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# Research progress and current application of weak turbulence and turbulence intermittency in stable boundary layers

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ABSTRACTS

Research on the stable boundary layer is not only a scientific challenge but is also the foundation of studies on the atmospheric environment, weather, and climate change, with significant practical value in social and economic development. Starting from the mutual transitions between weakly and strongly stable boundary layer states, we review the research progress and application of weak turbulent motions and turbulence intermittency. Turbulent intermittency can be driven by internal (the feedback interaction of wind shear and stability) and external factors (sub-mesoscale motions). We clarified the interaction mechanism between the internal and external factors of turbulent intermittency and elucidated how the interaction affects the evolution of stable boundary layer. Given the widespread existence and importance of sub-mesoscale motion, by separating and quantitatively characterizing sub-mesoscale and turbulent motions from the complex flow fields of stable boundary layers, turbulence intermittency can be identified and quantitatively characterized. Accordingly, the typical characteristics of alternating quiescent and bursting periods of turbulence intermittency events can be determined. Notably, during weak turbulence and quiescent periods of turbulence intermittency, the turbulent transport of matter and energy can be affected by sub-mesoscale motions, has been overestimated easily, relevant corrections are necessary. Eliminating the effects of sub-mesoscale motions can improve the similarity relationships of the stable boundary layers. Moreover, non-stationary turbulent transport during bursting periods of turbulence intermittency events will change the general understanding of classical problems. For example, the surface energy closure rate during the bursting periods can even be very close to totally closure. Turbulence intermittency has wide applications. In this study, turbulence intermittency is combined with haze pollution research to propose the concept of the turbulence barrier effect and investigate the physical mechanisms through which turbulence barriers can be strengthened or broken. The turbulence barrier effect significantly affects turbulent transport of matter, such as carbon dioxide and water vapor; thus, it is vital in practical issues, such as early warning for dust storms and dense fog events. However, three key challenges still require further investigation: physical mechanisms of state transitions and mechanisms of vertical structure evolution in stable boundary layers; physical origins, spatial and temporal evolution patterns, and parameterization of turbulence intermittency; and improvement of the similarity theory of stable boundary layers. Finally, we discussed future research directions on weak turbulence and turbulence intermittency in stable boundary layers, and explored the potential applications of observational facts, theoretical breakthroughs, and simulation advances in stable boundary layers to improve air pollution forecasts, extreme weather warning, and climate change projections.

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## 1. Introduction

Turbulence is a common but extremely complex form of fluid motion. It is widely recognized as a major challenge in natural sciences and is known as the last unsolved important problem in classical physics. Modern turbulence research began in 1883 when the Reynolds Experiment was conducted; namely, when the Reynolds number exceeds a certain critical value, the macroscopic motion of a viscous fluid changes from laminar to turbulent flow. The Reynolds number of the Earth's atmosphere is considerably high, whereas the fluid motion in the atmospheric boundary layer exhibits turbulence characteristics. Atmospheric turbulence is the foundation and core of physical research of the atmospheric boundary layer (Panofsky and Dutton, 1984). It dominates the transport of matter and energy between the Earth's surface and atmosphere and drives the development and evolution of the atmospheric boundary layer (Garratt, 1992). The atmospheric boundary layer, being the lowest part of the atmosphere where human activities occur, is closely associated with practical issues, including extreme weather events and air pollution, and reacts the most significantly to climate change. Therefore, to further understand climate change and atmospheric environmental issues in detail and improve forecasting and early warning models, thorough understanding of atmospheric turbulence is essential.

The development of the atmospheric turbulence theory has advanced boundary layer meteorology. Reynolds averaging separates turbulent fluctuations from the mean field, laying a foundation for the statistical theory of turbulence. Taylor (1915) analogized the atmospheric turbulent transport process to molecular diffusion and proposed the concept of mixing length to derive a semi-empirical theory of turbulence (Monin and Yaglom, 1971), which has been frequently adopted in boundary layer parameterization schemes for closure. Since the turbulent energy cascade theory and the power law for the inertial subrange were proposed (Kolmogorov, 1941; Obukhov, 1941), they have been widely used in turbulence modeling, convective boundary layer measurement, viscous dissipation estimation, and large-eddy simulations. Monin and Obukhov (1954) have established expressions for profiles of meteorological elements in the surface layer, that is Monin-Obukhov similarity theory. Nieuwstadt (1984) and Deardorff (1970, 1972) integrated local similarity and mixed layer similarity to apply these expressions to stable and convective boundary layers. The application of the local similarity theory is extended to heterogeneous underlying surfaces (Shao and Hacher, 1990; Zhang, 2003). The similarity theory is an important milestone and also a critical theoretical framework for measurement and analysis in the fields of atmospheric boundary layer and atmospheric turbulence research, and is the basis for parameterization of turbulence in the atmospheric boundary layer for air pollution prediction, numerical weather forecasting, and climate modeling. Strictly speaking, similarity theory only applies to stationary and homogeneous turbulence.

All atmospheric boundary layer turbulence problems that deviate from classical theoretical assumptions and premises require solutions and in-depth research. For example, the boundary layer over a heterogeneous or complex underlying surface causes the state of atmospheric turbulence to vary, posing significant challenges to the parameterization of the boundary layer in numerical models (Sterk et al., 2013). Owing to continuous urban expansion and vertical urbanization, the influence of boundary layers over cities becomes increasingly prominent while their structures are getting more complex (Miao et al., 2020). However, even with homogeneous underlying surfaces, heterogeneous and non-stationary turbulence is still present. Turbulence in the stable boundary layer is relatively weak and exhibiting strong intermittency (Mahrt, 2014). Mahrt (1999) identified two types of turbulence intermittency: small-scale (or fine-scale) intermittency, which appears as a substructure within the main eddies, and large-scale (or global) intermittency, characterized by aperiodic transitions in both time and space between turbulent and quasi-laminar states, with turbulence locally damped at all scales. Most atmospheric science studies, including this review, focus on this type of intermittency. Turbulence intermittency is one of the major discoveries in modern turbulence research, signifying strong non-stationarity and heterogeneity, making the classical similarity theory fail (Fernado and Weil, 2010; Mahrt et al., 2013).

Unsteady turbulence caused by non-stationarity and heterogeneity leads to difficulties in parametrizing turbulent diffusion in stable boundary layers (Sandu et al., 2013). Different mechanisms may trigger intermittent turbulence, such as the interaction between stable stratification and wind shear, surface heterogeneity, local shear and sub-mesoscale motions (Banta et al., 2007; Sun et al., 2015a; Mahrt, 2019). These factors may be non-linearly and non-stationary themselves, such as most sub-mesoscale motions, and their interactions can significantly make the dynamics of the stable boundary layer extremely complex (Mahrt and Bou-Zeid, 2020). Compared to the convective boundary layer with vigorous turbulence development, the impact of the complex underlying surface is amplified in the stable boundary layer, and even slight heterogeneity of the surface becomes highly significant (Mahrt, 2024). Renowned scholars in boundary layer meteorology have indicated that turbulence in the stable boundary layer is weak and highly sensitive to underlying terrain, resulting in greater structural heterogeneity and making observation and simulation challenging, which has led research on the stable boundary layer to lag behind that on the convective boundary layer (Lemone et al., 2018). Thus, the stable boundary layer has become a bottleneck restricting the advance of the atmospheric boundary layer theory and improvement of turbulence parameterization.

The stable boundary layer is closely associated with the occurrence of weather hazards (Geiss and Mahrt, 2015; Izett et al., 2018), including frost and dense fog events. The structural evolution of the stable boundary layer leads to the occurrence, development, and dissipation of air pollution (Wei et al., 2018; Ma et al., 2020). Weather hazards and air pollution affect the lives of billions of people worldwide. For example, particulate matter caused over four million deaths and hundreds of millions of disabilities worldwide in 2015 (Cohen et al., 2017), and aerosols substantially influence the weather and climate change (Liu et al., 2019a, 2019b). Atmospheric turbulence plays a crucial role in the transport and diffusion of pollutants, impacting every stage of air pollution development, including emission, dispersion, and deposition. Weak turbulence in the stable boundary layer is the main cause of pollution accumulation (Stjern et al., 2023), and the accumulation of heavy pollution has a bidirectional feedback with weather and climate processes (Zhang et al., 2018). Therefore, research on the stable boundary layer is the foundation of studies on the atmospheric environment, weather, and climate change. Nevertheless, the very stable boundary layer is not sufficiently represented in air pollution, weather, and climate models (Holtslag et al., 2013; Edwards et al., 2020). The resulting discrepancies of the simulated key parameters are substantial (Sandu et al., 2013; Bosveld et al., 2014), which in turn affect the daily lives of people. Some examples include low visibility warning (Bartok et al., 2012), air quality warning (Kulmala et al., 2023), agricultural production assurance (Van der Velde et al., 2010), wind power estimation (Storm and Basu, 2010), and carbon budget evaluation (El-Madany et al., 2014). Thus, research on the stable boundary layer is not only a scientific challenge but is also an unavoidable practical problem in social and economic development.

In this review, research and application progress of weak turbulence and turbulence intermittency in the stable boundary layer are briefly summarized. In the section 2, experimental observations, theoretical studies, and numerical simulations of weakly and strongly stable boundary layers are reviewed. The section 3 presents an overview on the research progress of the methods and theories of weak turbulence and turbulence intermittency in strongly stable boundary layers as well as their applications in key application problems. In the section 4, the current challenges in theoretical research of the stable boundary layer are introduced. Finally, in the section 5, conclusions are drawn and an outlook is provided on the research and application of weak turbulence and turbulence intermittency in the stable boundary layer.

## 2. Weakly and strongly stable boundary layers

A stable boundary layer can be easily developed in both nights and daytime through the advection of warmer air over cooler land or water surfaces as well as during winter in mid to high latitudes over snow and ice surfaces. Stable boundary layers have two well-known distinct regimes with distinct characteristics. In a certain stability range, a stable boundary layer has a well-defined structure, the turbulence is relatively continuous in both time and space. This agrees well with the description of the similarity theory. With increasing stability, turbulence becomes weak and exhibits intermittency, deviations among turbulent energy obtained through field observations, laboratory experimental results, and numerical simulation results become larger (Zilitinkevich et al., 2008), and vertical turbulent mixing is drastically reduced. The boundary layer is no longer coupled with the Earth's surface, and the vertical structure does not follow conventional patterns but varies in form (Mahrt, 2014). Consequently, the similarity theory is not valid anymore. Mahrt (1998) first used the terms 'weakly stable' and 'very stable' to describe the two different regimes mentioned above, also suggested a transitional stability regime between these two regimes and provided critical z/L (Monin-Obukhov Length) values that vary in different cases to classify these different regimes. Although there are some other studies proposed more detailed classification, such as five stable levels from near neutral to very stable regime based on local stability in Basu et al. (2006); weakly stable ($0.02 < Ri < 0.12$), very stable ($0.12 < \mathrm{Ri} < 0.7$), and extremely stable ($\mathrm{Ri} > 0.7$) boundary layers in Sorbjan (2010); turbulent, intermittent and radiative regime in Van de Wiel et al. (2003) based on pressure gradient and radiative forcing, a number of independent forcings influencing the stable boundary layer make any attempts to classify stable boundary layers be incomplete (Mahrt, 2014). Therefore, most studies have only conceptually referred to stable boundary layers with continuous turbulence as weakly stable boundary layers (WSBL), and referred to those with intermittent turbulence as strongly stable or very stable boundary layers (VSBL), which are also what this manuscript follow. In weakly stable boundary layers, the total energy generated by wind shear can only increase the kinetic energy of turbulence, whereras in strongly stable boundary layers, it is also used to increase the potential energy of turbulence to maintain stable stratification (Sun et al., 2016).

Notably, weakly stable boundary layers can transform into strongly stable counterparts and vice versa. Sun et al. (2012) found a critical wind speed based on the statistical relationship between the turbulence intensity and average wind speed to roughly distinguish the two states of stable boundary layers which is known as HOckey-Stick Transition

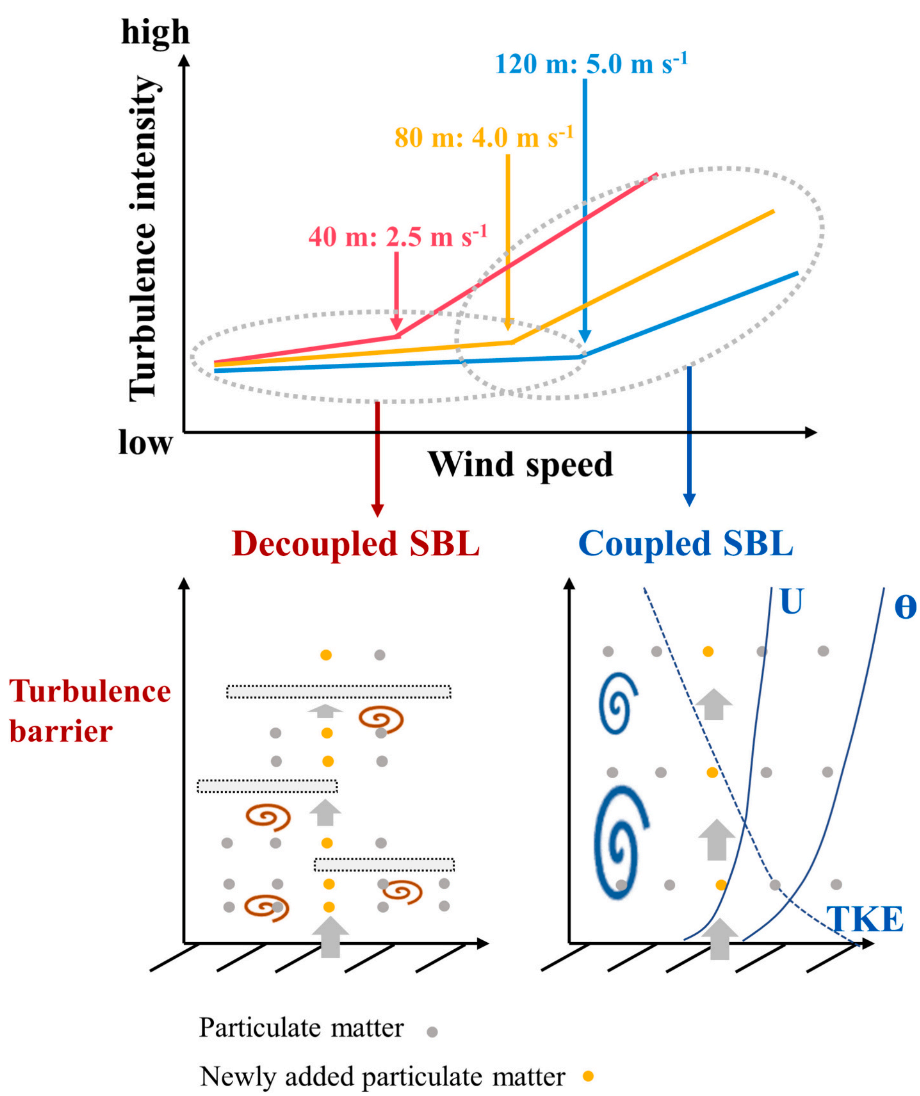


**Fig. 1.** Schematic of the distinctly different turbulence structures, pollutant transportation rate, and distributions of coupled and decoupled SBLs. (From Ren et al., 2023a).

