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Special Section:
Recent progress in atmospheric boundary layer turbulence and implications to surface-atmosphere exchange

Key Points:

- Bulk Richardson number (R_b) can be a useful parameter in assessing wind direction change (ΔWD) near the surface in the nocturnal boundary layer
- ΔWD is generally confined to small values under weakly stable conditions ($0.0 < R_b \leq 0.25$) but varies across a very wide range with increasing potential for large ΔWD under very stable conditions ($R_b > 1.0$), which implies a complicated relationship between R_b and ΔWD
- Presence of the Low-Level Jets (LLJ) enhances the turbulence activities, decreases the R_b values, leads to relatively large vertical momentum and sensible heat fluxes, and suppresses ΔWD values

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Effects of Low-Level Jets on Near-Surface Turbulence and Wind Direction Changes in the Nocturnal Boundary Layer

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Abstract In this study we examined a data set of nearly two-year collection and investigated the effects of low-level jets (LLJ) on near-surface turbulence, especially wind direction changes, in the nocturnal boundary layer. Typically, nocturnal boundary layer is thermally stratified and stable. When wind profiles exhibit low gradient (in the absence of LLJ), it is characterized by very weak turbulence and very large, abrupt, but intermittent wind direction changes (ΔWD) in the layers near the surface. In contrast, presence of LLJs can cause dramatic changes through inducing wind velocity shears, enhancing vertical mixing, and weakening the thermal stratification underneath. Ultimately, bulk Richardson number (R_b) is reduced and weakly stable conditions prevail, leading to active turbulence, close coupling across the layers between the LLJ height and ground surface, relatively large vertical momentum and sensible heat fluxes, and suppressed ΔWD values. R_b can be a useful parameter in assessing turbulence strength and ΔWD as well. The dependence of ΔWD on R_b appears to be well defined under weakly stable conditions ($0.0 < R_b \leq 0.25$) and ΔWD is generally confined to small values. However, the relationship between ΔWD and R_b breaks when R_b increases, especially $R_b > 1.0$ (very stable conditions), under which ΔWD varies across a very wide range and the potential for large ΔWD increases greatly. Our findings have provided important implications to the plume dispersion in the nocturnal boundary layers.

Plain Language Summary This paper investigated how low-level jets affect the near-surface turbulence, especially wind direction changes, in the nocturnal atmospheric boundary layers. Atmospheric stability parameter (e.g., R_b-bulk Richardson number) can be the key in determining the wind direction changes in the nocturnal atmospheric boundary layer. Under weakly stable conditions ($0.0 < R_b \leq 0.25$), in general, wind direction only changes within a small range (less than 10°) between two consecutive 10-min intervals. In contrast, when $R_b > 1.0$ (very stable conditions), wind direction can vary across a very wide range and the probability for large wind direction changes also increases. Low-level jets often enhance the turbulence near the surface, reduce the atmospheric stability and lead to small wind direction shifts. In absence of low-level jets, nocturnal boundary layers are characterized by very weak turbulence and very large, abrupt, but intermittent wind direction changes (from a couple of 10° to 100°) in the layers near the surface. Our findings have provided important implications to the plume dispersion in the nocturnal boundary layers.

1. Introduction

Nocturnal boundary layer in the atmosphere, typically characterized by thermal stratification and positive temperature gradient in vertical direction, has been a research interest for many decades. Another feature often associated with this stable boundary layer condition is the low-level jet (Banta et al., 2002, 2003; Brunsell et al., 2021; Duarte et al., 2015; Karipot et al., 2008 among many others). It is widely recognized that low-level jets (LLJ) can impact across the layers from the jet height to ground surface. For example, Banta et al. (2003) demonstrated the existence of a region of enhanced shear beneath the wind maxima of the LLJs and its association with the increase of turbulence kinetic energy (TKE) in the sub-jet layers. Brunsell et al. (2021) and Karipot et al. (2008) employed eddy covariance observations from different sites (tallgrass prairie and forest respectively) and showed that LLJs aloft were able to alter momentum and CO_2 fluxes in the canopy layers. Duarte et al. (2015) reported an impact of LLJs on the TKE budget near the surface through changing the TKE transport mechanism, although a high frequency of LLJ was found in a 300–400 m vertical range. All evidence points to a downward transport of turbulence to the ground from the jet level, where turbulence is generated as a result of wind shear.

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Another group of studies have focused on the effects of wind shear and LLJs on the temporal changes of near-surface wind direction in the nocturnal boundary layers under very stable conditions (Finn, Eckman, et al., 2018; Mahrt, 2008; Mortarini, Maldaner, et al., 2016; Mortarini, Stefanello, et al., 2016; Sun et al., 2012). These studies have demonstrated that wind directions under these conditions are characterized by quasi-steady periods interrupted by very large magnitude and intermittent changes, often 50° or more in less than 1–2 min, but the physics of such wind direction shifts remains poorly understood (Mahrt, 2008). The analysis in Finn, Eckman, et al. (2018) used the net wind direction changes (ΔWD) occurring over 2-min intervals to quantify this behavior. It was found that the absence of LLJs and, more generally, light winds and weak wind shear tended to be more strongly associated with large ΔWD and weak turbulence near the surface whereas strong wind shear and the presence of LLJs tended to increase turbulence and strongly suppress ΔWD. This work also presented clear examples in which LLJs and the associated maximum wind speeds triggered downward bursts of turbulence and caused corresponding changes in wind directions at the surface. Furthermore, this observation tended to be true regardless of the heights of the wind speed maxima.

