a modest right tail. This tail indicates that a limited number of 30-min periods experienced more pronounced intermittent turbulence. Values below 2% or close to zero were relatively uncommon, showing that threshold exceedances occurred in most retained 30-min segments, although they generally occupied only a small portion of each segment.

Overall, the time series and frequency distribution demonstrate that winter near-surface turbulence over the snow-covered Gurbantunggut Desert was strongly intermittent in time. Burst events did not dominate entire 30-min periods, but occurred as short enhanced intervals embedded within weak background turbulence, with an average time fraction of approximately 5%. These results provide the statistical basis for evaluating the contribution of burst periods to turbulent heat exchange.

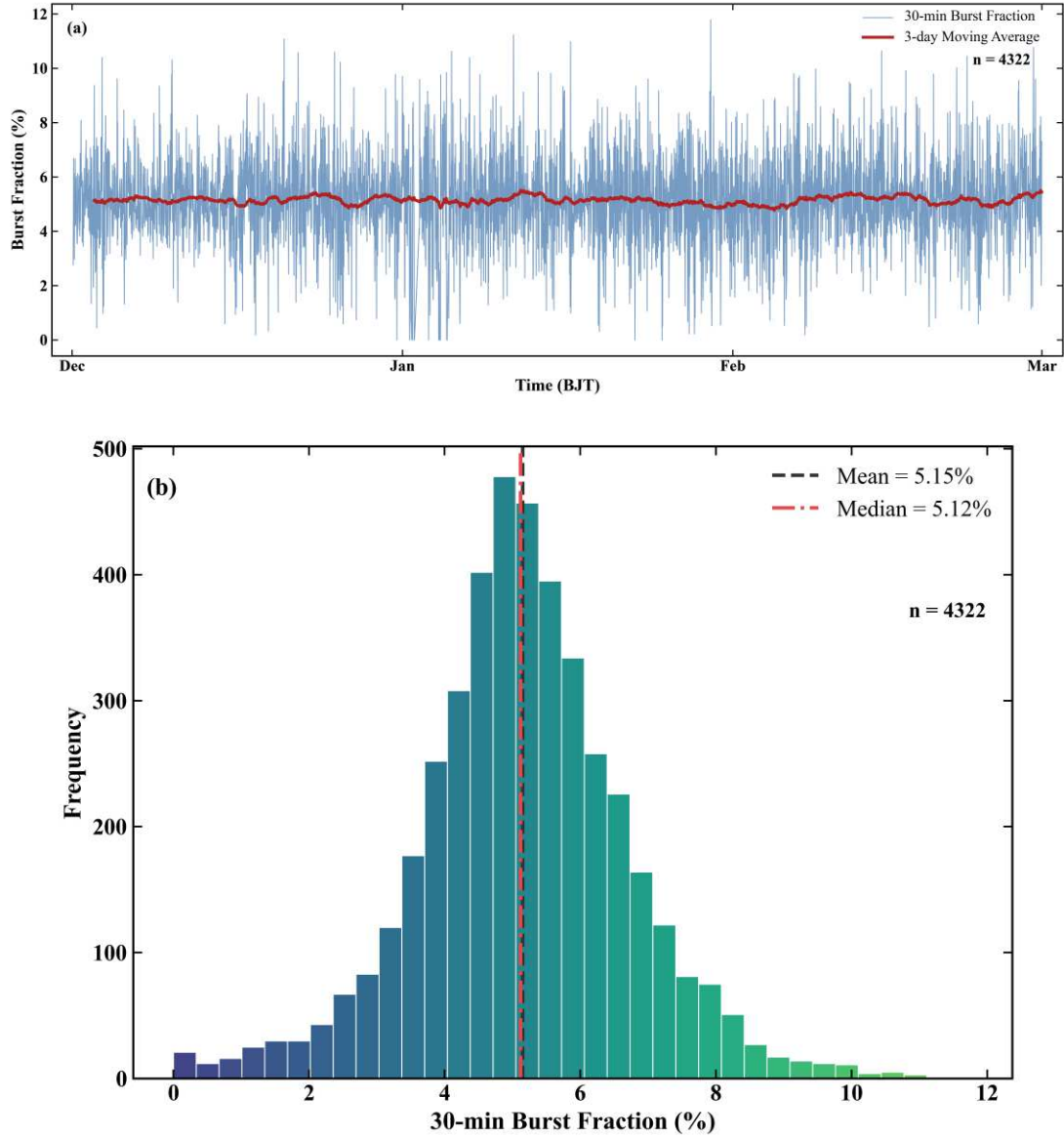


Figure 5. Time series and distribution characteristics of the near-surface 30-min burst fraction at the KLML station in winter.