(HOST) (Sun et al., 2016). However, many individual cases in actual observations deviate from this relationship, probably owing to sub-mesoscale motions, in which the temporal scale to evaluate the fluxes should be carefully considered. Experimental studies have revealed that under low wind speeds, some sub-mesoscale motions can generate turbulence through downward propagation (Udina et al., 2013; Soler et al., 2014), whereas upward propagation of terrain-related sub-mesoscale motions results in the formation of turbulence and transformation of strongly stable boundary layers to weakly stable counterparts (Mahrt et al., 2013; Wei et al., 2022). This wind speed threshold has been noted in field observations under different underlying surface and weather conditions (Acevedo et al., 2016; Lan et al., 2018; Yus-Díez et al., 2019). Ren et al. (2023a) applied the stable boundary layer classification method to haze pollution events and found two distinct stable boundary layers in the haze pollution process, namely, decoupled (strongly) stable boundary layers and coupled (weakly) stable boundary layers. The wind speed threshold increases with height, as shown in Fig. 1, which is consistent with those of previous studies (Bonin et al., 2015). The strong stable boundary layer accounts for more than 70 % of the haze pollution process, dominating the evolution of the latter. Based on the development of quasi-two-dimensional pancake vortices, Shao et al. (2023) proposed a critical Froude number($F_h = \frac{\sigma_u}{NL_h}$, where $\sigma_u$ is the standard deviation of streamwise velocity, $N$ is the Brunt-Väisälä frequency and $L_h$ is streamwise integral length scale) to characterize the state transition between weak and strong turbulence and verified its consistency with the wind speed threshold. Besides the HOST hypothesis, there are also other methods used to identify the state transition. For example, some works (Monahan et al., 2015; Abraham and Monahan, 2020) used a two-state hidden Markov model to analyze long observations of wind and temperature, and found two states: a low-wind speed, strong-stratification, low-turbulence state and a high-wind speed, weak stratification, high-turbulence states. Acevedo et al. (2016) found a wind speed threshold occurring when the average vertical gradient of the turbulent kinetic energy switches sign at all observational levels below 30 m, which can distinguish two states. Mortarini et al. (2019) observed that the ratio of the variance of the wind velocity vertical component over the variance of the composite of the wind velocity horizontal components ($\sigma_w^2/\sigma_H^2$) can divide the nocturnal boundary layer in two different regimes. Kaiser et al. (2020) applied a combination of methods from dynamical systems and statistical modeling, and then developed an early warning signal which can identify the regime transitions induced no-linearly. In classical research, it is generally believed that there exists a critical Richardson number. However, the value of the critical Richardson number can vary in different cases (Galperin et al., 2007; Grachev et al., 2013).

Van de Wiel et al. (2007, 2012a, 2012b) proposed the maximum sustainable heat flux theory, which suggests that there is a maximum heat flux related to wind speed. If the energy transferred by turbulence to the surface can compensate the heat loss caused by radiation, the boundary layer is in a weakly stable state, and turbulence can be maintained. Otherwise, turbulence collapses, and the boundary layer becomes strongly stable. Derived from the maximum heat flux theory, Van Hooijdonk et al. (2015) introduced the shear capacity to predict the turbulence collapse of the stable boundary layer on a specific night. Van de Wiel et al. (2017) further integrated various processes affecting the surface radiation budget into one parameter, and suggested that the wind speed threshold at which the state of the stable boundary layer changes depends on this parameter. However, in actual observations, the state of the stable boundary layer may undergo multiple transitions on a single night. In typical cases, the state transitions occur abruptly, accompanied by decreases in the temperature, wind speed, turbulent kinetic energy, and absolute heat flux (Acevedo et al., 2019). Notably, this conclusion is not universal. Acevedo et al. (2021) suggested that the Ri number and near-surface wind speed are internal variables of the stable boundary layer, whereas simultaneously, its state transition is influenced by external variables, including the geostrophic wind, cloud cover, and characteristics of the Earth's surface. At present, the physical mechanism of state transitions of the stable boundary layer is not fully understood.

Numerical simulation has also been applied to study state transitions of the stable boundary layer. Ideal single-column numerical atmospheric models have verified the importance of the wind speed and surface thermodynamic processes in the state transition of the stable boundary layer (Kaiser et al., 2020). Single-column models with first- or second-order closure can representatively simulate transitions from weakly to strongly stable states (Baas et al., 2019; Holdsworth and Monahan, 2019; Maroneze et al., 2019). Moreover, stable boundary layer parameterization that includes the heat flux and temperature variance budget equations can better simulate the two states of the stable boundary layer (Maroneze et al., 2021). The vertical stratification of the stable boundary layer can be reflected in single-column models. For instance, the weakly stable boundary layer immediately above the Earth's surface, strongly stable boundary layer in the middle, and topmost laminar flow layer can be represented (Costa et al., 2020). Direct numerical simulations have shown that local random disturbances, acting as an external phenomenon, can promote turbulence intermittency and trigger transitions from strongly to weakly stable boundary layers (Donda et al., 2015). The statistical scheme proposed by Vercauteren and Klein (2015) also indicates that small-scale, non-turbulent motions can affect the turbulent kinetic energy, thereby triggering state transitions of the stable boundary layer. However, these disturbances caused by sub-mesoscale motions are often not included in most commonly used models (Vercauteren et al., 2019). In actual observations, vertical structures of the strongly stable boundary layers vary greatly and can be altered with the slightest heterogeneity in the Earth's surface. Furthermore, turbulent motions at different altitudes may be influenced by different sub-mesoscale motions or have different origins (Mahrt and Acevedo, 2022). Fig. 2 below concludes the characteristics and mutual conversion of weakly stable boundary layer and strongly stable boundary layer based on existing knowledge. Because the numerical simulations are idealized, so many external phenomena that trigger turbulence are not represented in the models (Mahrt and Acevedo, 2022), a huge gap exists between existing research and the accurate simulation of the state transitions of stable boundary layers and vertical structures of strongly stable boundary layers.

## 3. Turbulence intermittency of the stable boundary layer

### 3.1. Physical mechanisms of turbulence intermittency

Turbulence intermittency is one of the basic characteristics of atmospheric turbulence, especially a prominent characteristic of the stable boundary layer (Van der Linden et al., 2020). By definition, turbulence intermittency includes two elements, namely, a long quiescent period and short bursting period interrupting the quiescent period (Coulter and Doran, 2002; Ohya et al., 2008). There are several mechanisms that may trigger intermittent turbulence in the stable boundary layer, such as large-scale atmospheric process, surface heterogeneity, the local wind shear, and sub-mesoscale motions. Based on numerous previous studies, mechanisms that trigger turbulence intermittency can be classified into two types: external and internal.

Businger (1973) proposed a theoretical mechanism for the occurrence of turbulence intermittency in the stable boundary layer at night when the sky is clear and cloudless, and this mechanism was verified by Van der Linden et al. (2020) through large-eddy simulation experiments. In particular, at a certain altitude, turbulence weakens or even disappears, and the vertical transfer of momentum and heat is hindered. Thus, above (or below) that altitude, the momentum flux converges (diverges), whereas the wind speed increases (decreases), ultimately increasing the shear. The flow becomes dynamically unstable and turbulence temporarily resumes. The resumption of turbulence causes

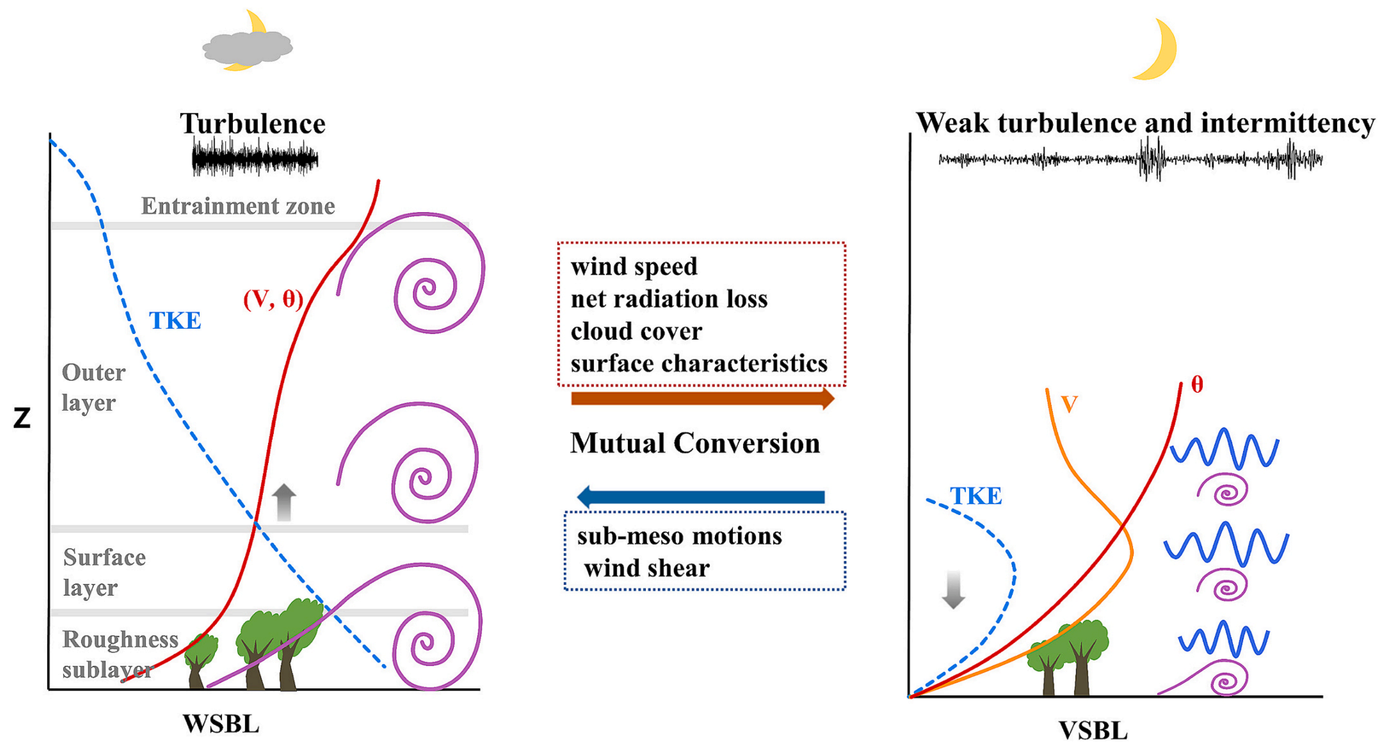


**Fig. 2.** Schematic of the characteristics and mutual conversion of weakly stable boundary layer and strongly stable boundary layer. For simplicity, only a kind of vertical structure of a strongly stable boundary layer is shown here. Purple circles represent turbulent eddies, and blue wavy lines represent sub-mesoscale motions. This figure is based on Fig. 1 from Mahrt (2014), and we have made some modifications and supplements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vertical mixing of momentum and heat and reduction of wind shear. Owing to continuous radiative cooling of the underlying surface, turbulence subsequently weakens and even disappears again. Experimental studies have also found that internal interactions between stable stratification, turbulent mixing, and mean shear can trigger turbulent intermittency (Pardyjak et al., 2002; Fernando, 2003). This type of triggering mechanism is referred to as internal factor for the occurrence of turbulent intermittency (Allouche et al., 2022), and is likely periodic and gives rise to a feedback loop (Van der Linden et al., 2020). The periodic characteristics of turbulence intermittency can be reproduced in large-eddy simulations and non-linear bulk models (Van de Wiel et al., 2002; Costa et al., 2011; Zhou and Chow, 2014; Van der Linden et al., 2020).

