

Two types of low-level jets in China during the warm season: Observational climatology from radiosonde data

Erqi Zheng^a, Yu Du^{a,b,c,d,*}, Yuhao Luo^e, Qinghong Zhang^f, Guixing Chen^{a,c,d}, Lin Su^{a,c,d},
Hoiio Kong^g

^a School of Atmospheric Sciences, Sun Yat-sen University, and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China

^b Heavy Rainfall Research Center of China/Institute of Heavy Rain, China Meteorological Administration, Wuhan, China

^c Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Zhuhai, China

^d Key Laboratory of Tropical Atmosphere-Ocean System, Sun Yat-sen University, Ministry of Education, Zhuhai, China

^e Institute of Tibetan Plateau Meteorology, Chinese Academy of Meteorological Sciences (CAMS/ITPM), Chengdu, China

^f Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, China

^g Faculty of Data Science, City University of Macau, Macau, China

ARTICLE INFO

Keywords:

Low-level jet

Boundary-layer jet

Synoptic-system-related low-level jet

Radiosonde data

关键词:

低空急流

边界层急流

天气系统相关低空急流

探空数据

ABSTRACT

Low-level jets (LLJs) are widespread across China and significantly shape warm-season precipitation. This study provides the first observational climatology of two LLJ types—boundary-layer jets (BLJs) and synoptic-system-related LLJs (SLLJs)—using nationwide high-vertical-resolution radiosonde data with from April to September during 2008–2017. LLJs occur most frequently in Northeast and South China, with BLJs concentrated in mountainous and coastal regions influenced by strong thermal contrasts, and SLLJs primarily in Southwest and South China under active synoptic disturbances. BLJs and SLLJs reach their maximum occurrence at ~0.7 km and 1.9 km above ground level, respectively. The diurnal peak in LLJ frequency shifts earlier with increasing latitude, consistent with inertial oscillation theory. Statistical analyses of spatial distributions, wind directions, and ERA5 diagnostics indicate that both BLJs and SLLJs are jointly modulated by topography, monsoon background flows, and synoptic systems. These nationwide observational results provide a comprehensive and realistic view of LLJ variability and their synoptic context across China.

摘要

低空急流(LLJ)在中国分布广泛,对暖季降水有显著影响。本研究利用2008–2017年4–9月全国高分辨率探空数据,首次针对边界层急流(BLJ)和天气系统相关低空急流(SLLJ)两类LLJ开展观测气候学研究。结果表明,LLJ在东北和华南地区发生频率最高,其中BLJ集中在受强热力差异影响的山区与沿海区域,SLLJ则多见于受活跃天气系统影响的西南和华南地区。LLJ频率的日变化峰值随纬度升高而提前。对空间分布、风向和ERA5数据的分析表明,BLJ和SLLJ都受到地形、季风背景气流和天气系统的共同调控。

1. Introduction

Low-level jets (LLJs), characterized by strong wind shear and high wind speeds in the lower troposphere, are a globally observed phenomenon (Doubler et al., 2015; Lima et al., 2022; Ranjha et al., 2013; Rife et al., 2010; Stensrud, 1996). They exert a pronounced influence on warm-season precipitation by enhancing moisture transport and inducing low-level convergence near their terminus (Du and Chen, 2018, 2019; Ferguson, 2022; Fu et al., 2022; Luo, Du, 2023; Monaghan et al., 2010; Su et al., 2025; Li et al., 2024).

The spatial and temporal distributions of LLJs have been extensively investigated using various datasets, including radiosonde observations, wind profiler radar, and reanalysis products. Using radiosonde data, LLJs over the U.S. Great Plains were systematically characterized by Bonner (1968), with Whiteman et al. (1997) exploring their seasonal variations. More recent studies have leveraged reanalysis products for broader spatial coverage. For global studies, Rife et al. (2010) mapped nocturnal LLJs via a downscaled reanalysis and a new LLJ index, while Luiz and Fiedler (2024) estimated LLJs frequencies with ERA5 data.

Peer review under the responsibility of Editorial Board of Atmospheric and Oceanic Science Letters.

* Corresponding author.

E-mail address: duyu7@mail.sysu.edu.cn (Y. Du).