Grachev et al. (2005) represented one of the examples addressing the spatial changes of wind direction in the stable boundary layer (SBL). They divided the SBLs into four major regimes by analyzing the data collected over the Arctic pack ice. Moreover, they identified the development of the turbulent Ekman layer at a certain high level of stability, in which the near-surface turbulence was affected by the turning effects of the Coriolis force and wind changed its direction along the vertical extent of the measurements. It was concluded that, from their observations, near-surface turbulence was generated by surface roughness or local shear, that is, wind at a certain level relative to the zero wind at the ground.

It has been known that plume dispersion in the SBL can be more complicated and difficult to predict than is often assumed (Finn, Carter, et al., 2018; Hiscox et al., 2010; Sagendorf & Dickson, 1974). Observations from these studies revealed large variations and uncertainties in measured tracer concentrations, which were linked to intermittent turbulence, wind meandering and direction shifts under the very stable conditions. Advances have been made in the development of unifying models for the turbulence regime in the SBL (Lan et al., 2018; Mahrt, 2014; Mortarini et al., 2018; Sun et al., 2012, 2015); however, the mechanisms governing plume dispersion in the SBL are not yet fully understood.

Some previous efforts have highlighted the role of wind shear and LLJs in the SBL but utilized relatively limited datasets (Banta et al., 2002, 2003, 2007; Finn, Eckman, et al., 2018; Sun et al., 2012). For instance, Banta et al. (2002, 2003, 2007) and Sun et al. (2012) were all based on a one-month long data set collected through a field experiment campaign in southeast Kansas, USA during October 1999; the specific experiment described by Finn, Eckman, et al. (2018) was carried out in eastern Idaho, USA with limited observations over nine nocturnal periods in October 2016 that featured extended intervals of very stable boundary layer conditions. In terms of wind direction changes in the nocturnal boundary layer, moreover, previous studies simply made reference to their magnitudes (Mortarini, Maldaner, et al., 2016; Mortarini, Stefanello, et al., 2016; Sun et al., 2012) or provided a qualitative relationship (Finn, Eckman, et al., 2018) instead of a quantitative one between the wind direction changes and LLJs. In this study we intend to continue and expand the work reported by Finn, Eckman, et al. (2018) in concern of its relatively incomplete view on this particular topic due to the limited data set. We collected data from the same field site as Finn, Eckman, et al. (2018), but with a much long temporal span from April 2016 to September 2017. The purpose of this paper is to examine the effects of LLJs on turbulence and especially wind direction changes near the surface in the SBL with an eye toward better understanding the plume dispersion mechanisms and improving plume forecast models. Our tasks are twofold: (a) we will explore a nearly two-year data set to strengthen and advance the findings reported by Finn, Eckman, et al. (2018) through contrasting the near surface turbulence regimes between presence and absence of LLJs; and (b) we will quantitatively examine the mechanisms that control wind direction changes in the SBL by explicitly taking both wind shears and thermal stratification into account.

2. Data and Methodology

The data used in the analysis were collected at the same study site (43.5959°N, 112.9288°W; elevation ∼1,500 m) as described in Finn, Eckman, et al. (2018), on a 60-m tower in the Grid 3 area of the NOAA/INL (National Oceanic and Atmospheric Administration/Idaho National Laboratory) mesonet. The site is generally open and flat with a low canopy of sagebrush and grass and lies on the Snake River Plain in eastern Idaho, USA. A picture showing the tall tower and surrounding vegetation can be found in Finn et al. (2016). This site was also utilized by other field experiments, such as the Project Sagebrush Phase 1 and 2 tracer field studies (Finn, Carter, et al., 2018;

Finn et al., 2017). Many detailed description of this site has been provided by these previous publications (Clawson et al., 2018; Finn, Carter, et al., 2018; Finn et al., 2016, 2017) and will not be further elaborated here.

Two datasets were collected in this study. The first one contained wind profiles that were measured by an Atmospheric Systems Corporation ASC4000 sodar and used for LLJ identification. The second one was obtained by an array of six sonic anemometers at different heights along the tall tower and used for calculating all turbulence parameters near the surface. Both datasets covered a period from April 2016 through September 2017.

The ASC4000 sodar measured wind profiles and calculated 10-min averages online at 10-m height intervals from 20 m up to a maximum of 250 m. The actual maximum data recovery for a 10-min period was often less than 250 m. Nocturnal sodar wind velocity profiles were assigned to one of two sub-populations following these specific criteria: (a) LLJ category, that is, wind velocity profiles featuring a jet-like structure with a maximum wind speed U at least 2 m s^{-1} greater than winds just above it (Stull, 1988) and (b) wind profiles exhibiting a low gradient (LG). The LG profiles featured low wind speeds over the entire measurement extents, generally less than 4 m s^{-1} and often less than 2 m s^{-1}, with very little or no gradient in the vertical. All available nighttime wind profiles from April 2016 through September 2017 were examined and any periods satisfying either (a) or (b) being assigned accordingly. The totals for sub-populations LLJ and LG included 2,996 and 2,234 10-min cases, respectively.

The near surface wind and turbulence data were obtained by R. M. Young Ultrasonic anemometers (model 81000, R. M. Young Company, Traverse City, Michigan, USA) for the same measurement period as the ASC4000 sodar. These sonic anemometers outputted three wind velocity components and virtual temperature at 10-Hz frequency. The sonic anemometer data were available from six levels at 2.0, 3.7, 9.0, 16.5, 30.0, and 60.0 m on a tall tower; but we primarily used data from the bottom three levels in this study.

Mean wind speed, wind direction and turbulence parameters (TKE, momentum and sensible heat fluxes, etc.) at 2 m were calculated over 2-min intervals using the sonic anemometer data. ΔWD values were obtained by taking the absolute difference of wind direction at 2 m between any two consecutive 2-min periods. Data from 3.7 m were used as the substitutes for 2-m level observations when the latter was missing from 8 December 2016 to 3 January 2017. Next, these parameters were averaged to 10 min to match the sodar averaging period. The averaging had the effect of reducing the largest values in ΔWD. All turbulence parameters and ΔWD at 2 m were correspondingly assigned to sub-populations LLJ and LG as well.