Turbulence intermittency can also be triggered by other atmospheric processes, such as low-level jets (LLJ) (Banta et al., 2007; Cuxart and Jim'enez, 2007). LLJ is an important process in the stable boundary layer, referring to a local wind-speed maximum typically observed at night within the lowest kilometer of the atmosphere when a stable boundary layer develops (Bonin et al., 2020). Blackadar (1957) described the LLJ as an inertial oscillation, Holton (1967) studied the oscillations resulting from the diurnal heating and cooling of a sloping surface, while Shapiro et al. (2016) combined both mechanisms to explain the observed LLJ over the Great Plains. In addition, gravity waves can also drive the occurrence of turbulence intermittency events (Cava et al., 2019a; Sun et al., 2015b). Wavelike motions are ubiquitous in the stable boundary layer (Belušić and Mahrt, 2012). Furthermore, Donda et al. (2015) conducted direct numerical simulations and discovered that by applying finite-amplitude disturbances to the laminar flow and allowing sufficient time for flow acceleration, turbulence will naturally resume. In real atmosphere, these disturbances are frequently observed, such as surface heterogeneity. More commonly, weak turbulence can be enhanced by several types of sub-mesoscale motions (Cava et al., 2017; Vercauteren et al., 2019; Stefanello et al., 2020). Sub-mesoscale motions are considered as external factors causing turbulence intermittency (Mahrt, 2010; Sun et al., 2015a).

Mahrt (2014) defined sub-mesoscale motions as "motions between the primary turbulent eddies and smallest mesoscale motions, traditionally specified as having a horizontal scale of 2 km.". Fig. 3a shows the spatial and temporal relationships between sub-mesoscale motions and turbulence. Few sub-mesoscale motions can be specifically named, whereas most of them are random disturbances in strongly stable boundary layers and can only be detected in collected data. Sub-mesoscale motions triggering turbulence intermittency have been noted in field observations include drainage flows (Hiscox et al., 2023), horizontal meandering (Mortarini et al., 2019), internal gravity waves (IGWs) (Sun et al., 2015a), and small-scale fronts (Mahrt, 2019). The definition of sub-mesoscale motions is relatively broad and overlaps with that of wave motions. Sun et al. (2015a) indicated that "the periodic motions generated by buoyancy forcing and shear instability are often known as waves." On the one hand, the difference between the two is that waves are periodic, whereas sub-mesoscale motions are not necessarily periodic. Conversely, both of them are non-stationary motions, and their scales are larger than that of turbulence but smaller than that of mesoscale motions. Fig. 3 (b-c) shows wave-like motions and horizontal meandering motions observed in field experiments.

There are often complex interactions between different atmospheric processes driven turbulence intermittency. Mortarini et al. (2018) found that the vertical turbulence structure during LLJ events can be divided into three layers: a very stable boundary layer at the lowest level, a quiescent layer near the LLJ peak, and a turbulent layer above. Gravity waves were found to form in the quiescent layer and propagate both upward and downward, triggering intermittent turbulent bursts outside the quiescent layer. Persistent horizontal meandering was detected throughout the observation area. This study suggests that the LLJ activates both horizontal meandering and gravity waves, and there is some interaction between these two sub-mesoscale motions. In the stable

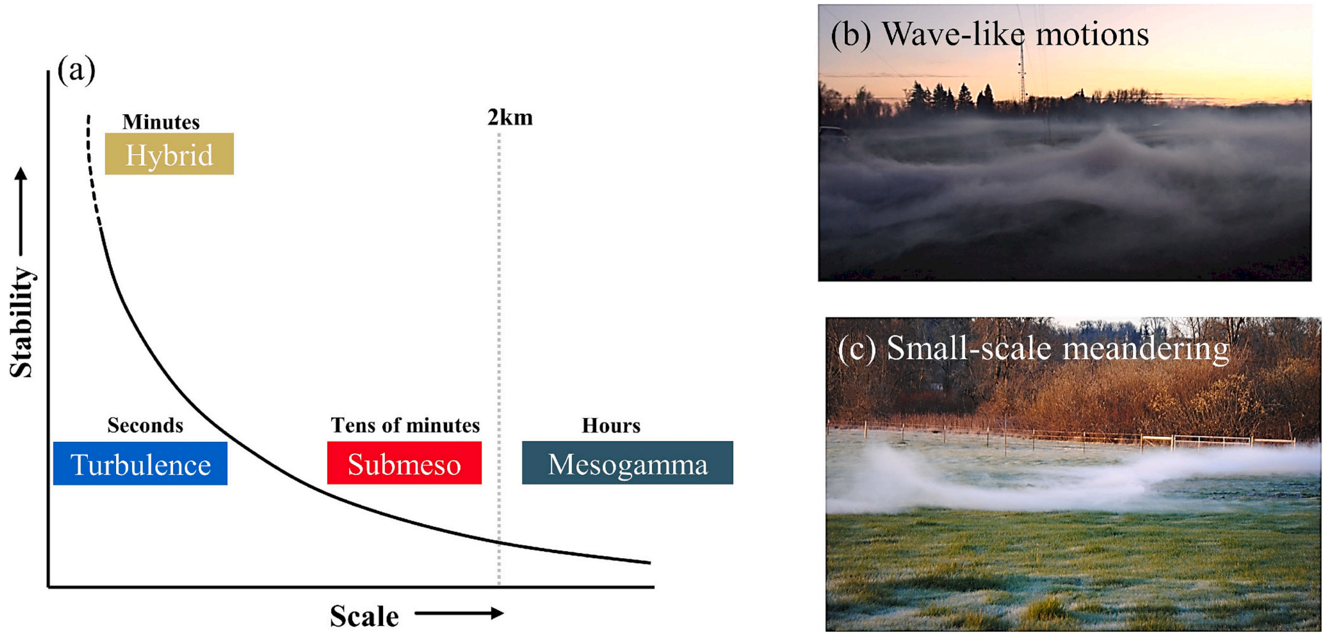


**Fig. 3.** (a) The relationship between the spatiotemporal scales of turbulent motion, hybrid motion, sub-mesoscale motion, and mesoscale motion and atmospheric stability. This figure is revised from Fig. 2 of Mahrt (2014). Wave-like motions (b) and small-scale meandering (c) motions observed in field experiments. These two pictures were cited from www.submeso.org.

boundary layer, where motions of various scales are intertwined, the vertical structure is highly localized. Ding et al. (2024) used near-surface eddy covariance observations and wind profiling radar to examine the turbulence structure evolution across the nocturnal stable boundary layer and found two distinct stable boundary layer evolution processes. The first situation represents a strongly stable boundary layer characterized by a lower-position, longer-duration, and stronger LLJ interacting with short-duration, stronger IGWs, where LLJ plays a dominant role, as shown in Fig. 4 a; whereas the second situation represents a weakly stable boundary layer characterized by a higher-position, shorter-duration, and weaker LLJ interacting with long-duration and weaker IGWs, where IGWs play a dominant role, as shown in Fig. 4 b. In a strongly stable boundary layer, turbulence energy accumulates in higher layers and, during downward transfer, generates local LLJ and IGWs, triggering intermittent turbulence events. That process conforms with the mechanism proposed by Businger (1973), which is the internal factors of turbulence intermittency contributing more. Immediately afterward, the interaction between LLJ and IGWs maintains intermittent turbulence burst near surface, accompanied by the conversion of sub-mesoscale motions energy to turbulent energy. That means the external factors also begin to play a role. The near-surface material and energy transport, as well as the turbulence intensity, were significantly enhanced during this process. The boundary layer transformed from a strongly stable state to a weakly stable state. In the vertical space, the strong turbulence intensity leads to uniform mixing of material and energy and reduces the mean field gradient, contributes to the lift of the LLJ. In the weakly stable boundary layer, driven by sub-mesoscale motion energy conversion (IGW wave energy breaking), an intermittent turbulence burst occurred at the near-surface. Simultaneously, possible energy exchanges between small- and large-scale IGWs occurred, with energy being exchanged between different scales of sub-mesoscale motions without fully transferring to turbulence scales. Thus, the burst intensity of this intermittent turbulence event was not as strong as that in the strongly stable case. Subsequently, the LLJ sustained this intermittent turbulence burst and reduced the stability of the near-surface region, potentially hindering the propagation of IGWs. Apparently, the external factors contributing more to turbulence intermittency events in the second situation.

The internal and external factors contributing to turbulence intermittency are often intertwined. In a strongly stable boundary layer, there are complex interactions among different sub-mesoscale motions (Cava et al., 2019b), along with nonlinear and nonstationary interactions between sub-mesoscale and turbulent motions. The flow field near the surface in a stable boundary layer is often a complex mix of motions of various scales (Mahrt, 2010). Therefore, in practical observations, it is challenging to detect the periodicity of turbulent intermittency events and to clarify the sources and physical mechanisms driving the intermittent bursts of turbulence. This also makes understanding and modeling stable boundary layers extremely difficult (Mahrt and Bou-Zeid, 2020; Schiavon et al., 2023).

### 3.2. *Identification and quantitative characterization of turbulence intermittency*

At present, turbulence intermittency research largely depends on station observations, and no general theory exists. One reason for this situation is that no unified quantitative characterization of turbulent intermittency exists. No consensus has been reached regarding the detection and quantitative description of turbulence intermittency events in different studies, leading to different or even contradictory research results. The most direct approach to characterize turbulence intermittency is to identify turbulence intermittency intervals in fluctuation time series. Unfortunately, no well-defined threshold has been established, making this approach subjective (Sun et al., 2004; Ohya et al., 2008). In some studies, a turbulent flux threshold is set for the bursting period to distinguish turbulence intermittency events (Nappo, 1991). For example, the threshold value given by Katul et al. (1994) was $Hc = 3.8\langle\overline{w'\theta'}\rangle$, which is 3.8 times the average heat flux over the entire night. Katul et al. (1994) defined the intermittency factor $\gamma$ = number of $(\overline{w'\theta'} > Hc)/$ N, where N is the total number of heat fluxes. Using this kind of methods makes comparing different intermittency events challenging. Meanwhile, some studies have overcome this difficulty by characterizing the intermittency strength by dividing the turbulence duration by the total sampling time (Doran, 2004; Drüe and Heinemann, 2007). For example, Doran (2004) chose $-0.015$ K m $s^{-1}$ as the threshold for intermittent events and used turbulent event fraction

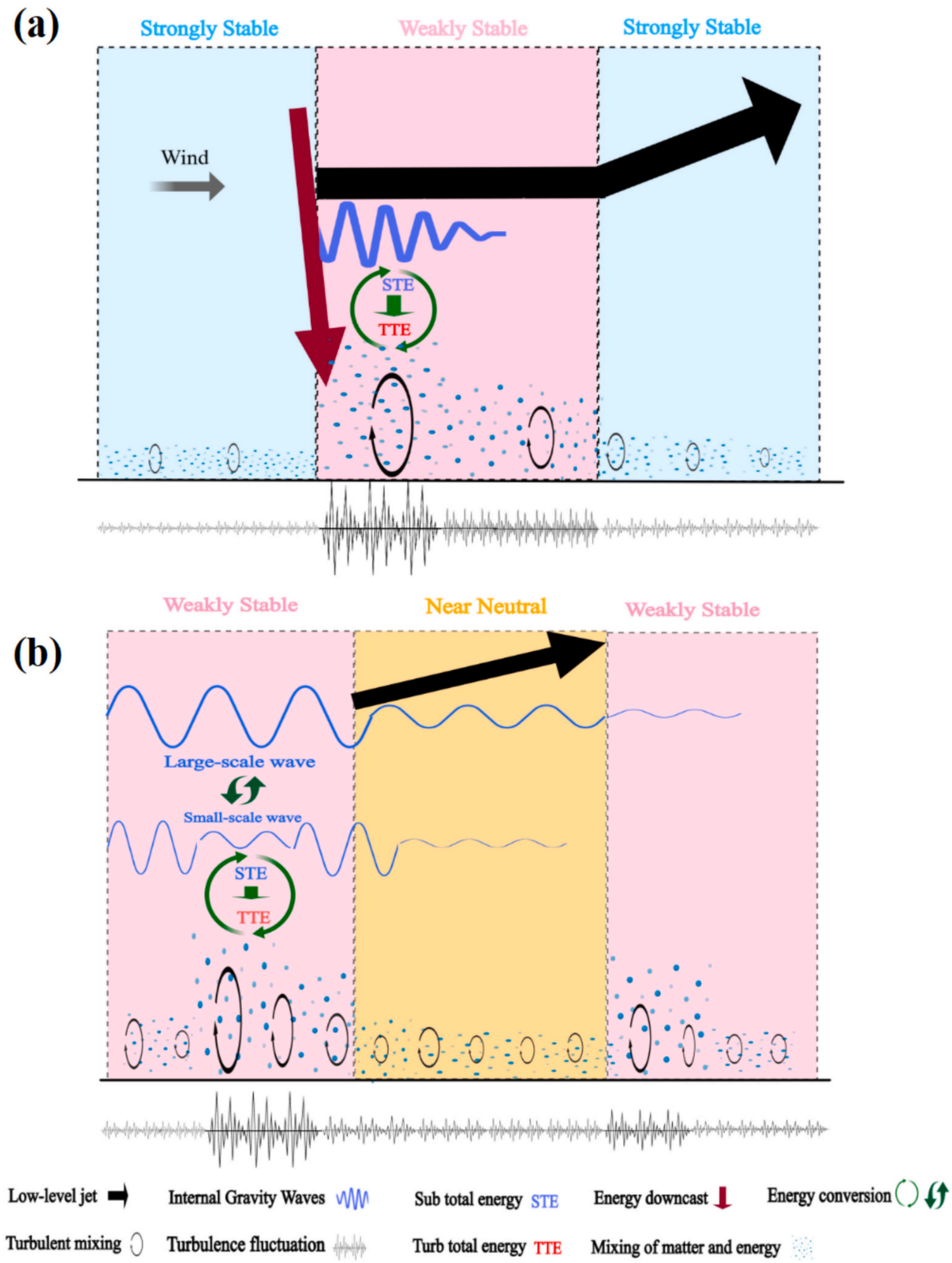


**Fig. 4.** Schematic representation of the mechanism of the effect of the interactions between low-level jets (LLJ) and internal gravity waves (IGWs) on the boundary layer turbulent structure: (a) case with a lower-positioned, long-duration, stronger LLJ interacting with short-duration, stronger IGWs; (b) case with a higher-positioned, short-duration, weaker LLJ interacting with longer-duration, weaker IGWs. (Cited from Ding et al., 2024).