<https://doi.org/10.1016/j.aosl.2026.100791>

Received 2 November 2025; Revised 16 January 2026; Accepted 27 February 2026

Available online xxx

1674-2834/© 2026 The Authors. Publishing Services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

Please cite this article as: E. Zheng, Y. Du, Y. Luo et al., Two types of low-level jets in China during the warm season: Observational climatology from radiosonde data, Atmospheric and Oceanic Science Letters, <https://doi.org/10.1016/j.aosl.2026.100791>

In China, the distribution of LLJs has been studied through numerical simulations and reanalysis datasets. Du et al. (2014), using numerical simulations of early summer in China, identified frequent LLJ activity over the Northeast Plain, southeastern coastal regions, the Tarim Basin, and the Tibetan Plateau. Shu et al. (2024) used ERA5 data to study the horizontal and vertical distributions of LLJs in Northeast China and found that warm-season LLJs in this region occur most frequently in the central region, peaking near 925 hPa with prevailing southwesterly winds. LLJs in China are typically categorized into two types based on their altitude and formation mechanisms: (1) boundary-layer jets (BLJs), typically found below 1 km; and (2) synoptic-system-related LLJs (SLLJs), usually occurring between 900 and 600 hPa (Chen et al., 1994; Cui et al., 2023; Du et al., 2014, 2012). Du et al. (2014) further distinguished these types in China, showing that SLLJs are prevalent in northeastern and southern China and migrate northward from May to July along with the mei-yu front, while BLJs occur more frequently over elevated terrain and coastal regions.

Despite these insights, direct observational studies distinguishing LLJ types remain limited, and most have been confined to individual stations. Some studies have classified LLJs by wind speed into intensity categories (Whiteman et al., 1997; Yan et al., 2021), but such schemes do not directly reflect the underlying physical mechanisms as BLJ/SLLJ classification does. For example, Miao et al. (2018) analyzed four intensity-based LLJ types in Beijing and Guangzhou using wind profiler data. Cui et al. (2023) investigated BLJs and SLLJs over Wuhan using radiosonde data. In contrast to these site-specific observational studies, Yan et al. (2021) conducted a nationwide analysis using radiosonde data and identified LLJs hotspots over the Northeast Plain, southeastern coastal areas, the Huai River basin, and northwestern China. However, their study did not distinguish between BLJs and SLLJs.

The formation mechanisms of LLJs also vary by type. BLJs are strongly influenced by diurnal variations, including: (1) inertial oscillations following the weakening of boundary-layer turbulence after sunset (Blackadar, 1957); (2) diurnal thermal contrasts between land and sea or mountain and valley (Holton, 1967); and (3) orographic effects such as flow blocking and channeling (Kong et al., 2020; Li et al., 2018). In contrast, SLLJs are closely associated with synoptic-scale weather systems, especially during the warm season in China, including the western Pacific subtropical high (WPSH), the Southwest Vortex, and the mei-yu front (He et al., 2016; Stensrud, 1996; Zhao, 2012). However, the distinct characteristics of BLJs and SLLJs remain insufficiently understood due to the scarcity of observational analyses that explicitly separate them.

The objective of this study is to investigate the spatiotemporal distributions and associated synoptic conditions of warm-season BLJs and SLLJs across China using nationwide radiosonde data with high vertical resolution. Section 2 introduces the data and methodology. Section 3 presents the spatial distributions, wind direction, and diurnal variations of BLJs and SLLJs. Section 4 discusses the synoptic conditions influencing LLJ formation based on ERA5. Conclusions and implications are summarized in Section 5.

2. Data and methods

2.1. Data

This study utilizes radiosonde observations collected during the warm season (April–September) from 2008 to 2017. The dataset consists of minute-level vertical profiles with a vertical resolution of ~ 300 m, which is finer than the standard pressure-level data in the Integrated Global Radiosonde Archive (IGRA). Twice-daily soundings were obtained at 0000 UTC (0800 Beijing Time, BJT) and 1200 UTC (2000 BJT) from 123 L-band radiosonde stations operated by the China Meteorological Administration (CMA). Each observational record provides vertical profiles of wind speed, wind directions, and height above ground level

(AGL). In addition, typhoon-affected days were excluded based on the CMA Tropical Cyclone Best Track Dataset.

2.2. Identification of LLJs

LLJs were identified using criteria adapted from Du et al. (2014): (1) the presence of a wind speed maximum exceeding 10 m s^{-1} below 4 km AGL; and (2) a decrease in wind speed of at least 3 m s^{-1} between the jet core and the overlying minimum.

Based on the height of the jet core, LLJs were further classified into two types: BLJs with jet cores located below 1.3 km AGL, and SLLJs with core heights at or above 1.3 km AGL. This classification follows the approach of Cui et al. (2023), with thresholds adjusted according to the vertical distribution patterns observed in our dataset.

3. Characteristics of LLJs

3.1. Climatological distributions of BLJs and SLLJs

First, we present a comprehensive analysis of the spatial distributions and wind characteristics of LLJs, including BLJs and SLLJs. Fig. 1(a) illustrates the horizontal distributions of LLJ occurrence frequency across China. The highest frequencies are observed over Northeast and South China, with regional means of 22% and 21%, respectively. This distribution broadly agrees with Du et al. (2014) in the main high-frequency regions, but deviates over the Tibetan Plateau, where LLJs show the lowest occurrence (11%), consistent with Yan et al. (2021).