The bulk wind shear is defined as $(U_{jet} - U_s)/(Z_{jet} - Z_s)$ where U_{jet} is the wind speed measured by the ASC4000 sodar at the maximum or nose of the jet, U_s is the wind speed measured by the sonic anemometer near the surface, and Z_{jet} and Z_s are the corresponding heights. Sonic anemometer data from the 2-m level were used for U_s. Given the absence of a jet, bulk shear was not calculated for the LG group. The LG sub-population serves as a control or reference to illustrate what ΔWD and turbulence are in the absence of bulk shear and LLJs. Local wind shear is defined as $\sqrt{\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2}$ where ΔU and ΔV are the differences in the vector components of sonic anemometer wind speed over the height interval ΔZ. U and V are wind velocity components along the north-south and east-west oriented sonic axes, respectively. The 2-min average local wind shears were computed for ΔZ from 2 m (or 3.7 m when 2-m data were missing) to 9 m and then averaged to 10 min.

We quantified the atmospheric stability in the near surface layer using the Richardson number (R_b; Equation 5.6.3 of Stull, 1988). In doing so, the finite differences of wind velocities (ΔU, ΔV) and air temperature (ΔT) were obtained between 2- and 9-m levels. Since the measurements were taken in such a shallow layer with very little variation of atmospheric moisture, we used the virtual temperatures recorded by the sonic anemometers as close approximations for the air temperatures (T). Stull (1988) suggested two well-accepted thresholds in describing the turbulence regimes, critical Richardson number ($R_c = 0.25$) and the indicator of turbulence termination ($R_T = 1.0$). In this study we adopted these values as references to separate all 10-min data into three stability categories, turbulent flow under weakly stable condition ($0 < R_b \le R_c$), transition flow under stable condition ($R_c < R_b \le R_T$), and laminar flow under very stable condition ($R_T < R_b$).

3. Results

3.1. Occurrence and Characteristics of LLJs

LLJs did not develop on all nights but, when they did develop, it could be at any hour of the night and even occasionally persist for a short time after sunrise. However, they tended to develop mainly after midnight with

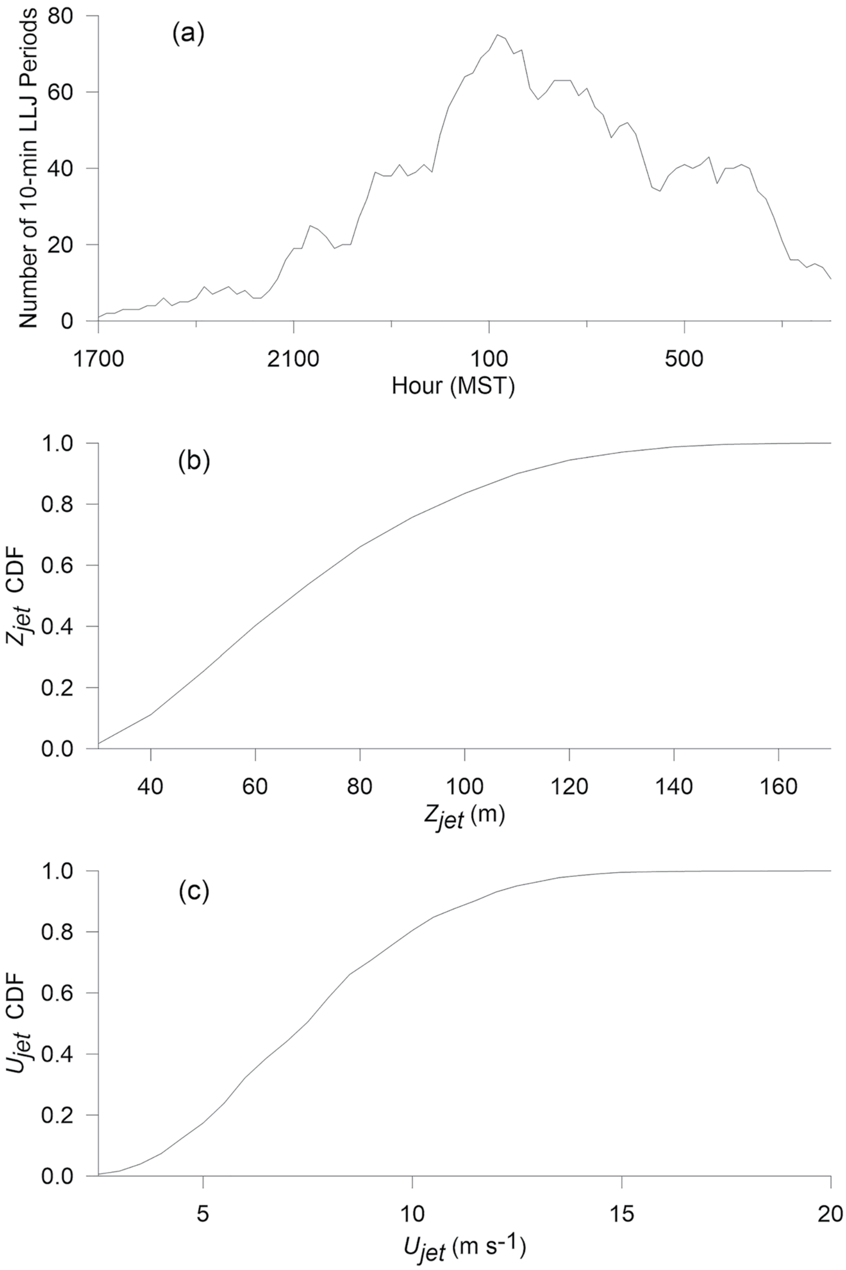

Figure 1. (a) Temporal distribution, in USA Mountain Standard Time (MST), of the number of the 10-min periods during which LLJs were identified at the INL site from April 2016 to September 2017; and cumulative distribution functions (CDF) from sodar data for (b) LLJ heights Z_{jet} and (c) LLJ wind speed maxima U_{jet}.