(a) 30-min burst fraction and its 3-day moving average from December 2023 to February 2024. (b) Frequency distribution of the 30-min burst fraction; dashed lines indicate the sample mean and median.

3.2.2 Contribution of Burst Events to Heat Exchange

Figure 6 presents the statistical distributions of burst-related heat-exchange characteristics across different 30-min burst-fraction intervals. Figure 6a shows that the burst contribution to total absolute kinematic heat exchange, C_{abs} , generally increased as the burst fraction B_f rose from 0–5% to 5–10% and 10–15%. Both the median and interquartile range shifted upward, indicating that longer burst duration generally led to

a larger cumulative contribution to absolute heat exchange within a 30-min period. Nevertheless, numerous high-value outliers occurred in the 0–5% and 5–10% groups, showing that a low burst fraction did not necessarily correspond to a small heat-exchange contribution. Some short-lived bursts still made substantial contributions because of strong instantaneous $w'T_s'$ fluctuations. Figure 6b shows that the burst-to-non-burst absolute kinematic heat-exchange intensity ratio, R_{abs} , differed only slightly between the 0–5% and 5–10% groups, with similar medians and interquartile ranges. This indicates that the unit-time exchange intensity during burst periods did not increase proportionally with burst duration. High-value outliers were present in all groups, and relatively large R_{abs} values also occurred in the lower- B_f groups, further demonstrating that some short bursts had much stronger unit-time exchange intensities than the surrounding non-burst periods. C_{abs} could be calculated for all 4,322 valid segments, whereas R_{abs} could not be calculated for 15 segments in which no valid burst samples were identified, leaving 4,307 valid segments for the R_{abs} analysis. Overall, burst fraction mainly affected the cumulative contribution to heat exchange, while burst duration was not simply proportional to unit-time exchange intensity.

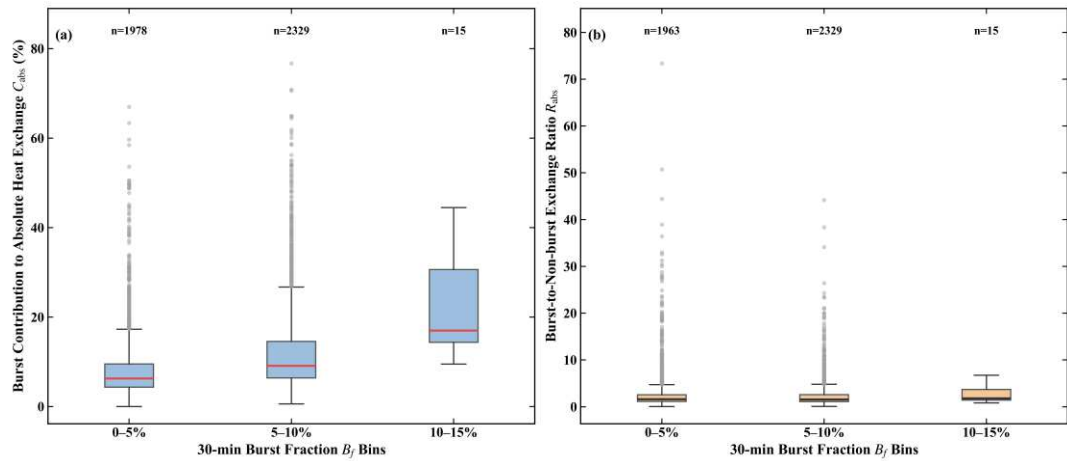


Figure 6. Statistical distributions of burst heat-exchange contribution and exchange intensity ratio under different burst-fraction intervals.

(a) Boxplot of the burst contribution to absolute heat flux, (C_{abs}), under different 30-min burst-fraction intervals. (b) Boxplot of the burst-to-non-burst exchange intensity ratio, (R_{abs}), under different 30-min burst-fraction intervals. Boxes indicate the interquartile range, red lines inside the boxes indicate the median, whiskers indicate the main distribution range, and gray dots indicate outliers.

3.2.3 Stability Dependence of Burst Characteristics

Figure 7 presents the stability-stratified distributions of burst characteristics based on the records successfully matched with valid gradient Richardson numbers. A total of 4,091 valid 30-min segments were used for the B_f and C_{abs} analyses, whereas 4,079 segments were retained for the R_{abs} analysis because R_{abs} was unavailable for 12 matched segments. Increasing stability had little systematic influence on the burst time fraction but was generally associated with larger burst contributions to absolute kinematic heat exchange and greater burst-to-non-burst exchange intensity. Across the four gradient Richardson number regimes, the median burst time fraction remained close to 5%, with only limited differences among the groups (Figure 7a). Thus, as the surface layer changed from unstable to increasingly stable conditions, burst periods did not occupy a markedly larger fraction of the 30-min records. Their occurrence remained characterized by short-duration intermittent activity.