In Northeast China, the high frequency of LLJs is primarily attributable to the prevalence of BLJs (Fig. 1(b)), which are influenced by inertial oscillations and mountain–valley circulations (Shu et al., 2024). Two additional BLJ hotspots are observed near the Tarim Basin in Northwest China and along the coastal regions in South China (near Hainan Island), as also reported by Du et al. (2014). These patterns are shaped by significant thermal gradients between mountain and valley or land and sea, with canyon effects probably enhancing the Tarim Basin hotspot and hydraulic jump effects affecting the southern coastal area (Kong et al., 2020).

In contrast, SLLJs occur most frequently in Southwest and South China, with regional occurrence frequencies of $\sim 14\%$ (Fig. 1(c)). Southwest China emerges as a newly identified high-frequency area for SLLJs. These jets are closely associated with synoptic systems prevalent in the warm season, including mei-yu fronts and the Southwest Vortex, the WPSH, and monsoonal flows (Chen and Chen, 1995; Du et al., 2014; He et al., 2016; Liu and Wang, 2012; Wang et al., 2003; Zhao et al., 2003).

The vertical distribution of LLJ occurrence (Fig. 1(d)) highlights a primary peak at around 0.7 km AGL and a secondary peak at around 1.9 km AGL. Mean maximum wind speeds occur near 0.7 km AGL for BLJs and 2.5 km AGL for SLLJs, with both types reaching $\sim 13 \text{ m s}^{-1}$.

Fig. 1(e–g) summarizes the wind directions and speed characteristics. Overall, LLJs are dominated by southwesterly winds with speeds of $10\text{--}20 \text{ m s}^{-1}$. BLJs show a relatively higher fraction of northeasterly winds, likely influenced by regional topography, while SLLJs feature stronger westerly components and occasionally exceed 30 m s^{-1} , reflecting their synoptic-scale nature.

3.2. Regional variability of LLJ occurrence and vertical structure

To further examine the regional variability highlighted in Section 3.1, Fig. 2 presents the occurrence frequencies of BLJs and SLLJs and the vertical distributions of LLJ core heights across different regions of China. Overall, SLLJs dominate in most areas (Fig. 2(a)), possibly due to their broader vertical range of occurrence. In contrast, BLJs are more prevalent along the coasts of North China and Central China, the western Tibetan Plateau, the eastern part of Northwest China, and central Northeast China. These regional contrasts