their frequency gradually decreasing overnight toward sunrise (Figure 1a). Song et al. (2005) and Whiteman et al. (1997) also observed relatively high frequency of LLJs in the hours after midnight in the Southern Great Plains, USA. According to the inertial oscillation theory (Stull, 1988), occurrence of nocturnal LLJs is mainly a result of stable boundary layer condition through radiative cooling on the surface and a transition from subgeostrophic to supergeostrophic wind speeds through acceleration by the Coriolis force, both of which process usually take several hours to develop after sunset. When LLJs were present, they tended to be intermittent and ephemeral. They could last for as little as 20–30 min or be sustained for as long as several hours with most lasting from 40 min to 2 hr.

Heights of the jet maxima (Z_{jet}), when present, were commonly from 50 to 100 m a.g.l. but ranged as low as 30 m to as much as 170 m (Figure 1b). The U_{jet} wind speeds were mainly between 5 and 10 m s^{-1} (Figure 1c). There is certainly the possibility of these observations being site dependent but observations of the lowermost LLJ maxima from the CASES-99 field study (Banta et al., 2002, 2003, 2007; Sun et al., 2012) were mostly consistent with observations from our site. Banta et al. (2002) found that about 25% of LLJs had maxima at heights greater than 150 m for the lowermost jets. This was much more common than in the present study although this could be due in part to height limitations on our sodar measurements. They also reported about 10% more LLJs with $U_{jet} > 10$ m s^{-1} than the observations presented in this study.

3.2. Relationships Between Bulk Shear, Local Shear, Near Surface Turbulence, and Wind Direction Changes

As mentioned above, bulk shear is specific to the presence of LLJs. The bulk shear calculation is intended to incorporate the effects of both the vertical differences in wind speed as well as the vertical distance of separation. Thus, it is anticipated that a larger vertical difference in wind speed between U_{jet} and U_s and/or a smaller difference between Z_{jet} and Z_s would be associated with larger shear and more shear-generated turbulence near the surface. In contrast, a smaller wind speed difference and/or larger Z_{jet} would be associated with lesser turbulence near the surface.

Figure 2 shows that U_s, the standard deviation of vertical wind velocity σ_w, and the square root of turbulent kinetic energy $\sqrt{e}$ are all positively correlated with bulk shear but with significant scatter. As anticipated, ΔWD is sensitive to and negatively correlated with bulk shear with almost all large values of ΔWD being associated with low values of bulk shear, σ_w, and $\sqrt{e}$ with $U_s < 1.5$ m s^{-1} (Finn, Eckman, et al., 2018). It is clear that larger ΔWD, for example, >20°, and weaker near-surface turbulence can occur in the presence of a LLJ but only if it is relatively weak due to smaller U_{jet} and/or higher Z_{jet}. In contrast, while large ΔWD are strongly associated with small σ_w and $\sqrt{e}$ in all cases, any correlation with local shear breaks down for small σ_w and $\sqrt{e}$ and $U_s < 2$–3 m s^{-1}. More generally, local shear shows poor correlation with σ_w, $\sqrt{e}$, and U_s across their respective ranges as indicated by the relatively small coefficients of determination in comparison to bulk shear.

3.3. Effects of Stability on Wind Direction Changes

Figure 3 shows the dependence of ΔWD on R_b for both sub-populations. For LLJ regime and when $R_b \le 0.25$, the dependence of ΔWD on R_b appears to be well defined with most of the ΔWD values below 10° (85.5% of total, see Table 1); when $R_b > 0.25$, ΔWD varies across a much large range, from a few degrees to greater than 80°, and shows no clear dependence on R_b. For LG regime, in contrast, relatively fewer ΔWD segments are found under $R_b \le 0.25$ and there appears to be little or no relationship between ΔWD and R_b across the entire range of R_b.

The percentages of different levels of ΔWD occurrence are listed in Table 1. In general, the occurrence percentages increase for any level of ΔWD when stability classes change from weakly stable ($0.0 < R_b \le 0.25$) to very stable ($R_b > 1.0$). This is true for both LLJ and LG sub-populations. Obviously, despite the poor relationship between ΔWD and R_b (Figure 3), very stable conditions or large R_b values have greater potentials to cause larger ΔWD than weakly stable conditions or small R_b values.

3.4. Effects of LLJ Versus LG on Wind Direction Changes

Striking difference of their effects on R_b between LLJ and LG regimes can be seen in Table 2. For the LLJ regime, 68.2% of the 10-min measurements fall into weakly stable class while only 12.2% occur under very stable conditions. In comparison, opposite is observed for the LG regime. This can be easily understood when we compare the distributions of local shear and temperature gradient between the two sub-populations (Figure 4). LLJ regime is dominated by large local shears (cumulatively, 41% of measurements with values >0.2 s^{-1} and 81% with values >0.1 s^{-1}) and small temperature gradients (cumulatively, 64% of measurements with values < 0.2 K/m). Following the definition of R_b, this combination inevitably leads to a majority of weakly stable conditions. In contrast, with prevalence of small local shears (67.6% of measurements with values <0.1 s^{-1}) and large temperature gradients (cumulatively, 64.6% of measurements with values >0.2 K/m), a majority of LG measurements occur under very stable conditions.