In contrast, the heat-exchange contribution of burst periods increased overall with stability. The median burst contribution to absolute heat exchange increased from approximately 7% under unstable conditions to nearly 10% under strongly stable conditions (Figure 7b). The upper quartiles and upper tails of the distributions also increased in the more stable regimes, indicating that some bursts under strong stability contributed relatively large fractions of the total absolute heat exchange despite their short duration.

A similar stability dependence was observed for the burst-to-non-burst absolute heat-exchange intensity ratio (Figure 7c). Its median increased from approximately 1.4 under unstable conditions to more than 1.9 under strongly stable conditions. This result indicates that when bursts occurred under stronger stability, their unit-time heat-exchange intensity was increasingly larger than that during the surrounding non-burst periods. The broader upper distributions in the stable groups further show that strongly enhanced exchange occasionally occurred during a small number of burst events.

Overall, the influence of stability was expressed mainly through changes in burst

exchange contribution and relative exchange intensity rather than through changes in burst duration. Under winter snow-covered conditions, stronger stability suppressed background turbulent exchange, thereby increasing the relative importance of short-lived burst events in maintaining near-surface heat transport.

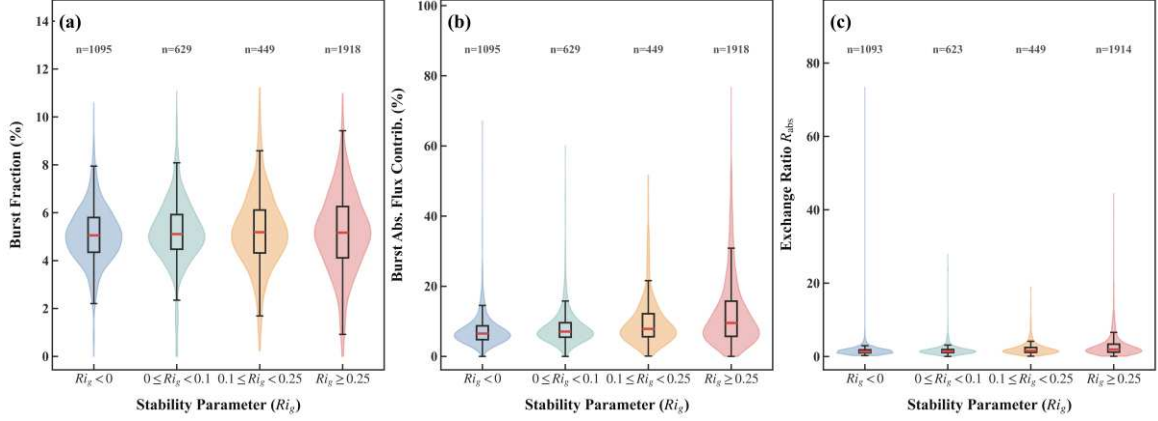


Figure 7. Burst characteristics and their heat-exchange effects under different stability regimes. (a) Distribution of the 30-min burst fraction under different gradient Richardson number Ri_g groups. (b) Distribution of the burst contribution to absolute heat flux, (C_{abs}), under different (Ri_g) groups. (c) Distribution of the burst-to-non-burst exchange intensity ratio, (R_{abs}), under different (Ri_g) groups. Violin plots indicate the probability density distribution of the samples; boxes indicate the interquartile range; horizontal lines inside the boxes indicate the median; whiskers indicate the main distribution range; and (n) above each plot denotes the number of valid samples in each stability group.

3.2.4 Representative Burst Cases

Figure 8 illustrates the high-frequency turbulent kinetic energy and instantaneous kinematic heat-flux characteristics during representative 30-min periods under weakly and strongly stable conditions. In the weakly stable case (Figures 8a and 8c), the 5-s moving-average TKE fluctuated continuously throughout most of the period, indicating that the background turbulence remained relatively active. Burst samples were mainly distributed around 13:12–13:15, near 13:20, and during approximately 13:25–13:30, with frequent threshold exceedances during the latter part of the period. The

corresponding $w'T'_s$ series generally showed enhanced positive and negative fluctuations during these burst intervals. However, appreciable heat-flux variability was also present during non-burst periods. This indicates that, under weak stability, heat exchange occurred within a comparatively continuous turbulent background, while the identified bursts mainly represented localized enhancements superimposed on that background.