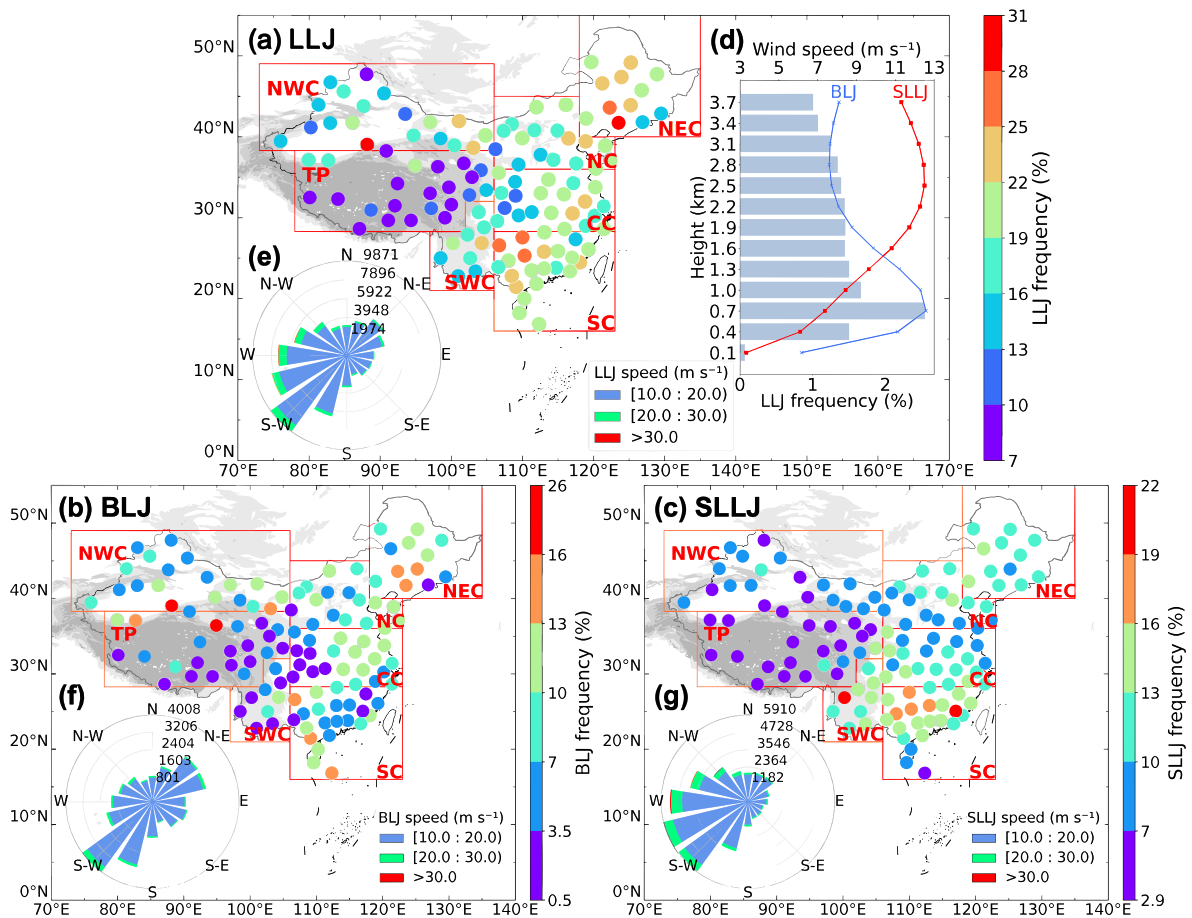


Fig. 1. (a–c) Horizontal distribution of LLJs, BLJs, and SLLJs across seven subregions: Northwest China (NWC), North China (NC), Northeast China (NEC), Tibetan Plateau (TP), Central China (CC), Southwest China (SWC), and South China (SC). (d) Vertical distribution of LLJ occurrence frequency (blue bars), with mean wind vertical profiles for BLJs (blue lines) and SLLJs (red lines). (e–g) Wind direction and speed distributions of all LLJs, BLJs, and SLLJs in China.

provide additional support for the spatial distribution characteristics of BLJs identified in Fig. 1.

Fig. 2(b–h) details the vertical distribution of LLJ core occurrence frequencies within the seven subregions. A double-peak structure is observed in Northwest China, North China, the Tibetan Plateau, and Central China, whereas the other regions exhibit a single peak (Fig. 2(b, c, e, f)). Although the secondary SLLJ peak is generally less pronounced than the primary BLJ peak, it still represents a local maximum in occurrence frequency and should not be negligible. In contrast, the remaining regions exhibit a single peak (Fig. 2(d, g, h)). Notably, the Tibetan Plateau shows an additional SLLJ peak, different from Du et al. (2014).

In regions with a single peak, LLJ cores in Southwest China are concentrated near 1.9 km AGL, with relatively few BLJs (Fig. 2(g)). This might be attributable to the higher elevation of the region, where enhanced sensible heat flux raises the boundary layer height during the warm season (Guo et al., 2019; He et al., 2016; Su et al., 2018; Wang and Liang, 2020). As a result, some BLJs are not captured below the 1.3 km threshold used for identification.

In South China, where dominant synoptic systems differ seasonally, LLJs are analyzed separately for the pre-summer and post-summer rainy seasons (Fig. 2(h)). During the pre-summer rainy season (April–June), the vertical distribution is bimodal, with peaks at approximately 0.7 km and 1.6 km AGL. In contrast, the post-summer rainy season (July–September) shows a single peak near 1 km AGL. The enhanced frequency of SLLJs during the pre-summer rainy season may be partly due to latent heat release associated with enhanced precipitation along the mei-yu front (Fig. S2) (Chen, 1982; Chen et al., 2022). In addition during

this period, the eastward propagation of the southern branch trough of the westerlies and Tibetan Plateau vortices, together with the westward position of the WPSH, enhances the low-level pressure gradient and convergence over South China, thereby promoting the formation and intensification of SLLJs (Chen et al., 2025; Fu et al., 2019; Liang et al., 2019; Lin et al., 2013; Lu et al., 2020; Ma et al., 2020; Yan et al., 2024). Compared with the bimodal distribution in July reported by Du et al. (2014), the vertical frequency covering April–September exhibits a dominant single peak near 1.6 km AGL.

3.3. LLJ wind directions

To further examine the wind direction characteristics of different LLJ types discussed in Section 3.1, Fig. 3(a) illustrates the dominant LLJ wind directions at each station. Overall, LLJs are dominated by southwesterly winds over the eastern plain regions of China, while northwesterly winds prevail in western regions, particularly along mountain edges. This pattern reflects the contrast between eastern China, controlled by the southwest monsoon during the warm season, and western China, influenced by midlatitude westerlies where terrain blocks the inland penetration of monsoonal flow.