characterizing turbulent intermittency intensity as $f_{turb}$, which represents the turbulence event maintenance time divided by total sampling time. However, threshold determination is still subjective. In addition to the time ratio, the flux ratio is also used to identify turbulence intermittency (Howell and Sun, 1999). For example, Coulter and Doran (2002) used all heat flux data during the 12-h period from sunset to sunrise to determine intermittency events. The individual 1-min fluxes that occupy 50 % of the total night-time integrated flux were considered turbulent intermittency events. Intermittency fraction (IF) was the percentage of time required to reach 50 % of the total flux. Another approach to determine the intermittency strength is by measuring the degree to which different statistical parameters of turbulence deviate from their average or normal-state values, such as the intermittency factor defined by Mahrt (1998), the intermittent index proposed by Wei et al. (2018), and two parameters (Iweak and CVe) given by Allouche et al. (2022). Specifically, Mahrt (1998) defined the flux intermittency factor, FI $= \sigma_F/\text{abs}[F]$, where $\sigma_F$ is the standard deviation of the flux value per 5 min over 1 h and abs[F] is the mean value of the absolute flux value over 1 h. Mahrt (2010a) is in line with Mahrt (1998), both of which highlight the ratio of extreme values to mean values. The methods mentioned above are all based on the manifestations of turbulence intermittency events, which often involve subjectivity and are limited by locality, making it difficult to compare different observation stations. Salmond (2005) believed that once the identification criteria for turbulence signals and sub-mesoscale motions are established, turbulence intermittency can be defined based on the intensity of turbulent and non-turbulent flows in fluctuation signals. To achieve this, turbulent and sub-mesoscale motions must be distinguished as objectively and reasonably as possible.

Separation of motions of different scales is a classical problem in atmospheric scientific research. Currently, the understanding of atmospheric turbulence heavily relies on Reynolds averaging, which is, in turn, dependent on the spectral gaps between turbulent and non-turbulent motions. In particular, considering turbulence in stable boundary layers, accuracy regarding the separation of motions of different scales directly affects the understanding of the turbulence process and may also lead to contradictory conclusions for problems related to stable boundary layers (Hong et al., 2010). Existing methods to separate atmospheric turbulence and sub-mesoscale motions can be classified into two categories. In one type of method, the specific forms of sub-mesoscale motions are considered, aiming to separate certain types of sub-mesoscale motions with prominent characteristics (Román-Cascón et al., 2015; Deb Burman et al., 2018). However, the mid-latitude atmospheric boundary layer is often filled with many different sub-mesoscale motions (Van der Linden et al., 2020; Allouche et al., 2022). A rare exception is when certain types of sub-mesoscale motions absolutely dominate. The other type of method does not focus on the specific forms of sub-mesoscale motions but on their statistical characteristics under specific conditions (Vickers and Mahrt, 2006; Durden, 2013; Vercauteren et al., 2019). In particular, multiresolution decomposition (MRD) is the most widely used method of this type. MRD, based on wavelet transforms, determines the average time window required for the calculation of statistical parameters of turbulence by examining the spectral gaps between turbulent and sub-mesoscale motions (Vickers and Mahrt, 2006). Although wavelet analysis offers higher resolution in both the time and frequency domains compared to Fourier transforms, in practical applications, it is only suitable for stationary nonlinear signals, and the signals within its window still cannot escape the requirements of linearity and stationarity (Hong et al., 2010; Wei et al., 2016). In addition to conventional mathematical analysis, Wei et al. (2016) introduced the Hilbert-Huang transform into atmospheric turbulence data analysis, whereas Ren et al. (2019a) developed an algorithm based on the Hilbert-Huang transform to separate and reconstruct sub-mesoscale and turbulent motions (SMT). The proposed algorithm looks for spectral gaps between large- (weather-scale) and small-scale (turbulence-scale) motions from the Hilbert spectra of observational data, based on which the algorithm subsequently reconstructs the turbulent motion series. Ren et al. (2023b) improved SMT algorithm from the perspective of dynamical spectral gap identification, thereby enhancing the accuracy of the identification of spectral gaps in turbulent fluctuation signals, as shown in Fig. 5. SMT can help process high-frequency pulsation data, any turbulent variable can be separated into two part, that is, $s' = s'_{turb} + s'_{sub}$, represent turbulent motion and sub-mesoscale motions respectively. Notably, although distinct spectral gaps have been detected in energy spectra of turbulence quantities in many studies with the help of different mathematical tools (Muschinski et al., 2004; Wei et al., 2013), Mahrt (2014) believed that some turbulent and sub-mesoscale motions in the stable boundary layers are of similar scales, and this leads to a certain degree of confusion when two types of motions are distinguished based on spectral gaps.

After the successful quantitative characterization of sub-mesoscale motions, some studies have utilized the ratios of turbulence and sub-mesoscale motions in the collected signals to represent the turbulence intermittency strength. For example, Acevedo and Fitzjarrald (2014)

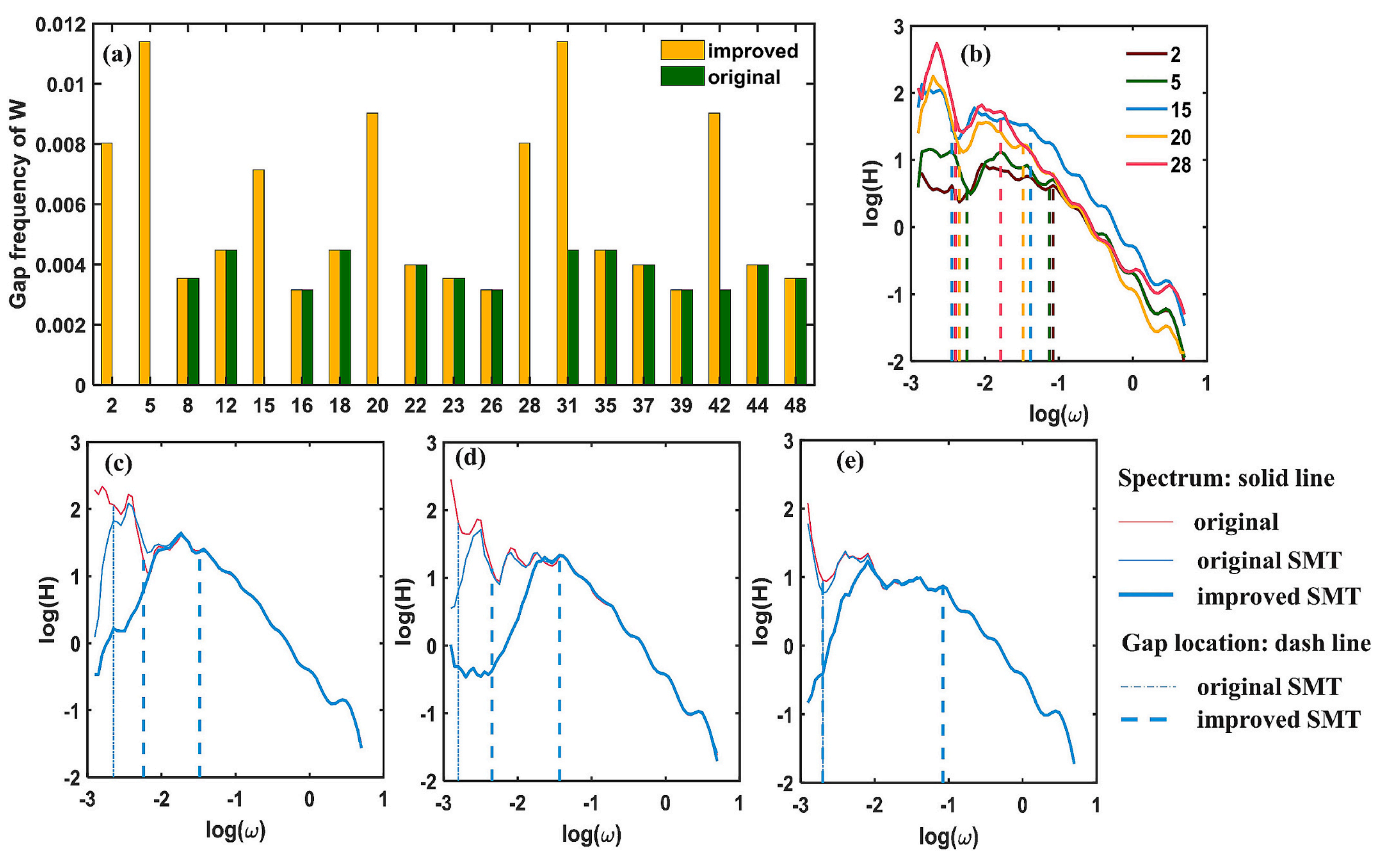


**Fig. 5.** The gap frequency of vertical wind speeds determined by improved (yellow) and original (green) SMT (a). The spectra of five groups of data (b). The original and reconstructed spectra of these two data sets: 31 (c) and 42 (d). The original and reconstructed spectra of a case with same gap frequency in both methods (d). The solid pink line represents the spectrum of the original data. The bold blue line represents the reconstructed spectrum of improved SMT. The thin blue line represents he reconstructed spectrum of original SMT. The dotted line marks the location of the spectral gap. (Cited from Ren et al., 2023b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

proposed the index $R_{sm} = e_{sm}/\sigma_w^2$ to quantify the intensity of turbulent intermittency by using the MRD method, $e_{sm}$ is the MRD spectrum of the TKE corresponding to the fraction of submeso motion. With the help of SMT, two indices, namely, local intermittent strength of turbulence (LIST) and intermittency strength (IS), were proposed to quantitatively characterize turbulence intermittency from the perspectives of kinetic energy of turbulence and sub-mesoscale motions (Ren et al., 2019a, 2019b). That is,

$$LIST = \sqrt{TKE}\Big/\sqrt{TKE + SKE} \tag{1}$$

$$IS = \sqrt{SKE}\Big/\sqrt{TKE} \tag{2}$$

SKE is the kinetic energy of sub-mesoscale motions, that is $SKE = \frac{1}{2}\left(\overline{u_{sub}'^2} + \overline{v_{sub}'^2} + \overline{w_{sub}'^2}\right)$. TKE is the turbulent kinetic energy, that is $TKE = \frac{1}{2}\left(\overline{u_{turb}'^2} + \overline{v_{turb}'^2} + \overline{w_{turb}'^2}\right)$. Furthermore, Ren et al. (2023b) revised LIST and IS by including heat fluctuation intermittency from the perspective of potential energy. The total energy intermittency can thus be obtained. The revised LIST and IS show as follows,

$$\mathrm{LIST} = C_{KE}LIST_{KE} + C_{PE}\mathrm{LIST}_{PE} \tag{3}$$

$$\mathrm{IS} = C_{KE}IS_{KE} + C_{PE}IS_{PE} \tag{4}$$

$LIST_{KE}$ and $IS_{KE}$ are calculated by Eqs. (1) and (2), which are the original *LIST* and *IS* defined only from the perspectives of kinetic energy. $LIST_{PE}$ and $IS_{PE}$ are defined from the perspective of potential energy, which are,

$$LIST_{PE} = \sqrt{|TPE|}\Big/\sqrt{|TPE| + |SPE|} \tag{5}$$

$$IS_{PE} = \sqrt{|SPE|}\Big/\sqrt{|TPE|} \tag{6}$$

SPE is the potential energy of sub-mesoscale motions, that is $SPE = \frac{1}{2}(g/T_0N)^2\overline{\theta_{sub}'^2}$. TPE is the potential energy of turbulence, that is $TPE = \frac{1}{2}(g/T_0N)^2\overline{\theta_{turb}'^2}$. The contributions of $LIST_{KE}$ ($IS_{KE}$) and $LIST_{PE}$ ($IS_{PE}$) to *LIST* (*IS*) are expressed as coefficients, $C_{KE}$ and $C_{PE}$. $C_{KE}$ and $C_{PE}$ are the contribution ratios of kinetic energy and potential energy to the total energy,

$$C_{KE} = \frac{TKE}{TKE + |TPE|} \tag{7}$$

$$C_{PE} = \frac{|TPE|}{TKE + |TPE|} \tag{8}$$

LIST and IS characterize the relative strength of turbulent and sub-mesoscale motions. Based on the previous understanding of turbulent intermittency, sub-mesoscale motions drives turbulent intermittency events, and changes in LIST and IS can characterize turbulent intermittency events. When LIST (IS) decreases (increases) or maintains a small (large) value, it means there is a strong influence of sub-mesoscale motions on weak turbulence, which may correspond to the period with weak fluctuation or even laminar flow in turbulent intermittency events (term as quiescent period). Alternatively, when LIST(IS) is maintained close to 1 (small value), this indicates that there is a very weak or even no influence of sub-mesoscale motions, which corresponds to pure turbulence. Between these two states, when LIST (IS) increases (decreases), this indicates a transition between weak turbulence and pure turbulence, which may correspond to transient turbulent bursts in turbulent intermittency events (term as burst period). The entire process of decreasing (increasing) and increasing (decreasing) LIST (IS) to close to 1 (maintaining very small values) corresponds to the occurrence of a complete turbulent intermittency event.