The strongly stable case (Figures 8b and 8d) exhibited more pronounced temporal intermittency. The 5-s moving-average TKE remained relatively low during most of the period and exceeded the burst-detection threshold only during several short intervals. The most prominent TKE enhancement occurred near 02:10 BJT, with a peak exceeding $1.2\text{m}^2\text{s}^{-2}$. Additional threshold exceedances occurred near 02:04, during approximately 02:15–02:20, and between 02:26 and 02:30. Relatively long intervals of low TKE separated these enhancement periods, indicating that turbulence enhancements under strongly stable conditions were temporally dispersed. The corresponding $w'T'_s$ series showed large positive and negative fluctuations around the identified burst periods. In particular, near 02:10, a pronounced negative heat-flux excursion occurred concurrently with the strongest TKE enhancement.

Overall, bursts under weakly stable conditions were embedded within comparatively continuous turbulent fluctuations and appeared mainly as localized enhancements. Under strongly stable conditions, TKE threshold exceedances were concentrated within several temporally separated short intervals, resulting in a clearer contrast between burst and non-burst periods in both turbulence intensity and instantaneous kinematic heat exchange. This result is consistent with the statistics shown in Figure 7, which indicate that increasing stability had only a limited influence on burst time fraction but generally enhanced the heat-exchange contribution and unit-time exchange intensity of bursts relative to non-burst periods.

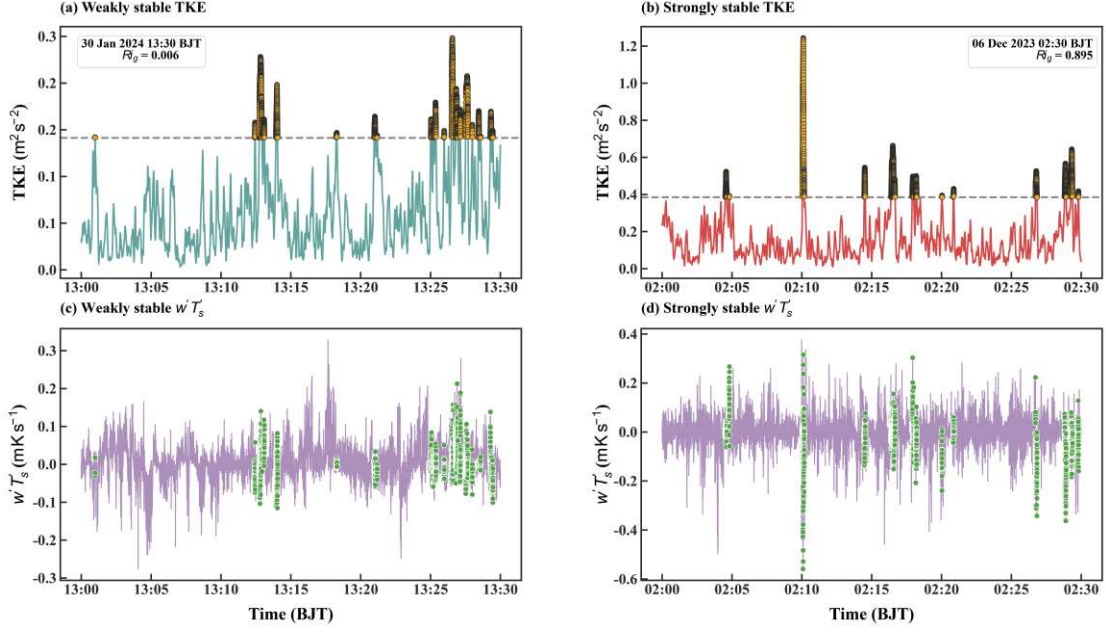


Figure 8. High-frequency turbulent kinetic energy and instantaneous kinematic heat-flux responses during representative burst cases under different stability regimes. Panels (a) and (c) show the weakly stable case during the 30-min period ending at 13:30 BJT on 30 January 2024 ($Ri_g = 0.006$), whereas panels (b) and (d) show the strongly stable case during the 30-min period ending at 02:30 BJT on 6 December 2023 ($Ri_g = 0.895$). In panels (a) and (b), the solid curves represent the 5-s moving-average turbulent kinetic energy, the gray dashed lines denote the burst-detection threshold $\mu + 2\sigma$, and the yellow markers indicate the identified burst periods. In panels (c) and (d), the purple curves represent the high-frequency instantaneous kinematic heat-flux term $w'T'_s$, and the green markers indicate the corresponding $w'T'_s$ values during the identified burst periods.