Different stability conditions between LLJ and LG regimes ultimately result in different ΔWD occurrence. The presence of the LLJs facilitates the turbulence development and vertical mixing processes by enhancing wind

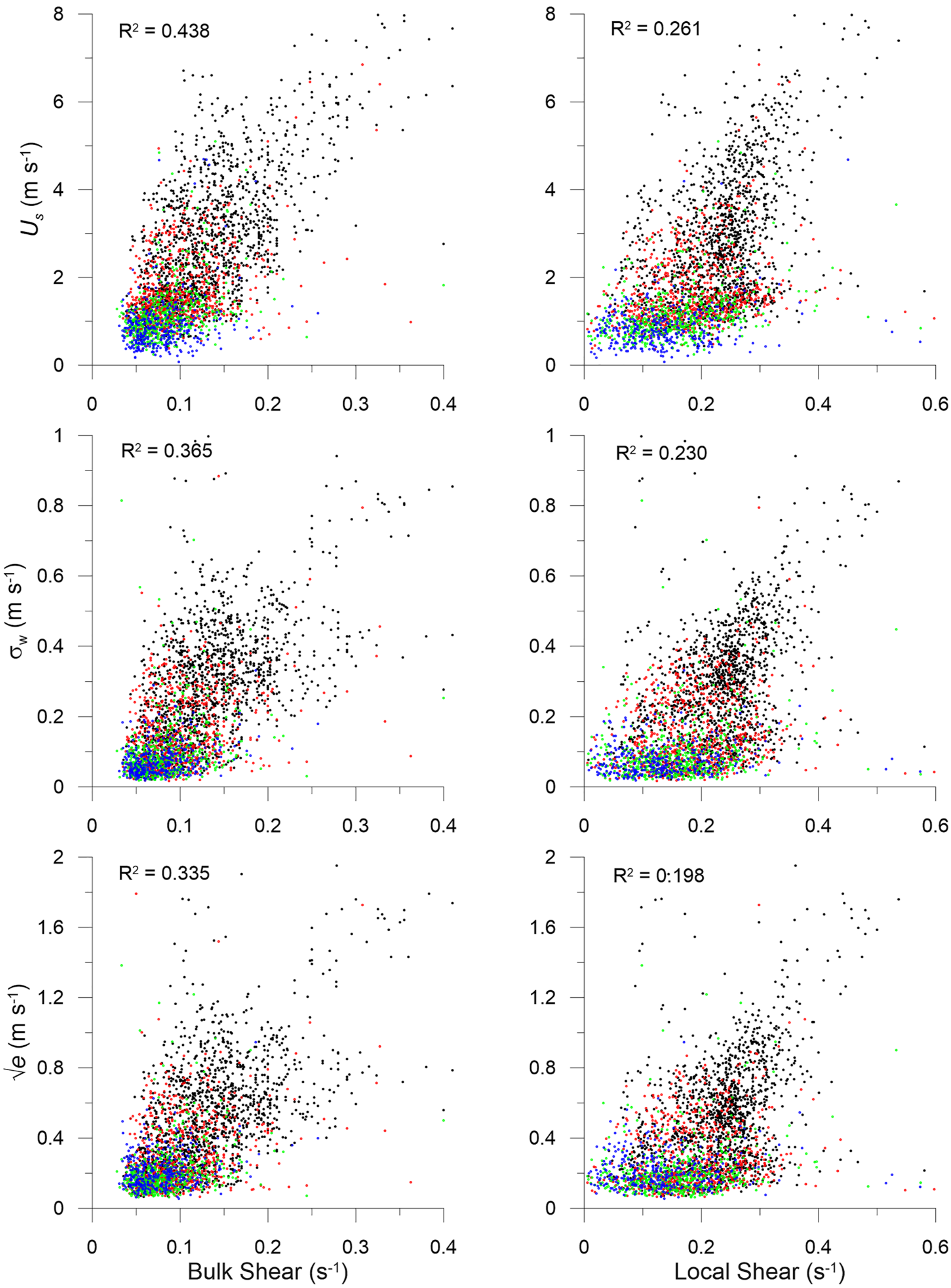

Figure 2. 10-min average U_s, σ_w, and $\sqrt{e}$ at 2 m as functions of bulk shear and local shear for the LLJ sub-population with 10-min average ΔWD expressed in color-coded ranges of degrees (ΔWD ≤ 5 black, 5 < ΔWD ≤ 10 red, 10 < ΔWD ≤ 20 green, ΔWD > 20 blue). Coefficients of determination (R^2) are given in each panel for the entire group of samples (2,996 in total) including all levels of ΔWD.

velocity shear and weakening the thermal stratification (Figure 4) and eventually improves the coupling between the flows near the ground surface and aloft. Consequently, probabilities for small R_b values, that is, weakly stable conditions increase (Table 2) and so do small ΔWD values (Table 1). For example, 70.3% of the ΔWD values are smaller than 10° for the LLJ regime while it is only 30.1% for the LG (see columns of "All R_b values" in Table 1). In other words, the LG cases (absence of LLJ) have a greater potential to cause larger ΔWD values. Although