Six methods and indices from various perspectives were selected to compare. Fig. 6 shows the performance of each method for a turbulence intermittency case and a fully turbulent case, including $\gamma$ in Katul et al. (1994), $f_{turb}$ in Doran (2004), IF in Coulter and Doran (2002), FI in Mahrt (1998), $R_{sm}$ in Acevedo and Fitzjarrald (2014) and LIST, IS in Ren et al. (2023b). Different methods and indices show consistency in turbulent intermittency case and fully turbulent case. Furthermore, the new indices (LIST and IS) can detect turbulence intermittency events and describe their characteristics, quiescent and burst periods as the Iweak (which measures turbulence intensity expressed as the first quartile of 10-s box-averaged TKE, characterizing the weakest turbulence sub-periods) and CVe (which measures the standard deviation of TKE and captures the variability in turbulence activity within the period) given by Allouche et al. (2022). As the definitions show, these two indices have slightly different physical meanings, LIST emphasizes the turbulence component in the collected signal, while IS emphasizes the sub-mesoscale motion component. In practical research, one can be chosen based on the specific focus of the study. LIST and IS can also be applied to analyze the energy-driven mechanisms involved. The SMT method and LIST (IS) index have been applied to quantitative turbulence intermittency studies with different types of underlying surfaces, including homogeneous surfaces (Ren et al., 2023b), arid complex regions (Wei et al., 2021; Chang et al., 2024), desert hinterland (Zhang et al., 2024), polar regions (Liu et al., 2023), and urban areas (Ren et al., 2019c; Ju et al., 2022; Zhang et al., 2022).

### 3.3. Influence and application of turbulence intermittency

The basic characteristics of turbulence intermittency events observed by single stations are relatively well-investigated. During a turbulent intermittency event, there is an alternating occurrence of long quiescent periods (weak turbulence fluctuations and turbulent transport of matter and energy) and short burst periods (violent fluctuations and turbulent transport of matter and energy). The conversion of energy from sub-mesoscale motion to turbulent motion drives the transition from a quiescent phase to a burst phase, accompanied by a decrease in atmospheric stability. On a completely intermittent night, the burst period undertakes most of the material and energy transport, and the transport capacity can be comparable to that of a completely turbulent night (Ren et al., 2023b; Chang et al., 2024). However, at present, only few studies have been conducted on the spatial and temporal evolution characteristics of turbulence intermittency events. Nakamura and Mahrt (2005) conducted an observation experiment with a dense network centered on a main meteorological tower with six surrounding meteorological towers to monitor turbulence intermittency events. They found that: the stronger the average turbulence intensity, the fewer the quiescent periods and turbulence intermittency events; most turbulence intermittency events had small horizontal scales, with a low frequency of simultaneous turbulence intermittency events occurring within the 100 m and 300 m range; the vertical scale of turbulence intermittency events was also small. The spatial and temporal evolution of turbulence intermittency directly affects the transport characteristics of matter and energy in the region, thereby impacting the applicability of the similarity theory and turbulence parameterization scheme based on this theory. Therefore, conducting experiments with intensive observations is crucial.

The characteristics of turbulence intermittency events will affect all practical problems involving turbulent transport. When weak turbulence dominates or during quiescent periods, the presence of sub-mesoscale motions leads to the overestimation of turbulent fluxes and "contamination" of statistical parameters of turbulence (Nappo et al., 2008). The degree of overestimation varies in studies (Durden, 2013; Cava et al., 2017; Stefanello et al., 2020), probably because different standards are adopted to characterize sub-mesoscale motions or owing to different effects of underlying surfaces and weather conditions on sub-mesoscale motions. Ren et al. (2019a) studied a continuous haze pollution process in Beijing, compared the original turbulence statistical parameters including sub-mesoscale motions with the pure turbulence

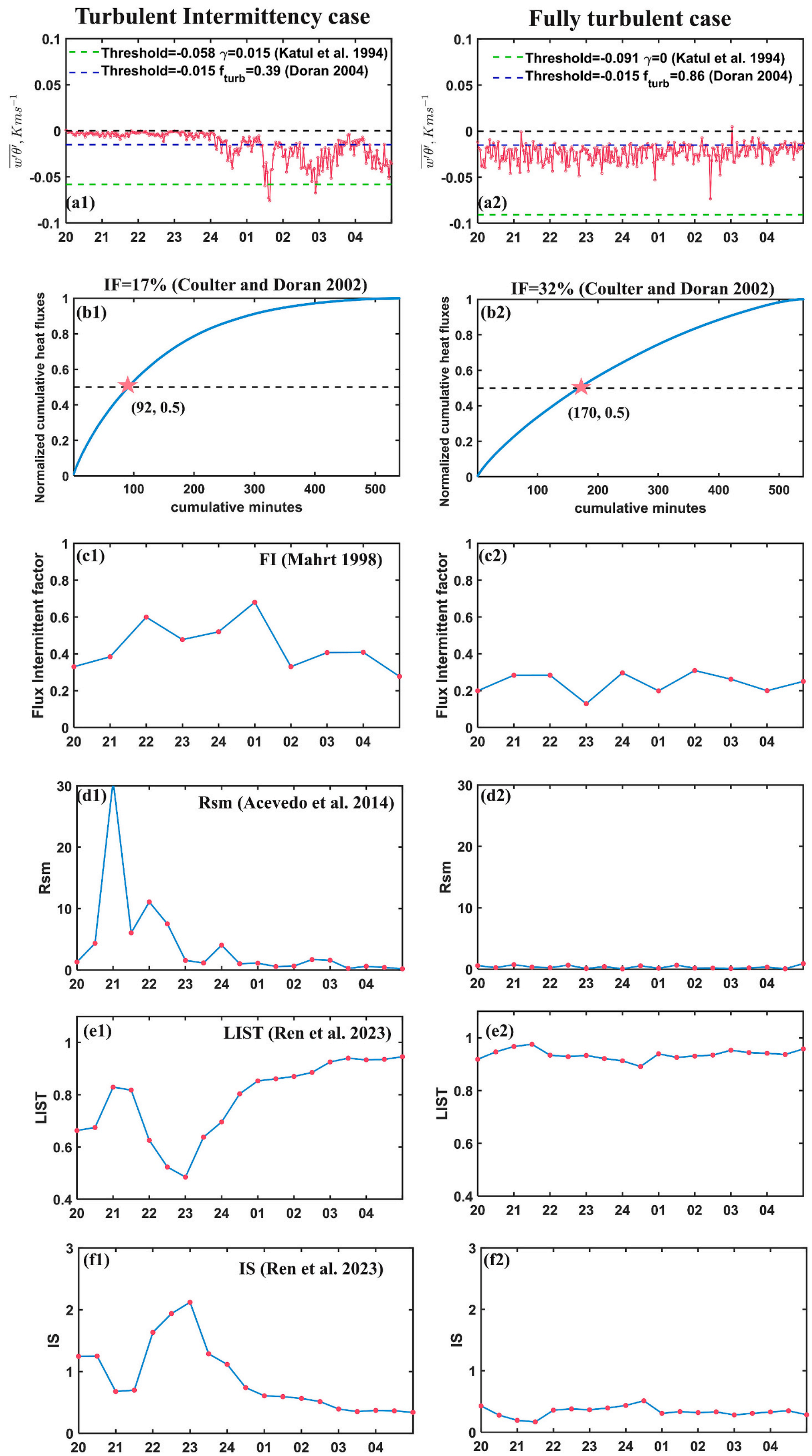


**Fig. 6.** Different indexes characterizing turbulence intermittency in turbulent intermittency case and fully turbulent case. (Reproduced from Ren et al., 2023b).

statistical parameters eliminating the effects of sub-mesoscale motions. As shown in Fig. 7, they found that the fitted slope parameter for TKE is 0.81 which means that the TKE originally calculated by the conventional method overestimated approximately 19 %. Similarly, this study also gave other correction parameters for specific turbulent statistical parameters in this haze pollution process, which are 27 % for $\sigma_u$(slope of 0.73), 21 % for $\sigma_v$(slope of 0.79) and 1 % for $\sigma_w$(slope of 0.99), 40 % for $\sigma_\theta$(slope of 0.60), 46 % for $\sigma_q$ (slope of 0.54), 12 % for $\overline{w'\theta'}$ (slope of 0.88), 15 % for $\overline{w'q'}$ (slope of 0.85) and 13 % for $-\overline{u'w'}$ (slope of 0.87). Some studies have reported that peak particulate matter concentrations observed in actual observations can rarely be captured in numerical simulations. The simulated mass concentrations of particulate matter increase and be similar to observed values only when turbulent diffusion parameters are forcibly reduced (Wang et al., 2018). This is possibly because existing models do not consider the overestimation of turbulent transport caused by turbulence intermittency and sub-mesoscale motions. The overestimation of near-surface turbulent transport implies that the exchange of matter and energy is overestimated, thereby leading to the overestimation of the boundary layer height and underestimation of the pollutant concentration.

Intermittent bursting of turbulence creates relatively substantial vertical turbulent transport in a short period of time, which is an important mechanism for transport of matter between the surface and atmosphere in the stable boundary layer (Hicks et al., 2015). The remarkable effects of turbulence intermittency on the estimation of carbon dioxide flux can even turn an ecosystem from a carbon sink to a carbon source (Acevedo et al., 2007). However, the turbulence transport during the turbulence intermittency burst process is often momentary and highly non-stationary, making it prone to being overlooked or smoothed out, which leads to an underestimation of the actual turbulence transport (Conangla et al., 2008; Vindel and Yagüe, 2011). Inaccurate estimation of turbulent transport during turbulence intermittency events directly affects the understanding of classical problems. For example, the surface energy balance is a key component of energy processes of the climate system. Chang et al. (2024) investigated the turbulence intermittency characteristics and impacts over a complex underlying surface, the Loess Plateau, by using LIST and IS. They found that the energy balance ratios in different stages of a turbulence intermittency event vary significantly. As shown in Fig. 8 a1 and a2, the presence of sub-mesoscale motions contributed to energy closure, with an energy closure of 86 % during daytime and 40 % during nighttime over the complex underlying surface of the Loess Plateau. The energy closure ratio become 78 % during daytime and 36 % during nighttime after eliminating the effects of sub-mesoscale motions. However, the results show that the energy closure during the burst period of turbulence intermittent events was approximately 98 % during daytime and 68 % during nighttime, approaching closure and far exceeding the overall closure rate at night, whereas the energy closure during the quiescent period was significantly low, at only 70 % during daytime and only 17 % during nighttime. This suggests that turbulence intermittency is a very important factor causing energy non-closure over complex underlying surfaces, especially in stable boundary layer during nighttime. Therefore, weak turbulent transport during the quiescent period and non-stationary strong turbulent transport during the bursting period must accurately be estimated and subsequently parameterized. This considerably affects the understanding of all problems involving turbulent transport and surface-air exchange. Nevertheless, the physical origins of intermittent turbulence bursting are complex. Current research can only separate and characterize sub-mesoscale motions from the complex flow field of the stable boundary layer as objectively and reasonably as possible, whereas no universal characteristics and patterns

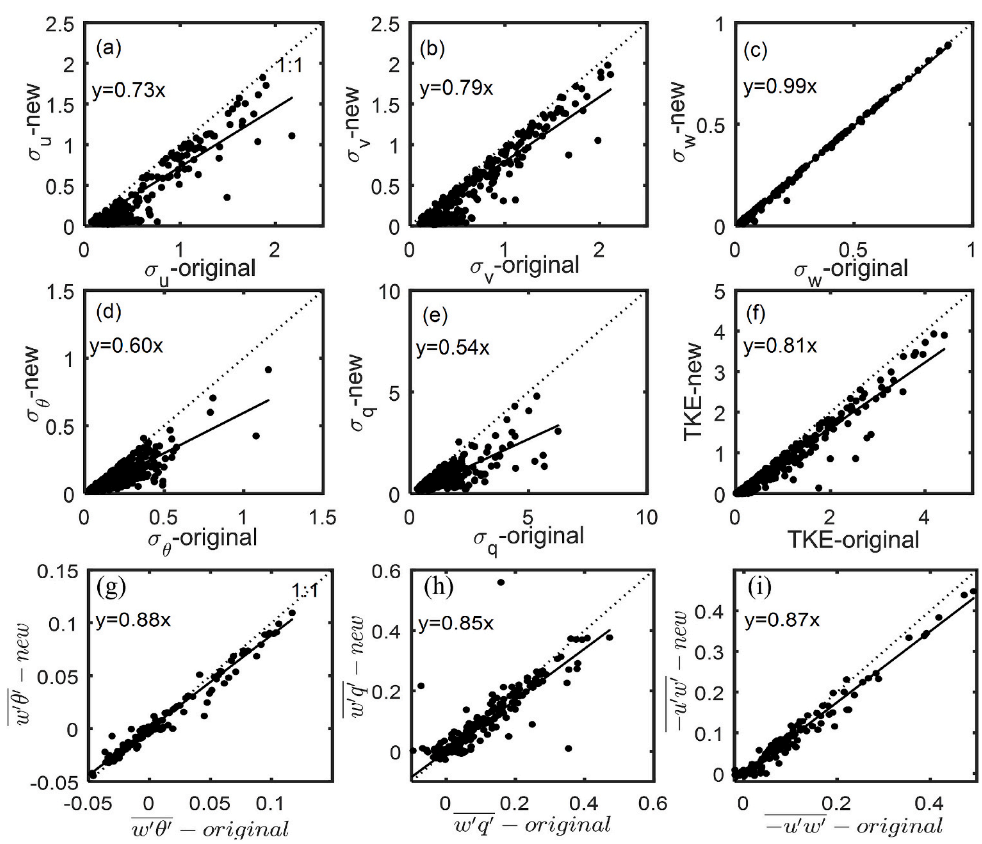


**Fig. 7.** Comparison of statistical parameters during a haze case from 16 December 2016 to 8 January 2017 in Beijing: $\sigma_u$ (a), $\sigma_v$ (b), $\sigma_w$ (c), $\sigma_\theta$ (d), $\sigma_q$ (e), $TKE$ (f), $\overline{w'\theta'}$ (g), $\overline{w'q'}$ (h), and $-\overline{u'w'}$ (i) calculated by turbulent part signal (y-axis) and original signal (x-axis). The black dotted line represents the 1:1 line in the figures. The black solid line represents the fitted results. (Reproduced from Ren et al., 2019a).