4 Discussion and Conclusions

4.1 Discussion

4.1.1 Potential Dynamical Drivers of Intermittent Turbulent Bursts

Figure 9 presents the concurrent variations in near-surface turbulence, heat exchange, and wind and thermal structures during the representative strongly stable burst period from 2:00 to 2:30 BJT on 29 February 2024. The corresponding Ri_g was 0.258, slightly above the strongly stable classification threshold of 0.25. TKE smoothed with a 5 s moving window briefly exceeded the $\mu + 2\sigma$ threshold near the beginning of the period and showed a more pronounced enhancement at approximately 2:23–2:25 BJT, with a peak exceeding $0.5 \text{ m}^2 \text{ s}^{-2}$, indicating that turbulence was concentrated in a limited number of short-lived burst episodes. During the same interval, the

fluctuations in $w'T'_s$ increased substantially and included alternating positive and negative excursions, demonstrating strong and highly nonstationary instantaneous heat exchange. The gradient-tower observations show vertically nonuniform wind-speed variations around the event, with enhanced winds at 20 m and several lower levels. The 2–10 m vector wind shear reached 0.233s^{-1} during the selected period, compared with a preceding 2-h mean of 0.094s^{-1} . The wind profiles further indicate marked vertical heterogeneity in the near-surface flow, whereas virtual potential temperature increased with height before, during, and after the burst, confirming that stable thermal stratification persisted throughout the event. Short data gaps occurred in the 10- and 32-m wind-speed records because of instrument malfunction, and the missing records were treated as invalid. Overall, the event occurred under persistent stable stratification and relatively strong near-surface mechanical shear, while the TKE enhancement coincided with pronounced heat-flux fluctuations. These concurrent variations suggest that enhanced local mechanical shear may have provided a favorable dynamical background for the burst; however, the different temporal resolutions of the high-frequency turbulence quantities and the 30-min gradient observations, together with the single-event nature of the analysis, preclude determination of a strict temporal sequence or direct causal relationship.