This hypothesis is further supported by the regional statistics of BLJ and SLLJ wind directions (Fig. 3(b–h)). Westerlies primarily influence the middle to upper troposphere at mid–high latitudes, producing westerly SLLJs in North China and Northeast China (Fig. 3(c, d)). They are also evident in BLJs over Northwest China and the Tibetan Plateau, where elevated terrain allows westerly flow to penetrate more effec-

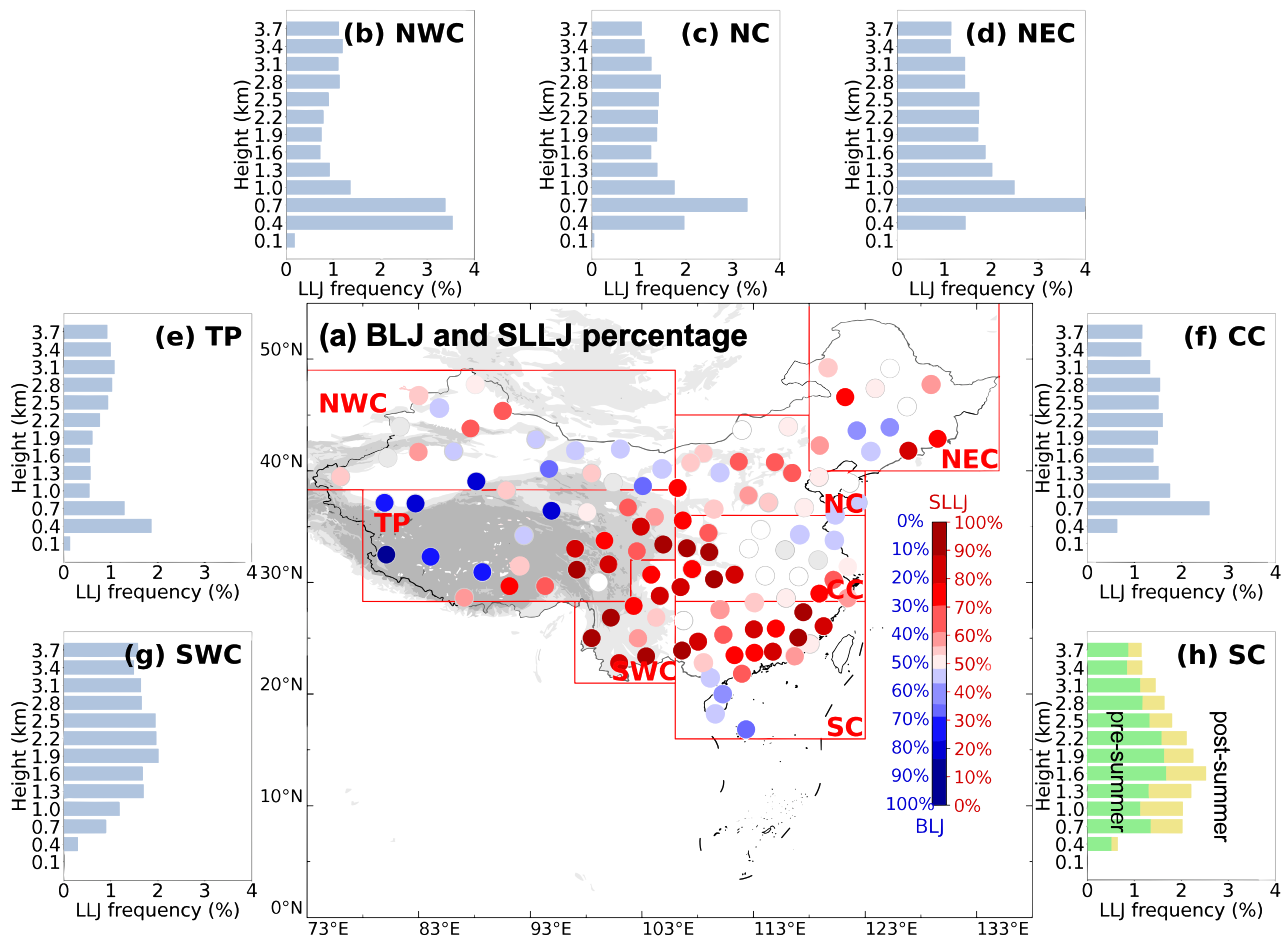


Fig. 2. (a) Station-based occurrence ratios of BLJs and SLLJs. Station color indicates jet dominance: red for SLLJs and blue for BLJs, with darker shades representing higher proportions. (b–h) Vertical frequencies of LLJ core occurrence across seven subregions: Northwest China (NWC), North China (NC), Northeast China (NEC), Tibetan Plateau (TP), Central China (CC), Southwest China (SWC), and South China (SC). In (h), green (yellow) bars represent LLJ frequencies during the pre-summer (post-summer) rainy season.

tively (Fig. 3(b, e)). Collectively, these results indicate that SLLJs exhibit a stronger westerly component across most regions, consistent with the overall wind direction characteristics outlined in Section 3.1.