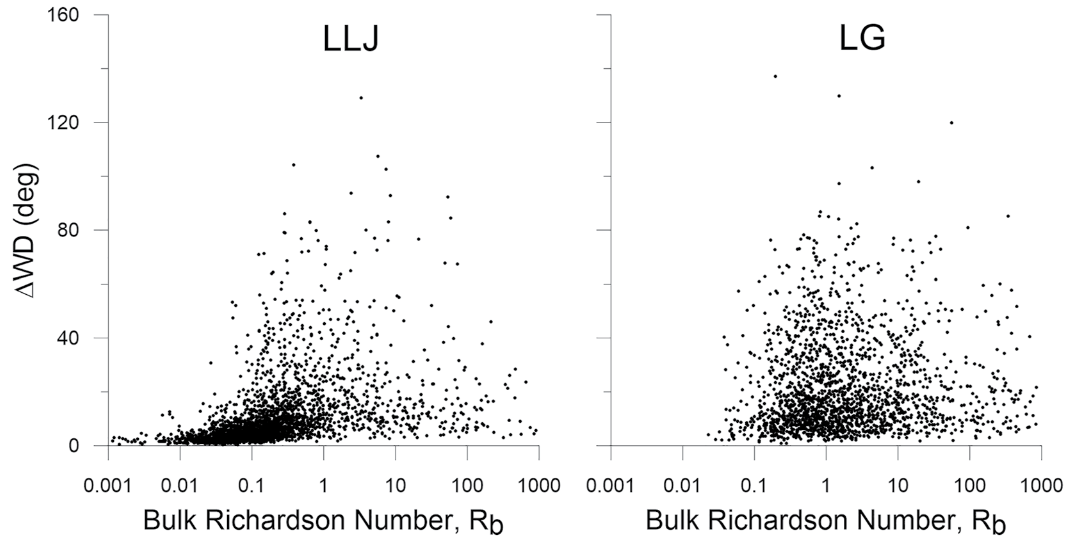

Figure 3. Dependence of ΔWD on R_b for LLJ (left) and LG (right) sub-populations; x-axis is on logarithmic scale.

large ΔWD values are generally suppressed in the LLJ regime, they can still occur but less frequently than in the LG regime (Table 1). In these occasions (a small portion of LLJ measurements with relatively small local shears but large $\Delta T/\Delta Z$ in Figure 4), mechanical mixing created by local shear is not strong enough to overcome the thermal stratification and thus stable or very stable conditions prevail.

It is evident that the enhanced local shear in the LLJ regime (Figure 4) is driven by large bulk shear as they are positively correlated (Figure 5). In turn, local shear promotes momentum and kinematic heat fluxes and strong turbulence (left column of Figure 6). Without LLJ or in the LG cases, both fluxes collapse implying very weak turbulence (right column of Figure 6). Again, large ΔWD values are associated with situations of weak turbulence (the majority of LG sub-population and a small number of LLJ cases when fluxes are low), as already shown in Figure 2.

4. Discussion

In this study we investigated the effects of LLJs on wind velocity shears, atmospheric stabilities (Richardson number, R_b), turbulence characteristics and especially wind direction changes in the nocturnal boundary layers just above the ground surface. Our results are in agreement with the view that turbulence in SBLs is largely generated aloft and decreases downward toward the surface (Lan et al., 2018; Mahrt, 2014). Wind velocity shears at layers just below the nose of LLJs are the primary mechanisms for turbulence production, which in turn drives the turbulent activities across the layers beneath the height of LLJs (Banta et al., 2002, 2003; Mortarini et al., 2018; Sun et al., 2012). Lan et al. (2018) provided a schematic (see their Figure 11) showing the boundary layer structure and flux transfer from upper layers to near surface in a coupled, weakly stable boundary layer. Finn, Eckman, et al. (2018) presented clear examples in which LLJs and the associated maximum wind speeds

Table 1
Occurrence (%) of Different Levels of ΔWD Within Each Stability Category for Both LLJ and LG Sub-Populations

	LLJ sub-population				LG sub-population			
	$0.0 < R_b \le 0.25$	$0.25 < R_b \le 1.0$	$1.0 < R_b$	All R_b values	$0.0 < R_b \le 0.25$	$0.25 < R_b \le 1.0$	$1.0 < R_b$	All R_b values
ΔWD > 10	14.5	56.5	70.7	29.7	52.7	69.6	73.8	69.9
ΔWD > 20	4.5	23.6	39.1	12.5	29.3	38.1	41.5	38.9
ΔWD > 40	1.3	8.5	14.3	4.3	10.2	15.2	14.5	14.2
ΔWD > 60	0.2	2.7	5.9	1.4	3.0	4.1	4.7	4.3
ΔWD > 80	0	0.8	2.2	0.4	0.4	0.3	1.1	0.8

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Table 2
Percentage Distribution (%) of R_b for Both LLJ and LG Sub-Populations

	$0.0 < R_b \leq 0.25$	$0.25 < R_b \leq 1.0$	$1.0 < R_b$
LLJ	68.2	19.6	12.2
LG	12.2	31.8	56.0

triggered downward bursts of turbulence. Data in this study showed notably different magnitudes of local shears between the LLJ and LG regimes (Figure 4) and a close correlation between bulk shear and local shear in the LLJ group (Figure 5). All evidence points to LLJs and the associated bulk shears, if present, as the driver for the local shears and turbulence near the ground surface. In the LG regime, however, the relatively weak local shears are mainly caused by the surface roughness or friction (Grachev et al., 2005).

In this study, local shears were calculated between 9 and 2 m wind measurements. As an alternative, local shears can be estimated between 9 m wind measurement and zero wind at the ground surface. Local shears obtained by these two approaches are highly correlated (figure not shown). However, values from the second approach (with larger ΔU and ΔV between 9 m and surface) are often greater than the first approach (with relatively smaller ΔU and ΔV between 9 and 2 m). We also realized that LLJs might not be the only sources for enhanced local shears and turbulence and the shear-generated turbulence of any origins could affect the wind direction changes near the surface. By contrasting the LLJ and LG regimes through our analyses, however, we showed that bulk shears associated with the LLJs (if present) directly drove the local wind shears near the surface, which in turn increased the turbulence and vertical mixing and suppressed the large wind direction changes. In this sense, LLJs, if strong enough, are indirect but ultimate controlling force on surface wind direction changes.