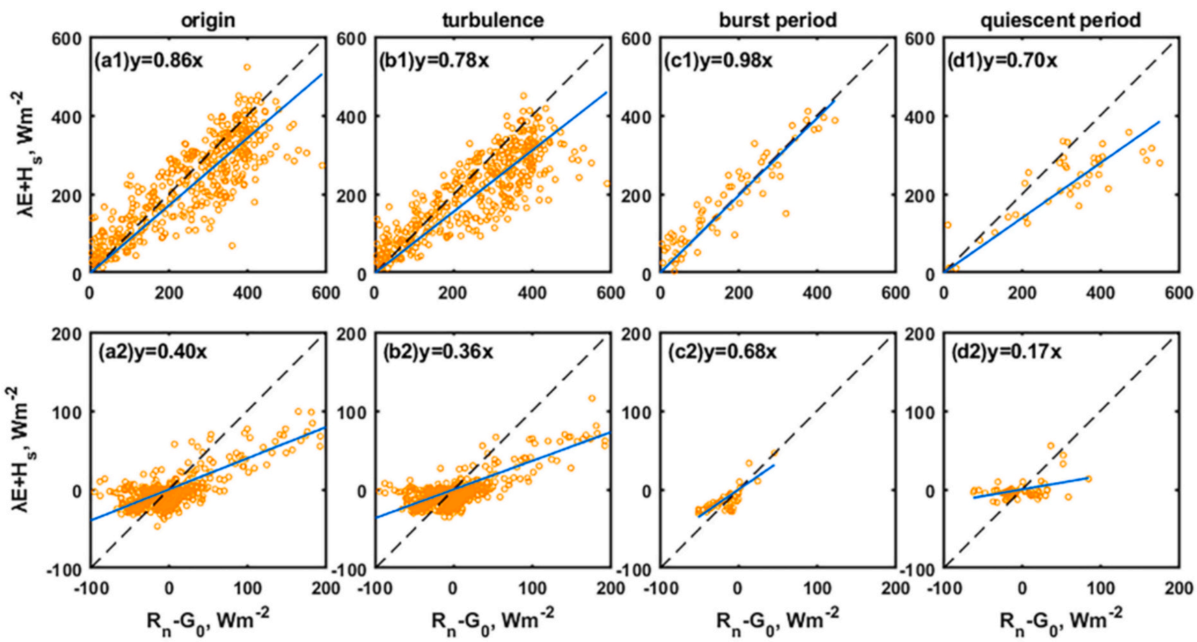


**Fig. 8.** Comparison of turbulent fluxes (λE + Hs) and effective energies (Rn − $G_0$) computed from the original data (a1), reconstructed turbulence data (b1), and data from the burst (c1) and quiescent(d1) periods of the intermittent turbulence event during daytime, respectively. Comparison of turbulent fluxes (λE + Hs) and effective energies (Rn − $G_0$) computed from the original data (a2), reconstructed turbulence data (b2), and data from the burst (c2) and quiescent(d2) periods of the intermittent turbulence event during nighttime, respectively. (Cited from Chang et al., 2024).

of these motions have been identified. Consequently, parameterizing the roles of these motions during turbulence intermittency is challenging. Boyko and Vercauteren (2023) introduced stochastic perturbation to include the stochastic mixing effects resulting from turbulence intermittency triggered by sub-mesoscale motions which is a prospective approach. However, the stochastic perturbation type of sub-mesoscale motions and the broader validity should be explored from more field experiments.

Moreover, turbulence intermittency plays important roles in practical problems related to the daily lives of people. The occurrence of haze

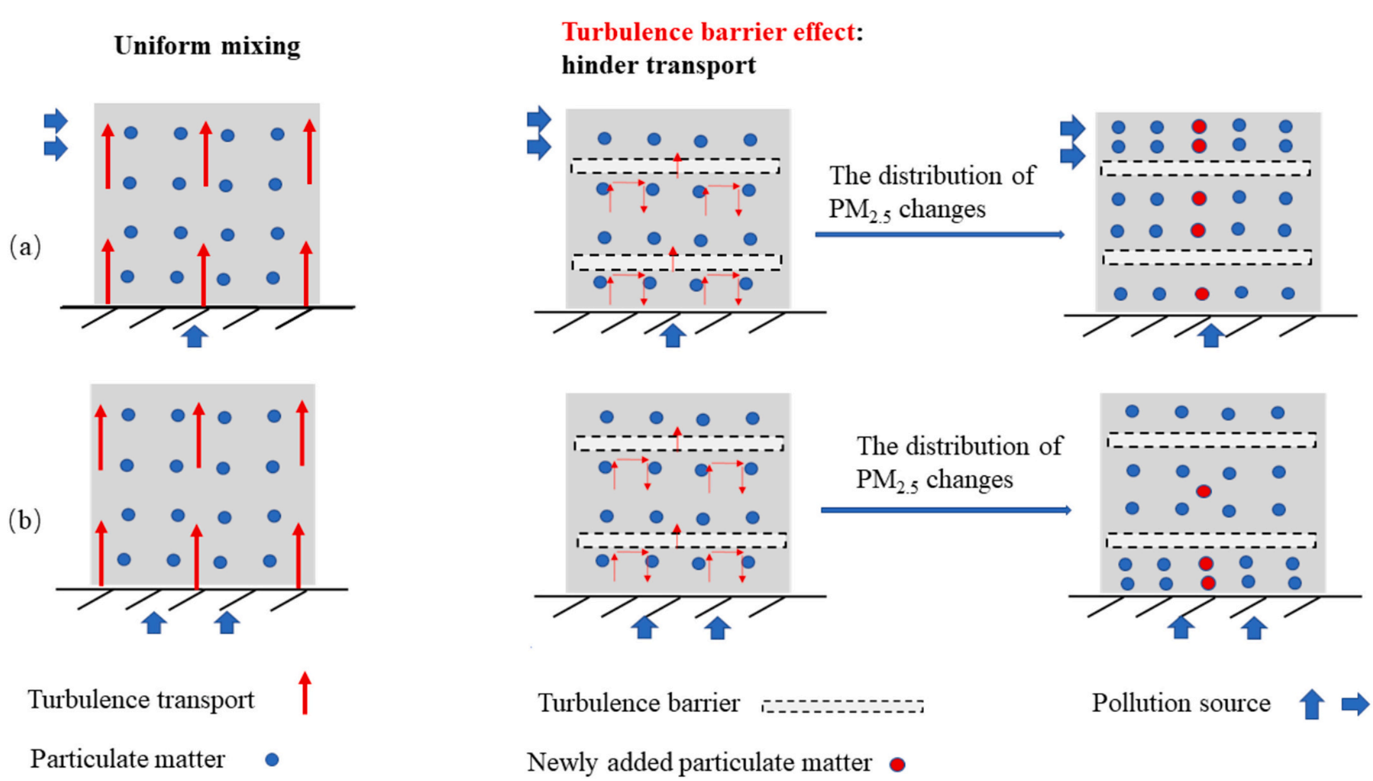


**Fig. 9.** Schematic of how the turbulence barrier effect hinders transport and is helpful for the accumulation of $PM_{2.5}$ in the surface layer. The first row shows the situation of relatively low emissions from ground sources and relatively high pollution at high altitudes from regional transport. The second row shows a simpler and more universal situation where only ground sources exist. (Cited from Ren et al., 2021a).

pollution is often accompanied by calm winds. Ren et al. (2019a) examined near-surface observations and discovered stronger turbulence intermittency during haze pollution but weaker intermittency in the absence of pollution. Thus, Ren et al. (2019b) compared the structures of turbulence in the stable boundary layers under light and heavy pollution conditions and found that turbulence intermittency was weaker under light pollution levels. Additionally, during pollution accumulation period under heavy pollution conditions, no vertical turbulence connection was observed between different heights, exhibiting strong intermittency. At this time, if sub-mesoscale motion disturbances occur at a certain height, driving intermittent bursts of turbulence, it will trigger a short-lived but intense turbulent exchange of pollutants. On this basis, Ren et al. (2021a) analyzed high-precision turbulence observations at five levels from 40 m to 200 m in the stable boundary layer during haze pollution. They found that the strength variations of turbulence intermittency at different heights remarkably affect the turbulent diffusion of pollutants in different spaces. Thus, the turbulence barrier effect was proposed: under calm wind conditions, turbulence intermittency is frequent, and turbulence at some heights becomes very weak or even disappears. Vertical turbulence connection between different heights no longer exists, and transport of matter is obstructed as if blocked by a barrier. Ideally, pollutants are evenly distributed by strong turbulent mixing, as shown in Fig. 9. However, when turbulence barriers are present, turbulent transport at different heights will be hindered. Owing to varied pollutant source distributions at different heights, vertical variations in the pollutant concentrations at different heights show significant differences. According to actual observations, the particulate matter concentration at 120 m decreases from 400 μg $m^{-3}$ to nearly 0 μg $m^{-3}$, while the particulate matter concentration of the surface remains as high as 200 μg $m^{-3}$. This is because of the obstruction by turbulence barriers below altitudes of 200 m. If a region is only dominated by local pollution sources, the presence of turbulence barriers will significantly inhibit the vertical transport of pollutants and dramatically increase the particulate matter concentration. There are some abnormal actual pollution cases, which has relatively high boundary layer height while with heavy load particulate matter concentration near surface. This might be caused by the presence of turbulence barriers in the lower atmosphere.

Due to the alternating occurrence of quiescent and burst periods of turbulent intermittency events, the turbulence barrier undergoes both strengthening and breaking processes. Ren et al. (2023c) identified three mechanisms driving the breakdown of turbulence barrier: Mechanism A, triggered when wind speeds abruptly exceed critical thresholds of strongly and weakly stable boundary layers, predominantly occurring in the lower boundary layer; Mechanism B, driven by sub-mesoscale motions under calm wind situations, can occur across all heights of the boundary layer, with the highest frequency of occurrence; Mechanism C, characterized by intermittent vertical propagation of turbulence, predominantly occurring in the upper boundary layer. For Mechanisms B and C, the breakdown of turbulence barrier typically involves the conversion of energy from sub-mesoscale motions to turbulent motions. The critical threshold for the breakdown of turbulence barriers can be characterized by the change in energy difference between the two. The characteristics of turbulence barrier enhancement and break, and possible breakpoint for different turbulence intermittency types were concluded in Fig. 10. In actual observations, Wei et al. (2022) found that the propagation of internal gravity waves triggered by terrain leads to both enhancement and break of turbulence barriers, corresponding to

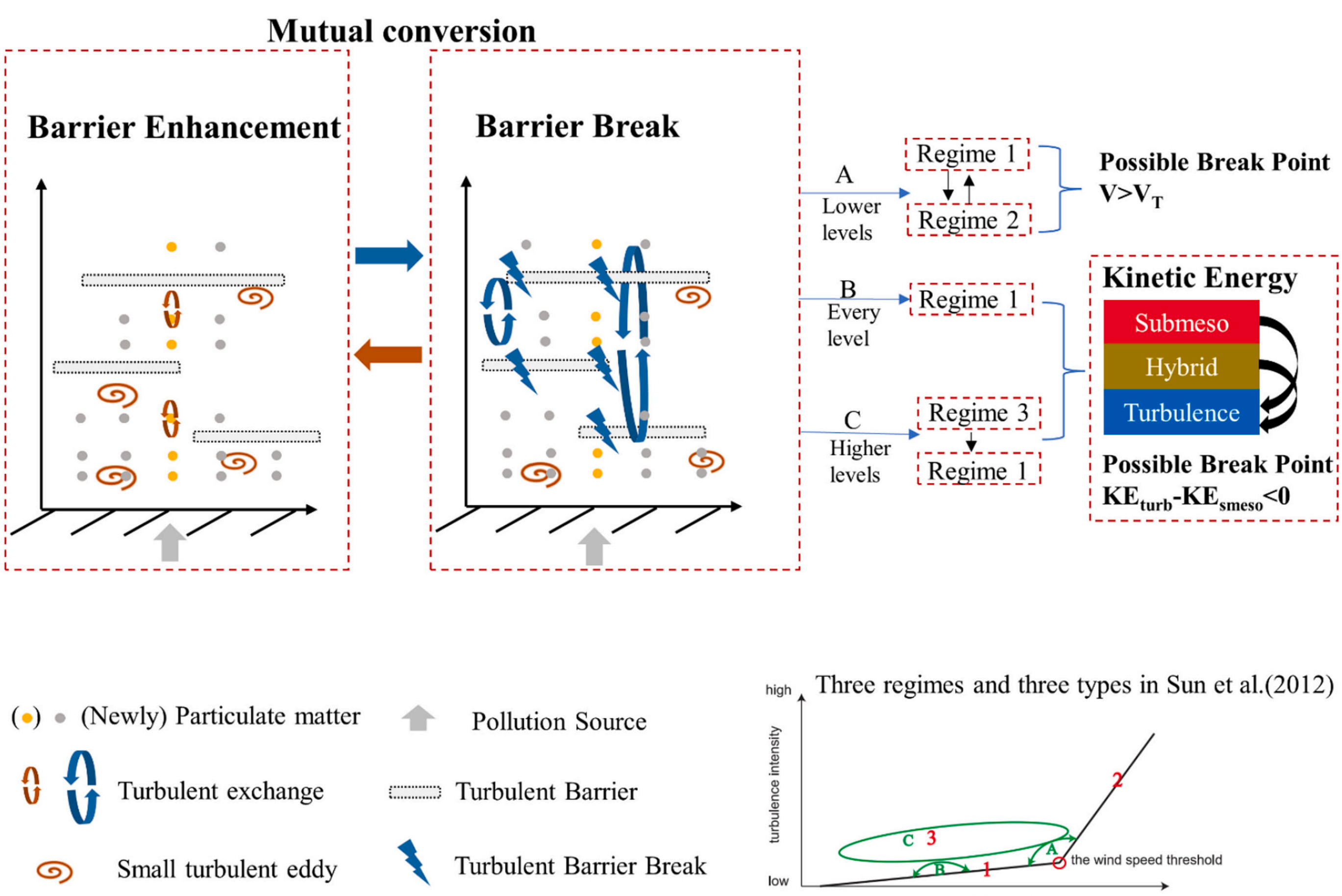


**Fig. 10.** Schematic of the characteristics of turbulence barrier enhancement and break, the energy transition and possible breakpoint for different turbulence intermittency types. (Cited from Ren et al., 2023c).