In contrast, the southwest monsoon dominates the lower troposphere in mid-low latitudes. As a result, BLJs over Southwest China, as well as both BLJs and SLLJs over South China and Central China, are primarily southwesterly (Fig. 3(f–h)). During the warm season, the southwesterly monsoonal flow also extends northward, affecting BLJs over Northeast China (Fig. 3(d)). In South China, SLLJs are predominantly southwesterly, while BLJs display a more southerly component.

As noted earlier, BLJs exhibit a higher proportion of northeasterly winds compared with SLLJs (Fig. 1(f, g)). Northeasterly winds are mainly found over the western part of Central China and the Tarim Basin (Fig. 3(a)). In Central China, southeasterly, southwesterly, and northeasterly flows appear sequentially from east to west, which is indicative of airflow around the periphery of a low vortex. In the Tarim Basin, the eastward-opening gaps between the northern and southern mountain ranges, combined with the canyon effect, facilitate the formation of near-surface northeasterly jets.

3.4. Diurnal variation of LLJs

The formation mechanisms of LLJs inherently lead to pronounced diurnal variability, and their diurnal characteristics have therefore been widely investigated in previous studies (Nicolini et al., 2004; Pu and

Dickinson, 2014; Rife et al., 2010). Following the analysis of spatial characteristics, we next examine the diurnal variation of LLJ occurrence. Fig. 4 presents the diurnal variation of LLJ occurrence, expressed as the ratio between 0800 BJT and 2000 BJT occurrences. Stations with a morning peak (0800 BJT) are marked in purple. A distinct morning peak is observed in Central China, Southwest China, and South China, where BLJs are particularly prevalent (Fig. 4(f–h)). This pattern is consistent with the Blackadar mechanism, which attributes nocturnal LLJ formation to inertial oscillations triggered by the weakening of boundary layer turbulence after sunset. At lower latitudes, the longer inertial oscillation period (small Coriolis parameter) delays the peak until early morning (Blackadar, 1957).

It is noteworthy that in Northwest China, the time-zone offset also plays an important role: by 2000 BJT (1800 LST), the sun has typically not yet set during the warm season, leading to higher LLJ frequencies in the morning (0800 BJT or 0600 LST) (Fig. 4(b)). This diurnal cycle matches the simulations of Du et al. (2014).

Over the Tibetan Plateau, BLJs occur more frequently at 2000 BJT, suggesting a different formation pathway (Fig. 4(a, e)). In this high-elevation region, strong daytime turbulent mixing likely facilitates downward momentum transport, producing late-afternoon BLJs (Zhang et al., 2024).

In North China, BLJ occurrence is more evenly distributed between day and night, though coastal stations show a slight morning preference (Fig. 4(a, c)). This behavior might be strongly influenced by