Banta et al. (2003) showed that R_b could be a proper parameter in estimating the turbulence strength in the presence of LLJs and the cutoff value between strong and weak turbulence was about 0.4. However, the relationship between the turbulence magnitudes and stability parameter (local gradient Richardson number) for LG regime can vary greatly from the LLJ regime (Sun et al., 2012). In the nocturnal boundary layers with LLJs present, strong vertical mixing induced by the wind velocity shears can greatly weaken the thermal stratification (positive temperature gradient), reduce values of R_b, and enhance the turbulence and momentum and heat fluxes (Banta et al., 2002, 2003; Sun et al., 2012). In the absence of LLJs under very stable conditions (LG regime), near-surface turbulence is strongly suppressed and large ΔWD values often take place (Mortarini, Maldaner, et al., 2016; Mortarini, Stefanello, et al., 2016). Our results consistently support and confirm these previous findings.

Despite that presence of LLJs intensifies the turbulence and fosters flow coupling across levels in the lower atmosphere, large ΔWD values at 2-m level can still occur occasionally at a much lower frequency than the LG regime (Table 1). Finn, Eckman, et al. (2018) also identified specific instances of this kind and showed that large ΔWD in very stable conditions was closely linked to the decoupling associated with the collapse of the momentum and sensible heat fluxes. When this happened, strong stabilities (large R_b values) sustained because LLJs

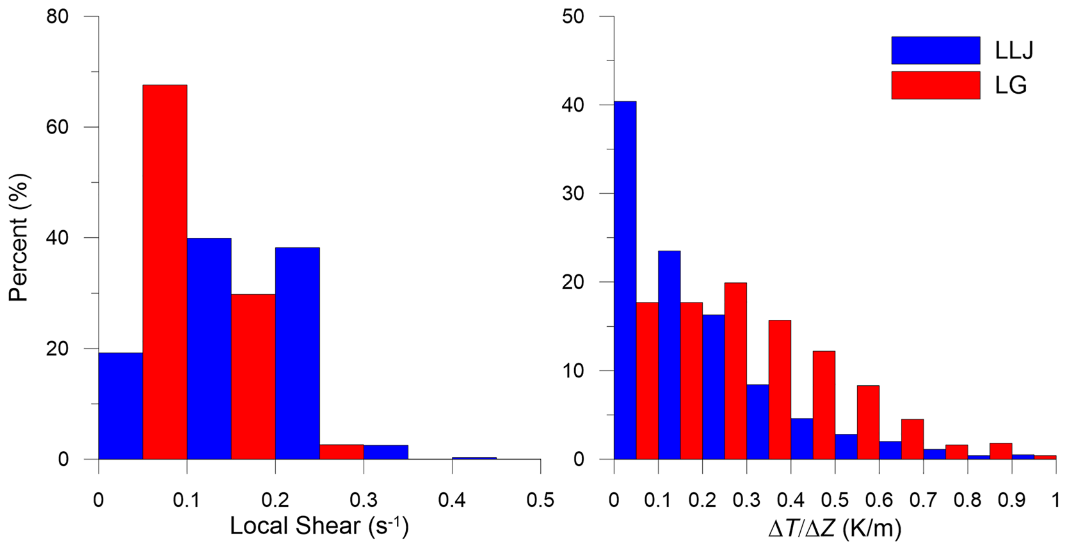

Figure 4. Percentage distribution (%) of local shear (left) and temperature gradient (right) for both LLJ and LG sub-populations.

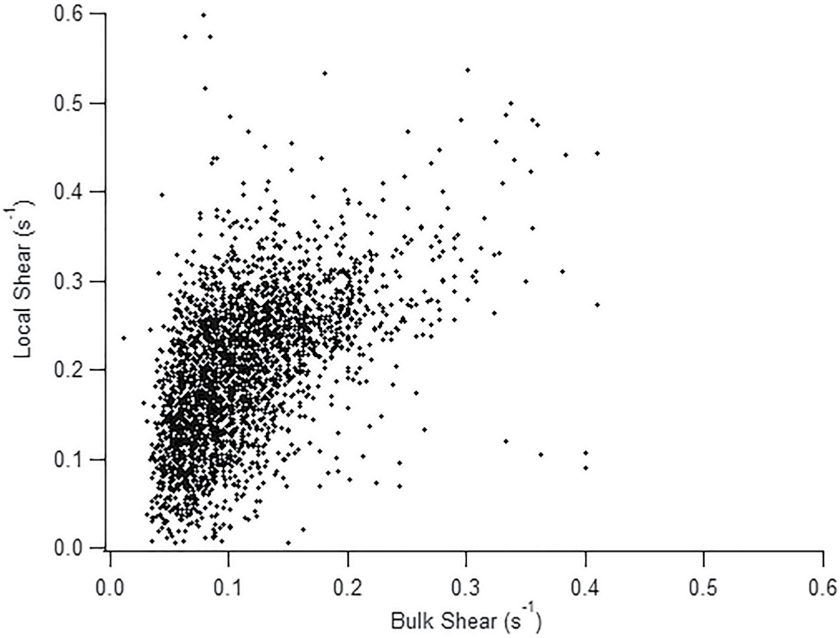

Figure 5. Local shear as a function of bulk shear for the LLJ sub-population.

(bulk and local shears) were relatively weak to overcome the strong positive temperature gradients. In the meantime, momentum and sensible heat fluxes were largely inhibited as well (Figure 6). For this reason, we believe that R_b (taking both wind shear and temperature gradient into account) is a better choice than bulk or local shears in estimating ΔWD.

The relationship between ΔWD and R_b is poorly defined at the high end of R_b for both LLJ and LG regimes and ΔWD ranges from a few degrees to around 100° (Figure 3). The lack of correlation between these two parameters can probably be related to the transition between weakly stable and very stable regimes (Mahrt, 2014). Sun et al. (2012) showed that turbulence levels were low and remained relatively invariant to changes in wind speed below certain wind speed thresholds, with the threshold varying by height. Mahrt et al. (2012) linked this to a transition in Richardson number above which turbulence became relatively invariant to further increase in the Richardson number. Thus, in an analogous way, ΔWD become de-linked from or independent of R_b under very stable conditions (large R_b values).