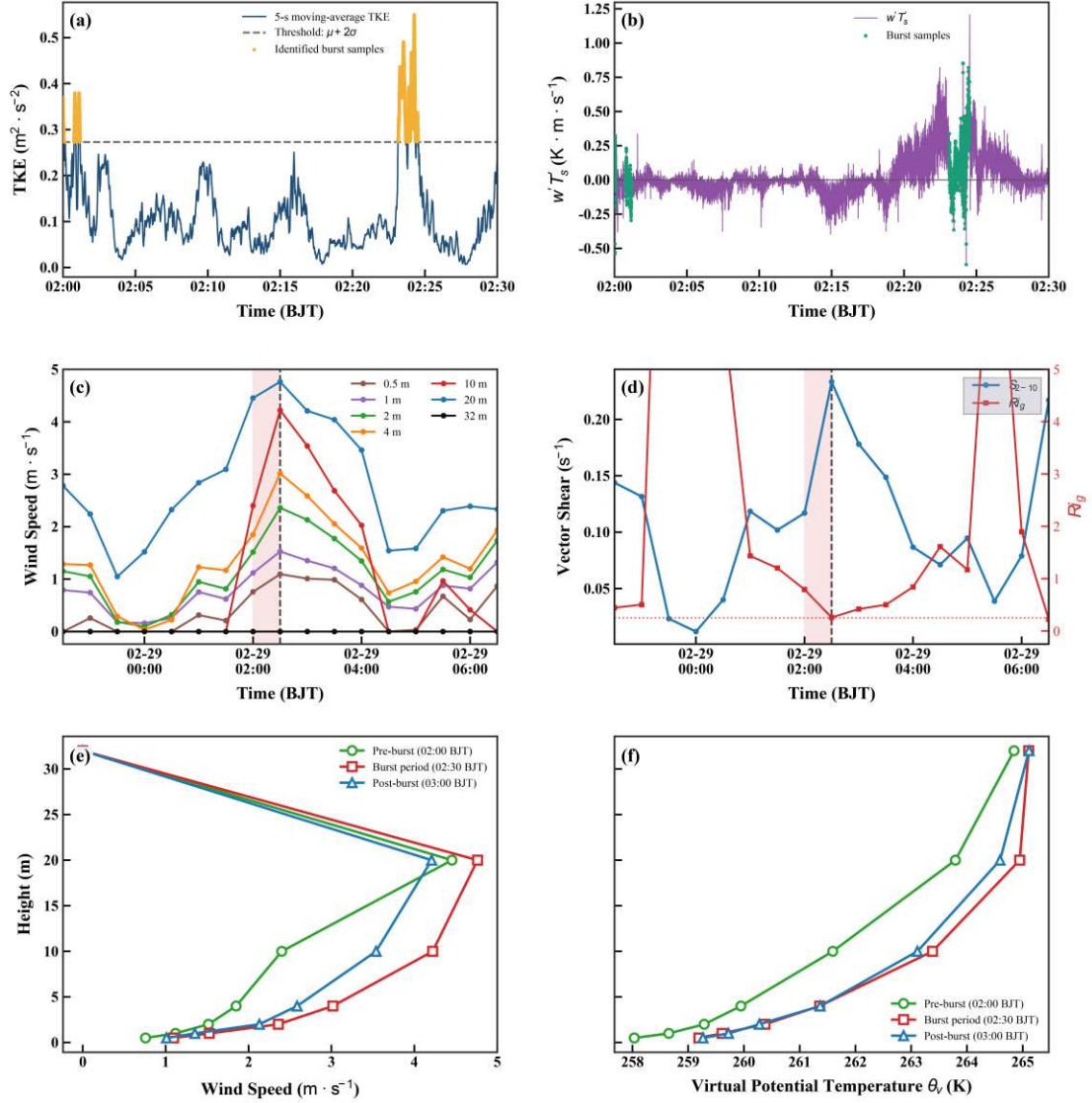


Figure 9. Near-surface dynamical and thermal evolution during a representative strongly stable turbulence-burst event ending at 02:30 BJT on 29 February 2024. (a) TKE smoothed with a 5s moving window and the burst threshold $\mu + 2\sigma$; (b) instantaneous kinematic heat-flux term $w'T'_s$; (c) wind speeds at different tower levels; (d) 2–10 m vector wind shear and Ri_g ; (e) wind-speed profiles; and (f) virtual potential-temperature profiles. Shading denotes the selected 30 min burst period, and the vertical dashed line marks its ending time.

4.1.2 Scale-Dependent Spectral Changes Under Different Stability Regimes

The normalized premultiplied spectra of the three velocity components exhibited a relatively shallow depression between the low-frequency range and the principal turbulent spectral range. Recent studies have emphasized that atmospheric boundary-layer wind fluctuations contain contributions from multiple temporal scales and that spectral breaks or transition ranges may occur where the dominant controlling processes

change. Gencarelli and Carbone (2026), for example, showed that compensated spectra can reveal scale-dependent changes in the contribution of wind fluctuations to total variance and identified distinct scaling behavior across different temporal ranges. Although their analysis covered longer timescales and a different atmospheric environment, it supports the interpretation that a depression or change in spectral slope may represent a transition between different dynamical ranges rather than a universal and sharply defined spectral gap. Similarly, Zhang et al. (2024) found that turbulence intermittency and fine-scale structures in the Taklimakan Desert were strongly affected by weak winds and thermal forcing, complicating the separation between turbulent and non-turbulent motions and influencing flux estimation. Considering the relatively shallow depression in the present spectra and the effects of stability-conditioned averaging, logarithmic binning, and smoothing, this feature is therefore interpreted as a scale-transition range rather than definitive evidence of a well-defined spectral gap.

The ordering of the spectra varied systematically with frequency. Under strongly stable conditions, the normalized spectral levels were relatively high in the low-frequency range but decreased to comparatively low values in the principal turbulent and high-frequency ranges. Mahrt (2024) showed that microfronts, wave-like motions, wind meandering, and other submesoscale structures can substantially modulate turbulent heat fluxes in very stable, low-wind boundary layers. Butterworth et al. (2024) also observed thin and intermittent turbulent layers embedded within otherwise strongly stable vertical profiles in the Arctic, indicating that turbulence under strong stability can be spatially and temporally localized rather than continuously distributed. More recently, Ding et al. (2025) demonstrated that interactions between a low-level jet and internal gravity waves can reorganize turbulence throughout the nocturnal boundary layer and generate marked vertical and temporal variability. These studies collectively indicate that strongly stable boundary layers may contain relatively slow, organized, or nonstationary motions together with localized turbulent activity. The relatively elevated low-frequency spectral levels found here are consistent with an increased relative importance of such slow motions, whereas the reduced high-frequency levels indicate

a smaller relative contribution from local rapid fluctuations.