Mechanism C, as shown in Fig. 11.

However, owing to the randomness and non-stationarity of the enhancement and breakdown of turbulence barriers, the key roles of sub-mesoscale motions in this process have yet to be quantified. Thus, their effects on the transport of matter cannot be described using general theories. Additionally, as existing quantitative research on turbulent transport of particulate matter is still in its infancy (Ren et al., 2020; Ren et al., 2021b), we cannot rationally parameterize the turbulent barrier effect and subsequently incorporate it into air pollution prediction models to improve the forecasting of pollutant concentrations during heavy pollution events. Although the turbulence barrier effect has been proposed based on the processes of haze pollution, it actually affects the turbulent transport of any matter and energy. Ren et al. (2022) investigated the impact of turbulence barriers on turbulent transport of $CO_2$, while Ren et al. (2023c) discussed the influence of turbulence barriers on water vapor transport. As expected, the turbulence barrier effect substantial contributes not only to haze pollution but also to dust storms (Zhang et al., 2022), dense fog (Ju et al., 2022), and other weather events. However, existing studies on the characteristics and effects of turbulence intermittency have only focused on terrestrial surfaces, and studies on air-lake and air-sea interactions are scarce. In short, detailed investigation and parameterization of turbulence intermittency and sub-mesoscale motions are essential, and are the fundamental scientific issues in atmospheric environment, weather forecasting, and climate change research.

## 4. Similarity theory for the stable boundary layer

The applicability of the similarity theory is affected by turbulence intermittency and non-stationary sub-mesoscale motions in the stable boundary layer (Acevedo et al., 2016; Sorbjan, 2016, 2017). This impact arises from two aspects. First, sub-mesoscale motions cause the overestimation of turbulence statistical parameters, which influences the applicability of the similarity theory (Liang et al., 2014). Wei et al. (2021) examined the relationship between the normalized standard deviations of the three-dimensional wind speed, potential temperature, water vapor, and carbon dioxide with stability. They found that after eliminating the effects of sub-mesoscale motions and retaining pure turbulence signals, the similarity relationships were improved, as shown in Fig. 12. Similarly, after removing the influence of sub-mesoscale motions, Zhang et al. (2024) found that the proportions of counter-gradient transport in both the momentum flux and sensible heat flux significantly decreased, as shown in Fig. 13. This is mainly attributed to the non-stationarity of sub-mesoscale motions. When they are included in the calculation of turbulence statistical parameters, the statistical results vary rapidly with increasing time scales (Vickers and Mahrt, 2003). Including such highly variable values will affect the correlation between the turbulent flux and average profile, reducing the correlation between the turbulence characteristics and stability parameters of the strongly stable boundary layers (Mahrt, 2010). The similarity theory cannot reasonably describe the sudden short-lived strong turbulent transport during intermittent turbulence bursting. As the similarity theory represents information over a long average time, whereas intermittent turbulence bursting is abrupt and momentary, the associated turbulent transport is hardly reflected in the average profiles of physical quantities represented by the similarity theory. Therefore, the similarity theory does not apply under very stable conditions and is not valid during the occurrence of intermittency in the stable boundary layer. The similarity theory utilizes the main contributing terms in the turbulent kinetic energy budget equation (shear generation and buoyancy terms) to establish the stability parameter (Monin-Obukhov length). However, this is under the assumption that turbulence is continuous and stationary. When sub-mesoscale motions cause highly significant non-stationarity, other terms in the turbulent kinetic energy budget equation may also remarkably contribute to the turbulent kinetic energy (Wei et al., 2022). Hence, the physical implication of the stability parameter becomes ambiguous.

Although removing sub-mesoscale motion signals from the collected data can reduce the gap between the observations and similarity theory (Acevedo and Fitzjarrald, 2014; Liang et al., 2014; Wei et al., 2021), this approach is obviously inadequate as non-stationary turbulent transport during intermittent bursting of turbulence is an objective fact that should not be neglected. Intermittent bursting of turbulence can alter the stability state of atmospheric stratification and transform a strongly stable boundary layer to a weakly stable boundary layer (Oliveira et al., 2017). In the stable boundary layer, regional variability within a grid is significant; thus, a single stability parameter value cannot effectively reflect the level of stability of the entire grid (Mahrt, 1987). In the interim, when the average atmospheric stratification state of a grid in the numerical simulation exceeds the critical stability parameter value, some turbulent fluxes still exist in certain small areas of the grid (Acevedo and Fitzjarrald, 2003; Medeiros and Fitzjarrald, 2014). That is, in some localities, parts are still connected with the upper boundary layer, whereas others are not. Therefore, Mahrt (1987) and Delage (1997) suggested that under such conditions, some turbulent motions should be included in the boundary layer parameterization schemes of numerical mesoscale weather prediction models. Grisogono et al. (2020) examined the applicability of the momentum flux-profile relationship using measured data and proposed that a turbulent transport background value may be introduced into the similarity relation to represent the effects of sub-mesoscale motions and turbulence intermittency. However, this implies that such effects must first be clarified. According to other studies, completely different parameterization scales and different stability functions might be required to correct the similarity theory (Basu et al., 2006; Van Dop and Axelsen, 2007; Sandu et al., 2013). Nevertheless, owing to the complex influence mechanism of sub-mesoscale motions on turbulent transport, the associated formation of turbulence differs from conventional ones. Limited research progress has been made regarding the use of different characteristic scales (Sorbjan, 2017). Recently, our findings on intermittent turbulence may provide some insights for parameterizing turbulence intermittency in future studies. We have found that the intermittency indices LIST and IS show promising relationships with wind shear, horizontal wind speed, temperature gradient and Ri, as shown in Fig. 14 below. These promising relationships are confirmed by observations over flat (Ren et al., 2023a), complex (Chang et al., 2024), and urban terrains (Ren et al., 2023c). In summary, non-stationarity of turbulence intermittency and sub-mesoscale motions and their unconventional contributions to turbulent transport impose huge challenges to the applicability of the similarity theory of the stable boundary layer. This results in deviations in turbulent exchange calculations using model parameterization schemes and therefore, inaccurate modeling results (Sterk et al., 2016). Unfortunately, although the non-stationarity of sub-mesoscale motions and the intermittent turbulence process have remarkable effects on the applicability of the similarity theory, these effects have not been quantitatively described and reasonably parameterized in existing research (Acevedo and Fitzjarrald, 2014; Mahrt and Bou-Zeid, 2020).

## 5. Conclusions and prospects

The stable boundary layer has become a bottleneck restricting the advance of the atmospheric boundary layer theory and improvement of turbulence parameterization. Research on the stable boundary layer is not only a scientific challenge but is also an unavoidable practical problem in social and economic development. In this review, research and application progress of weak turbulence and turbulence intermittency in the stable boundary layer are briefly summarized. We discovered that in actual weather events, for example, during haze pollution, the occurrence frequency of strong stable boundary layers can account for more than 70 %, and weak turbulence and turbulence intermittency in these layers are inevitable problems. Turbulent intermittency events can be driven by internal (the feedback interaction of wind shear and

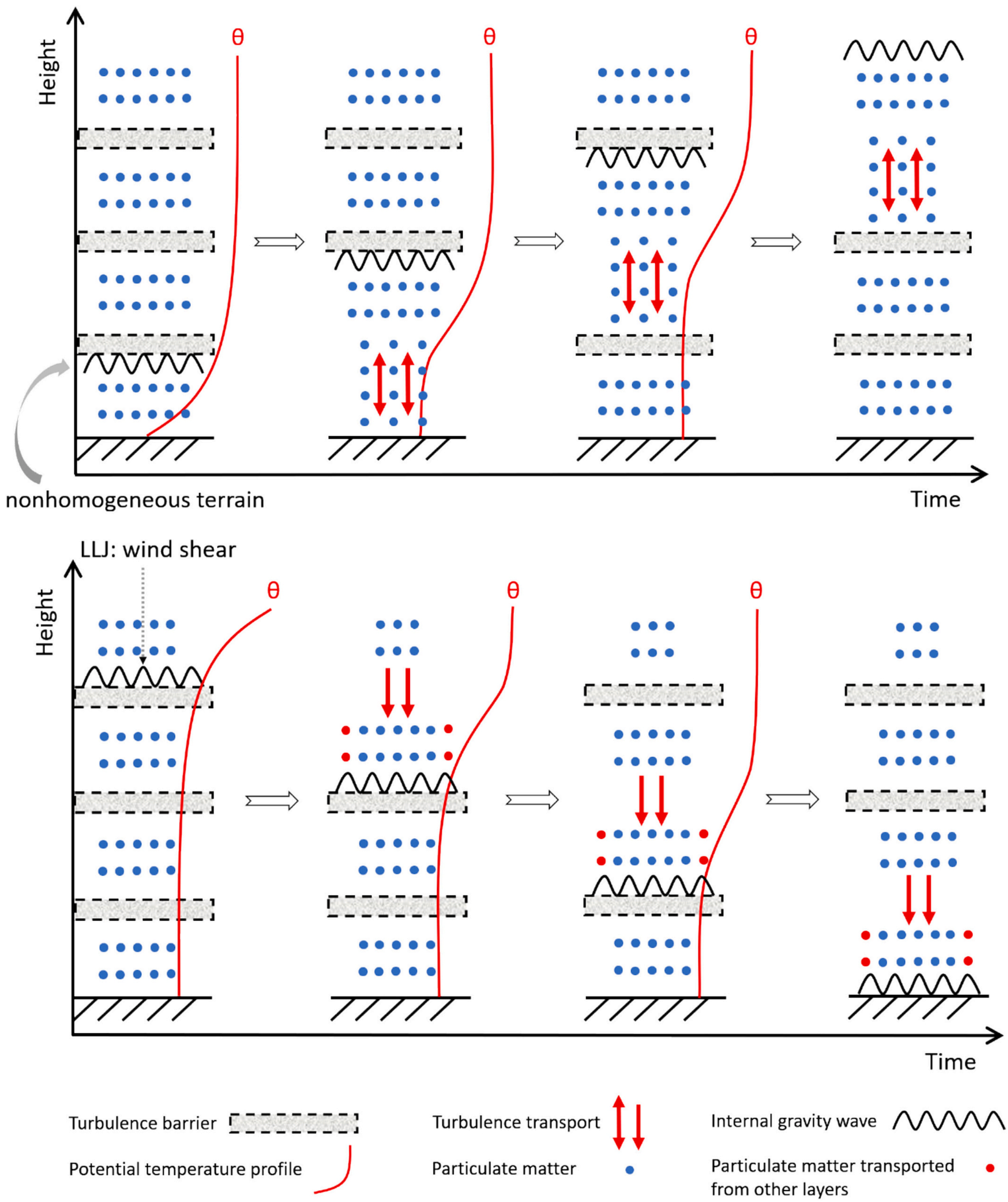


**Fig. 11.** Schematic of the destruction of turbulence barrier by vertically propagating IGWs and the resultant diffusion of pollutants during this process. The upper panel shows the situation when IGWs are generated by the nonhomogeneous terrain near the ground and propagate upward in the upward developing temperature inversion layer. The lower panel shows the situation when IGWs are generated by the wind shear around LLJ at the upper layers and propagate downward in the downward developing elevated temperature inversion layer. (Cited from Wei et al., 2022).