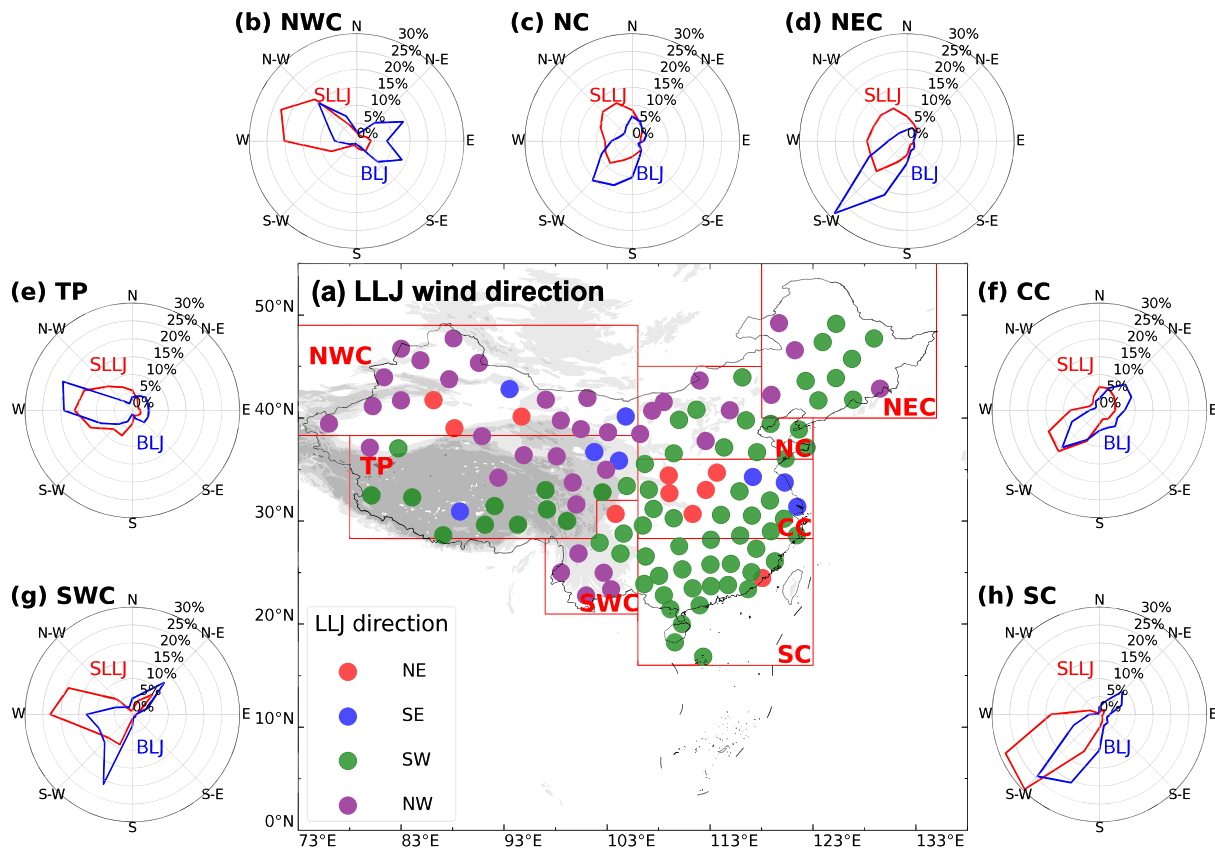


Fig. 3. (a) Horizontal distribution of dominant LLJ wind directions (NE: northeasterly, SE: southeasterly, SW: southwesterly, NW: northwesterly). (b–h) Frequency distributions of BLJs (blue contour) and SLLJs (red contour) wind directions in seven subregions: Northwest China (NWC), North China (NC), Northeast China (NEC), Tibetan Plateau (TP), Central China (CC), Southwest China (SWC), and South China (SC).

the Holton mechanism, wherein ageostrophic easterlies induced by land–sea thermal contrast rotate into southerlies earlier than friction-induced ageostrophic northerlies, allowing southerly jets to form earlier than predicted by the Blackadar mechanism (Du and Rotunno, 2014; Shapiro et al., 2016).

In Northeast China, LLJs occur more frequently in the early evening, consistent with the shorter inertial oscillation period at higher latitude and with valley wind circulations linked to the Holton mechanism (Fig. 4(h)) (Shu et al., 2024).

4. Weather patterns associated with the two types of LLJs based on ERA5

Composite mean geopotential height and wind fields during regional BLJ and SLLJ events (Fig. S1) reveal distinct high- and low-pressure centers across most regions, suggesting that both jet types are closely related to synoptic systems. The associated strong pressure gradients provide favorable background conditions for LLJ formation.

In Northwest China, valley effects formed by northwest–southeast and east–west-oriented mountain ranges contribute to the development of BLJs with prevailing northwesterly and easterly winds (Fig. S1(a1)). Over the Tibetan Plateau, the geopotential height contours are relatively zonal, and LLJs primarily exhibit westerly winds (Fig. S1(c1, c2)). In North China, BLJs are dominated by southwesterly winds (Fig. S1(d1)), while SLLJs are mainly northwesterly due to the clockwise turning with height associated with warm advection (Fig. S1(d2)). The northwestward extension of the high-pressure system south of the SLLJ region weakens the southerly wind components of SLLJs.

In Northeast China, the Northeast Cold Vortex plays a dominant role in the formation of LLJs during the warm season (Fu and Sun, 2012).

BLJs typically occur with southwesterly winds on their southeast flank (Fig. S1(e1)). When the vortex shifts eastward, SLLJs develop with northwesterlies on their southeastern flank and southwesterlies on their southwestern flank (Fig. S1(e2)).

In Southwest China, the Southwest Vortex is a key driver of LLJs. Its southeastern flank supports southwesterly BLJs (Fig. S1(g1)), while its peripheral circulation produces southwesterly, southeasterly, and northeasterly winds in Central China (Fig. S1(d1)) (Liu et al., 2014).