5. Conclusions

In this study we showed that LLJs could strongly affect the near-surface turbulence through changing the atmospheric stability regimes in the nocturnal boundary layers. The strong bulk and local wind shears, induced by the LLJs, enhance the vertical mixing processes, weaken the thermal stratification (or positive temperature gradients), and result in weakly stable conditions ($0.0 < R_b \leq 0.25$) for the majority of observational periods. The boundary layers are characterized by energetic turbulence indicated by relatively large values of U_s, σ_w, $\sqrt{e}$ and momentum and sensible heat fluxes in the layers just above the ground surface. In this case, flows in the lower atmospheric layers are closely coupled and engaged with those aloft. Therefore, wind direction largely remains unchanged, leading to small ΔWD values.

In contrast, weak wind shears and strong thermal stratification are characteristic of LG regime with absence of the LLJs. This combination leads to the dominance of very stable conditions ($R_b > 1.0$) with very weak near-surface turbulence, small values of U_s, σ_w, $\sqrt{e}$ and collapsed fluxes for momentum and sensible heat. In this case, lower atmospheric layers are almost completely decoupled from those aloft. Therefore, wind behaves erratically and its direction remains unsettled, leading to large ΔWD values.

R_b can be a useful parameter in assessing turbulence strength and ΔWD in the nocturnal boundary layers without referring to LLJ or LG regime. Weakly stable conditions ($0.0 < R_b \leq 0.25$) are associated with strong turbulence

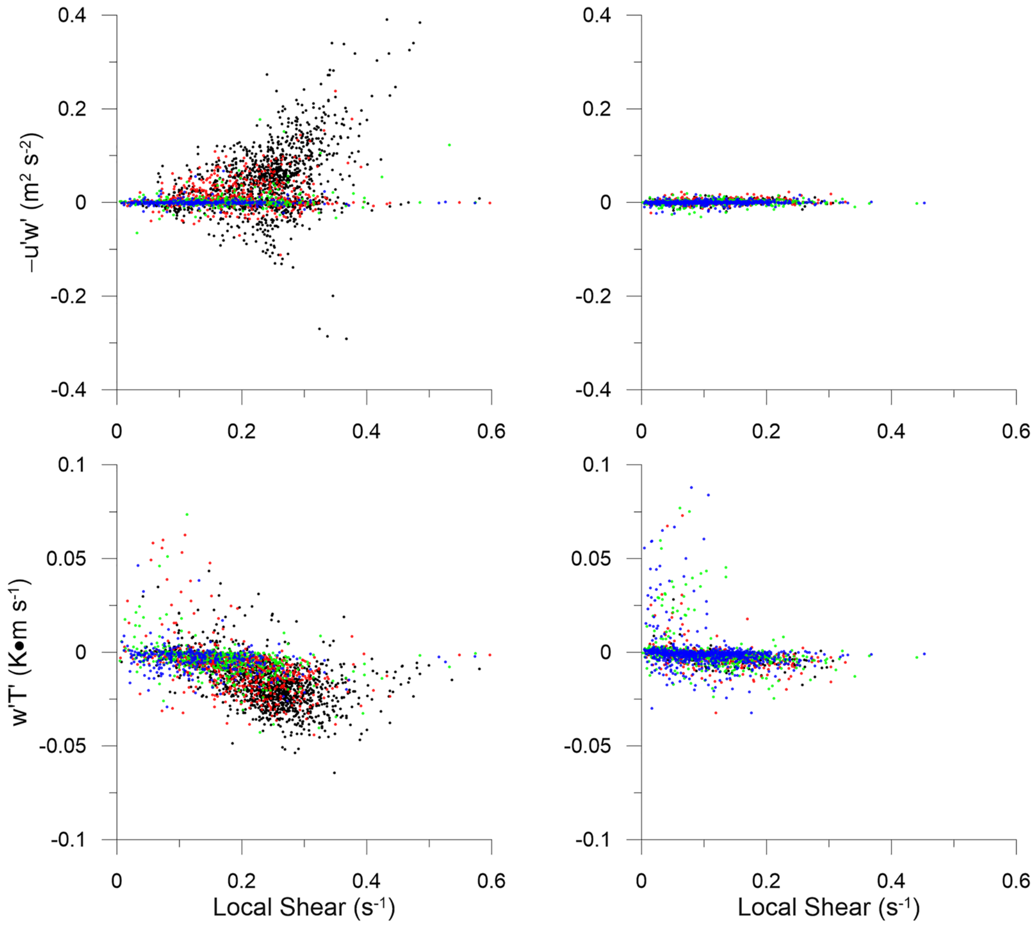

Figure 6. Momentum flux and kinematic heat flux as functions of local shear for the LLJ (left column) and LG (right column) sub-populations with breakout of data by ranges of ΔWD degrees (ΔWD ≤ 5 black, 5 < ΔWD ≤ 10 red, 10 < ΔWD ≤ 20 green, ΔWD > 20 blue). Momentum flux and kinematic heat flux were calculated at 2-m level.

and generally small ΔWD values. On the other hand, very stable conditions ($R_b > 1.0$) are associated with weak turbulence and elevated potentials of large ΔWD values. In addition, the relationship between ΔWD and R_b breaks when R_b increases or atmospheric stability changes from weakly stable to very stable. As a result, ΔWD varies across a very wide range under very stable conditions.

The remarkable difference between LLJ and LG regimes and their effects on the wind direction change and near-surface turbulence have provided important implications to the plume dispersion in the nocturnal boundary layers.

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Data Availability Statement

The observational data used in this study are publicly available at OSF, https://osf.io/ufqsx (Yang et al., 2023).

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