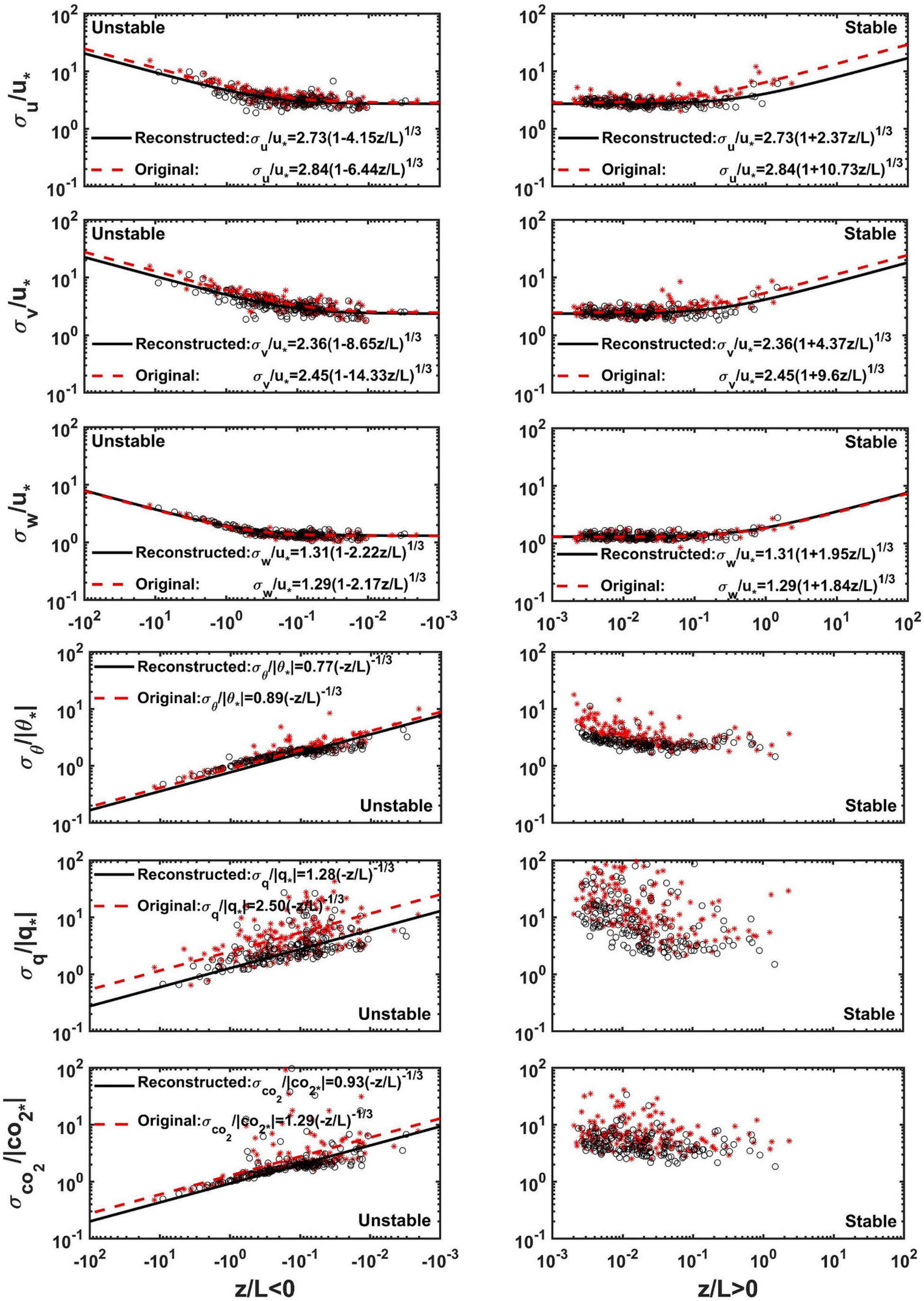


**Fig. 12.** Variation of the normalized standard deviations of the three-dimensional wind speeds ($\sigma_u/u_*$, $\sigma_v/u_*$, $\sigma_w/u_*$) and with the potential temperature ($\sigma_\theta/|\theta_*|$), moisture ($\sigma_q/|q_*|$), and CO2 ($\sigma_q/|q_*|$) stability parameter $z/L$. The observations marked with black hollow circles (red asterisks) are the reconstructed data (original data). The black solid (red dashed) lines in the figures represent the fitting results of the reconstructed data (original data). (Reproduced from Wei et al., 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stability) and external factors (sub-mesoscale motions). We clarified the interaction mechanism between the internal and external factors of turbulent intermittency and elucidated how the interaction affects the evolution of stable boundary layer. Based on the Hilbert-Huang transform, an algorithm was proposed to separate and reconstruct sub-mesoscale and turbulent motions which was named as SMT. Subsequently, improvements have been made to enhance the accuracy in reconstructing these motions. Based on the quantitative characteristics of sub-mesoscale motions, LIST and IS, parameters to identify and quantitatively characterize turbulence intermittency have been proposed to reveal its fundamental characteristics. The physical mechanisms through which interactions between various sub-mesoscale motions drive the occurrence of turbulence intermittency events have been analyzed. Additionally, the structural evolution mechanism of turbulence in the stable boundary layer in this process has been examined. Owing to the typical characteristics of alternating quiescent and bursting periods of turbulence intermittency events, the overestimation of turbulent transport of matter and energy caused by sub-mesoscale motions during weak turbulence and quiescent periods is quantitatively corrected. The significant effects of turbulent transport characteristics in different stages of turbulence intermittency events on the surface energy balance ratio have been elucidated. Moreover,

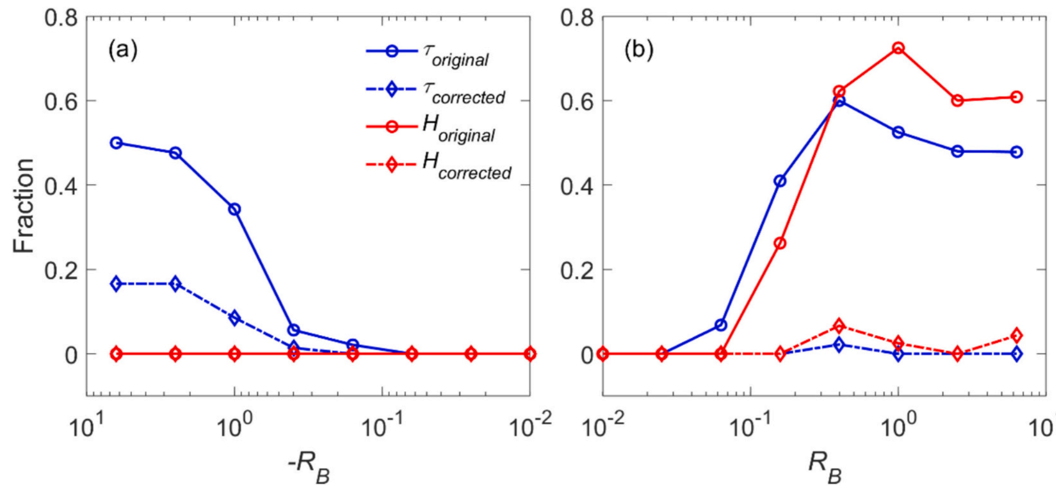


**Fig. 13.** Time fraction of counter-gradient momentum flux (blue) and sensible heat flux (red) as a function of bulk Richardson number. The solid and dashed lines represent original and corrected fluxes, respectively. (Cited from Zhang et al., 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

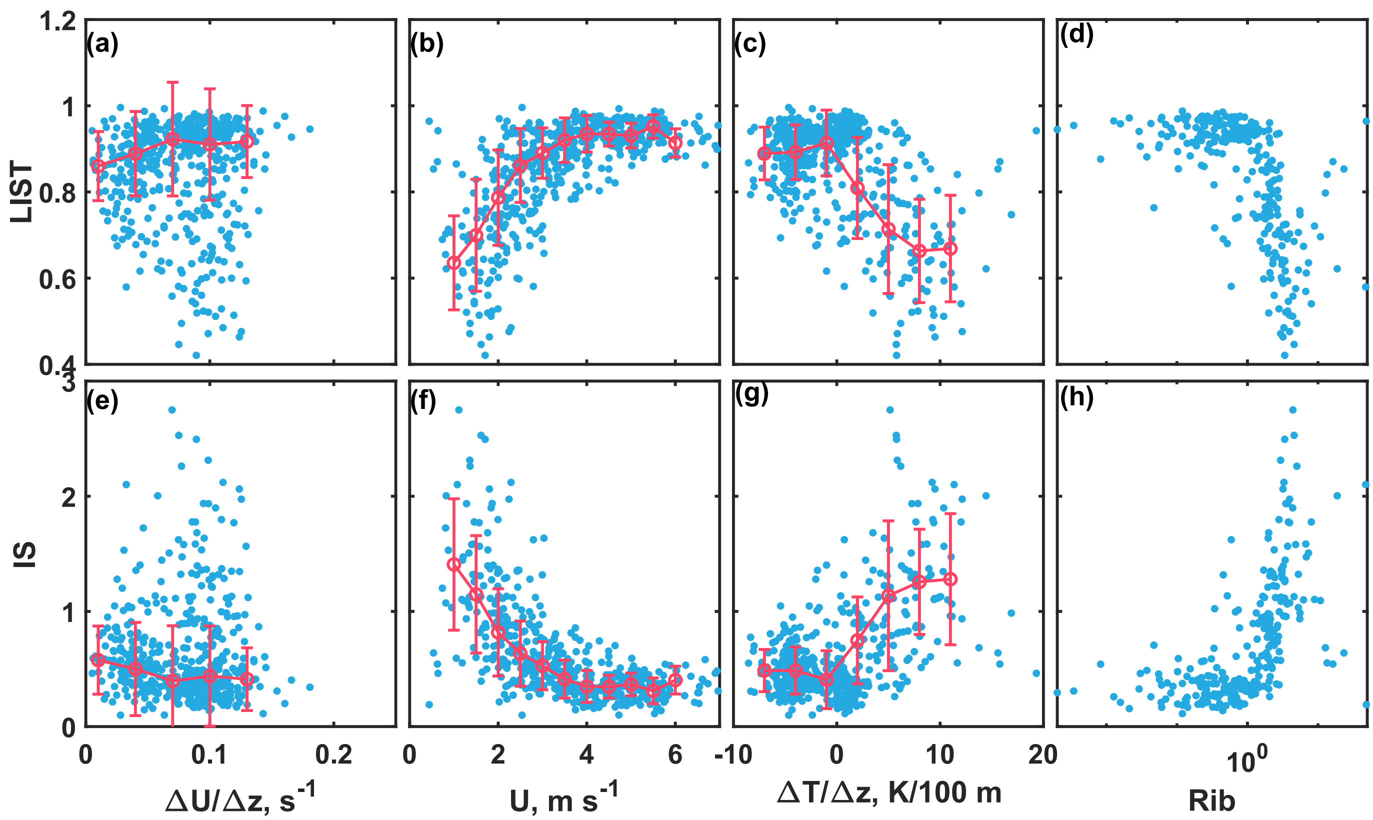


**Fig. 14.** Scatter of LIST and wind shear $\Delta U/\Delta z$ (a), horizontal wind speed U (b), temperature gradient $\Delta T/\Delta z$ (c), and Ri (d). Scatter of IS and wind shear $\Delta U/\Delta z$ (e), horizontal wind speed U (f), temperature gradient $\Delta T/\Delta z$ (g), and Ri (h). The gray lines indicate the median and standard deviation of these parameters. (Cited from Ren et al., 2023a).

combining practical issues of haze pollution, the turbulence barrier effect was proposed. The physical mechanisms through which this effect can be enhanced and broken were investigated, and the energy conversion between sub-mesoscale and turbulent motions was determined. The turbulence barrier effect can provide atmospheric physical reasons to explain why existing air pollution prediction models can hardly capture the peak pollutant concentrations and the observed mismatch between the boundary layer height and pollutant concentration. Additionally, this effect reveals the contributions of turbulence to the dramatic increase and vertical variation of particulate matter concentrations. Furthermore, the impacts of the turbulence barrier effect on turbulent transport of matter, such as carbon dioxide and water vapor, are analyzed. This effect is also applied to other practical issues, such as dust storms and dense fog events. Finally, we improved the stable boundary layer similarity relationship by removing the influence of sub mesoscale motion.

Although worthwhile research results have been achieved regarding weak turbulence and turbulence intermittency in the stable boundary layer in terms of the methods, physical mechanisms, theories, and applications, the following three challenges in the stable boundary layer require further investigation:

1. Physical mechanisms of state transitions and evolution mechanisms of the vertical structure of the stable boundary layer.
2. Physical origins, temporal and spatial evolution patterns, and parameterization of turbulence intermittency.
3. Improvement of the similarity theory of the stable boundary layer.

Notably, these research challenges are interrelated, and their core is weak turbulence and turbulence intermittency. These two topics involve the physical nature of generation and dissipation of turbulent motions, and they are century-old problems in classical physics. Additionally, both the physical origins and temporal and spatial evolution patterns of turbulence intermittency and the improvement of the similarity theory are closely related to the substantial contributions of sub-mesoscale motions. Therefore, these three challenges implicitly contain important scientific questions regarding the quantitative characterization, universal patterns, and influence mechanisms of sub-mesoscale motions on turbulent transport.

To address these challenges, future studies on the stable boundary layer should enhance intensive tower-based boundary layer observations, conduct fine-resolution three-dimensional turbulence observation experiments, and integrate high-precision and high temporal and spatial-resolution continuous-sounding measurements. The objected must be oriented toward exploring the temporal and spatial evolution patterns of weak turbulence and turbulence intermittency. This will help quantitatively describe the effects of sub-mesoscale motions, and accurately evaluate and parameterize weak turbulent transport during the quiescent periods and non-stationary strong turbulent transport during the bursting periods. Subsequently, based on quantitative research on the non-stationarity of turbulence intermittency and sub-mesoscale motions as well as their unconventional contributions to turbulent transport, the similarity theory of the stable boundary layer can be improved. In addition to high-precision and high temporal and spatial-resolution observation experiments, the integration of direct simulations and large-eddy simulations must be prioritized. Parameterization of the states of turbulence in the stable boundary layer should be applied to the models to analyze the evolution of the vertical structure of the stable boundary layer. Experiments and numerical simulations of weak turbulence and turbulence intermittency in the stable boundary layer over water surfaces should be conducted to study their effects on air-sea interactions and their roles in climate change. Finally, field observations, theoretical breakthroughs, and modeling advances of the stable boundary layer should be applied to important practical problems of public concern, such as improving air pollution forecasts, extreme weather warnings, and climate change projections.

## Declaration of competing interest

The authors declare no competing interests.

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## Data availability

Data will be made available on request.

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