The stability-related spectral contrast was clearest for the vertical velocity component. The strongly stable w spectrum remained comparatively low near the principal spectral maximum and throughout much of the high-frequency range, whereas differences among the horizontal components were less pronounced. Shao et al. (2026) recently argued that atmospheric stability may damp vertical velocity fluctuations more strongly than horizontal fluctuations, thereby contributing to the observed increase in normalized streamwise velocity variance with stability in stable atmospheric surface layers. Although their analysis focused on velocity variances rather than premultiplied spectra, the anisotropic response identified in their study is consistent with the more pronounced reduction in the relative high-frequency spectral levels of w observed here. This result is also consistent with the Arctic observations of Butterworth et al. (2024), in which strong stratification confined turbulent activity to relatively thin layers, and with the findings of Ding et al. (2025), which showed that the vertical turbulence structure evolved markedly under the combined influence of shear and wave disturbances. The present results therefore suggest that increasing stability constrained high-frequency vertical fluctuations more strongly than horizontal motions, thereby enhancing the scale-dependent horizontal–vertical heterogeneity of near-surface turbulence. However, the current spectra alone cannot distinguish whether the low-frequency components were associated specifically with wind meandering, gravity waves, microfronts, or other nonstationary processes.

4.1.3 Comparison of Near-Surface Turbulence Over Different Surface Types

Near-surface turbulence is jointly controlled by surface thermal properties, aerodynamic roughness, vegetation, terrain, atmospheric stability, and external dynamical disturbances. The snow-covered desert examined here differs substantially from bare deserts, semiarid grasslands, the Tibetan Plateau, and urban surfaces because it combines a high surface albedo, low temperatures, weak winds, a relatively smooth surface, and persistent stable stratification. During the observation period, bursts

occupied only approximately 5.15% of each 30-min segment on average, whereas the mean absolute heat-exchange intensity during burst periods was approximately 2.58 times that during non-burst periods. Thus, despite their short duration, bursts represented an efficient component of winter near-surface heat exchange. Because previous studies used different sampling heights, averaging periods, and intermittency measures, the following comparisons focus on differences in physical controls rather than direct numerical contrasts.

The Taklimakan Desert provides the most comparable arid-surface environment. Wei et al. (2019) found that turbulence intermittency was stronger at night than during daytime and that stronger intermittency was generally associated with more stable clear-sky conditions. Both the Taklimakan and Gurbantunggut Deserts therefore exhibit nonstationary turbulence under stable conditions. However, many previous observations in the Taklimakan were obtained over bare sand or during relatively warm periods, whereas the present study focuses on a persistently snow-covered winter surface. Snow cover increases surface albedo and reduces daytime shortwave absorption, while nighttime radiative cooling and weak winds favor the maintenance of stable stratification. These conditions produce weaker background turbulence and increase the contrast between short-lived bursts and surrounding non-burst periods.

Desert and sandy-grassland ecosystems in Inner Mongolia provide a second comparison. Energy partitioning at the Dengkou desert ecosystem varies seasonally and is regulated by net radiation, soil moisture, and other environmental conditions (Pan et al., 2022). Field observations over the Horqin Sandy Land further showed that pressure fluctuations and pressure transport made non-negligible contributions to the turbulence kinetic energy budget, particularly at relatively large temporal scales (Wei et al., 2021). In such environments, vegetation activity, soil moisture, and evapotranspiration contribute to land–atmosphere coupling, especially during the growing season. In contrast, vegetation activity and evapotranspiration were weak during the winter observation period in the Gurbantunggut Desert, and the snow-covered surface was comparatively smooth. The intermittency observed here was therefore more directly

associated with strong stability, weak background turbulence, and short-term dynamical disturbances than with active vegetation–soil–atmosphere interactions.

The Tibetan Plateau also experiences stable boundary layers and intermittent turbulence, but the controlling environment is different. The plateau is characterized by high elevation, strong solar forcing, and complex terrain. Che and Zhao (2021) showed that regional differences in summer boundary-layer development over the Tibetan Plateau were related to cloud cover, surface solar radiation, soil moisture, and sensible heat flux. Wang et al. (2015) further demonstrated that boundary-layer convection and turbulence kinetic energy over the southeastern plateau margin were influenced by thermal forcing and vertical wind shear. Turbulence over the plateau may additionally be affected by slope flows, terrain-induced circulations, and topographic waves. By comparison, the interior of the Gurbantungut Desert has relatively limited topographic relief, and the representative case examined here was accompanied by enhanced lower-tropospheric winds and increased vertical wind-speed contrasts. This suggests that upper-level wind disturbances may be particularly relevant to intermittent turbulence over the weak-wind, snow-covered desert, although the available case does not establish a direct triggering mechanism.

Urban surfaces represent a contrasting high-roughness environment. Buildings and other obstacles generate mechanical turbulence and produce strong spatial heterogeneity in momentum and heat exchange. Measurements from the 325-m meteorological tower in Beijing showed that urban roughness affects the vertical distributions of turbulence statistics and scalar transport (Liu et al., 2017). Anthropogenic heat release and complex urban geometry provide additional sources of turbulence that are absent over the study site. In contrast, the smooth snow-covered desert surface and weak near-surface winds provide limited mechanical turbulence production. Consequently, intermittent bursts can make a more distinct contribution relative to the weak background exchange.

Overall, nonstationary turbulence occurs over deserts, semiarid grasslands, high-elevation terrain, and urban surfaces, but the controlling factors vary among

environments. Turbulence over the Taklimakan Desert is strongly affected by arid-surface heating and nocturnal stability; Inner Mongolian desert and grassland ecosystems are additionally regulated by vegetation, soil moisture, and seasonal energy partitioning; the Tibetan Plateau is influenced by complex terrain and coupled thermal and dynamical forcing; and urban turbulence is enhanced by large aerodynamic roughness and surface heterogeneity. The distinctive feature of the winter Gurbantunggut Desert is the simultaneous influence of snow-modified radiation, weak background winds, and persistent stable stratification. These conditions favor a turbulence regime in which weak background exchange is intermittently interrupted by short-lived but relatively efficient burst events.

4.2 Conclusions

Using gradient-tower observations and 10-m eddy-covariance measurements collected at the KLML station from 1 December 2023 to 29 February 2024, this study investigated near-surface turbulence structure, intermittent burst activity, and burst-related kinematic heat exchange over a winter snow-covered desert. The principal conclusions are as follows.

(1) The winter near-surface environment was characterized by low temperature, weak wind, high snow-surface albedo, and predominantly stable stratification. Among the 3944 common valid half-hourly records used for stability-stratified turbulence statistics, strongly stable conditions accounted for 46.3%, and stable conditions collectively accounted for 72.7%. Friction velocity generally decreased with increasing stability, whereas TKE did not exhibit a monotonic response and retained a broad distribution under strongly stable conditions. Sensible heat flux showed a clearer diurnal cycle and stronger stability dependence than the dynamical turbulence variables.

(2) Stability modified the relative spectral distribution of velocity fluctuations in a scale-dependent manner. The normalized premultiplied spectra contained a shallow depression between the low-frequency and principal turbulent ranges. The strongly stable regime showed relatively elevated spectral levels at low frequencies but lower values in the principal turbulent and high-frequency ranges. This contrast was most apparent for vertical velocity, indicating stronger suppression of high-frequency local vertical fluctuations and increasingly pronounced horizontal–vertical heterogeneity.

Because the spectra were normalized, these differences represent changes in relative spectral weight rather than direct differences in absolute turbulent energy.

(3) Turbulent bursts were short-lived but comparatively efficient in producing instantaneous kinematic heat exchange. The seasonal mean and median burst fractions were 5.15% and 5.11%, respectively, and most values were concentrated between 4% and 6%. Nevertheless, the mean absolute $w'T'_s$ intensity during burst periods was approximately 2.58 times that during non-burst periods. A larger burst fraction was generally associated with a larger contribution to total absolute kinematic heat exchange, whereas burst duration and the burst-to-non-burst exchange intensity ratio were not related through a simple proportional relationship.

(4) Increasing stability affected the relative heat-exchange importance of bursts more clearly than their duration. Burst fractions differed only slightly among the stability regimes, whereas the burst contribution to absolute kinematic heat exchange and the burst-to-non-burst intensity ratio increased overall with stability. Representative cases showed that weakly stable bursts were embedded in comparatively continuous background turbulence, whereas strongly stable bursts appeared as shorter and more isolated pulses. During the strongly stable mechanism case, enhanced winds at several tower levels and increased 2–10 m vector shear occurred concurrently with the TKE burst and pronounced $w'T'_s$ fluctuations, while the virtual potential-temperature profile remained stable. These observations suggest that enhanced local mechanical shear may provide a favorable dynamical background, but the single-case evidence does not establish a unique triggering mechanism.

Overall, winter near-surface exchange over the snow-covered desert was not maintained solely by continuous background turbulence. Short-lived turbulent bursts provided a disproportionate contribution to nonstationary kinematic heat exchange, particularly when the surrounding background turbulence was weak under stable stratification. These results demonstrate the importance of representing turbulence intermittency and scale-dependent transport in studies and parameterizations of winter land–atmosphere exchange over arid regions.

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Statements and Declarations

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Competing Interests

The authors declare that they have no relevant financial or non-financial interests to disclose.

Data Availability

The observational datasets used in this study are not publicly available because

they were collected from a long-term field observation program. The data may be obtained from the corresponding author upon reasonable request and subject to approval from the data provider. The ERA5 reanalysis data used in this study are publicly available from the Copernicus Climate Change Service Climate Data Store.