In South China, BLJs and SLLJs exhibit contrasting wind patterns due to differing mechanisms. BLJs are dominated by southerlies, largely influenced by the baroclinic land–sea thermal contrasts and channeled by north–south-oriented mountain ranges (Fig. S1(f1)). In contrast, SLLJs are characterized by southwesterly winds and typically occur on the northwestern flank of the WPSH (Fig. S1(f2)) (Liu et al., 2023). During the warm season, enhanced cold-air activity in the Southern Hemisphere strengthens the cross-equatorial flow, leading to intensified southerly monsoon flow over the South China Sea, southwesterly monsoon flow over South Asia, and southeasterly monsoon flow over the northwestern Pacific (Ding and Chan, 2005; Zhu, 2012). Together, these monsoon systems establish a persistent large-scale low-level southerly–southwesterly background that is favorable for the development and maintenance of SLLJs over South China and the northern South China Sea (Sun, 1986). In addition, the WPSH enhances the zonal horizontal pressure gradient force and provides a southwesterly background circulation for SLLJs via monsoon flows along its northwestern flank (Liu and Wang, 2012; Wang et al., 2013; Zhao et al., 2003). Superimposed on this favorable large-scale environment, synoptic-scale disturbances such as fronts and low-level vortices further contribute to the initiation and intensification of SLLJs (Chen et al., 2006; He et al., 2016).

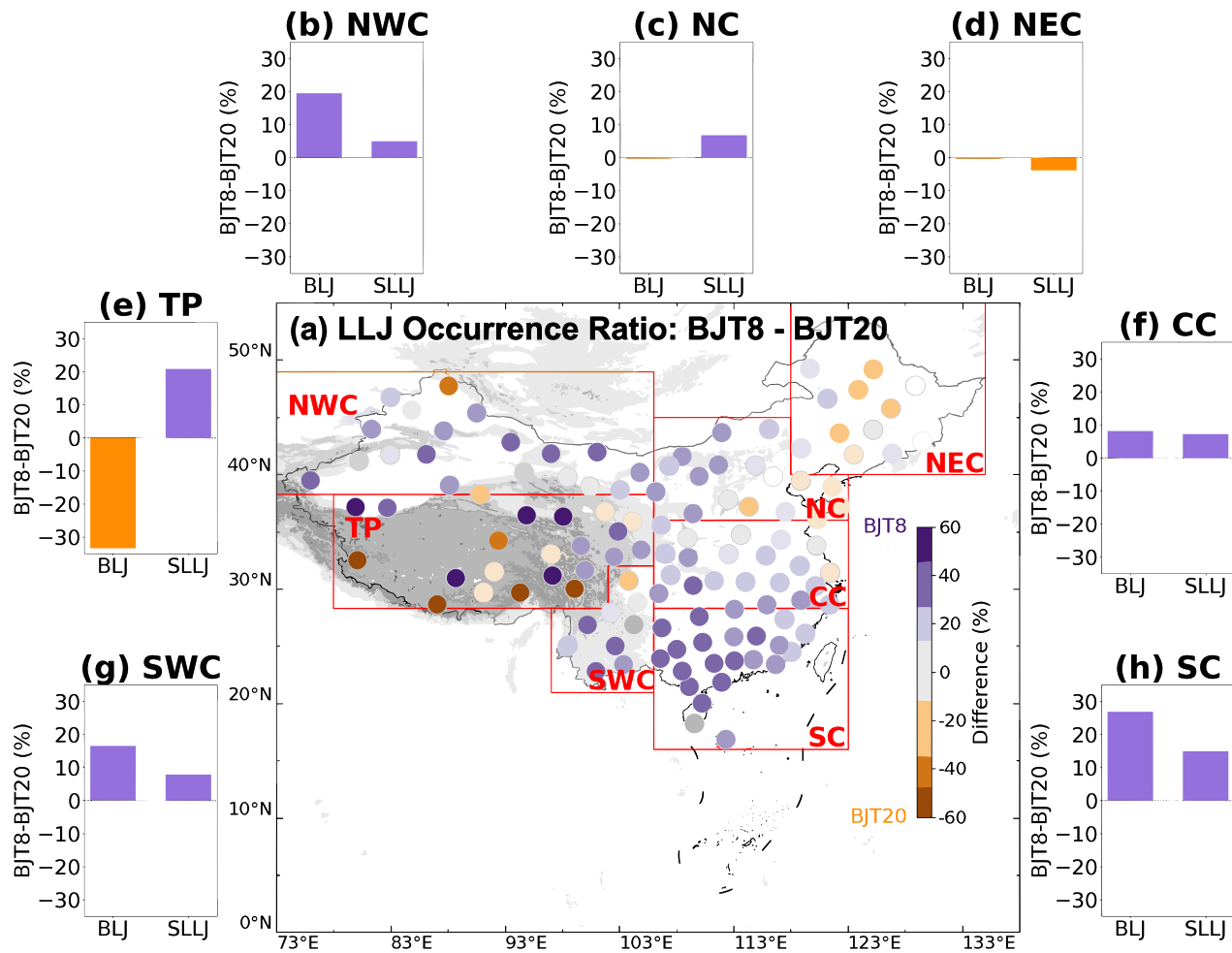


Fig. 4. (a) Spatial distribution of the difference in LLJ occurrence ratio between 0800 BJT and 2000 BJT. Stations shaded in purple (orange) indicate more frequent LLJ occurrence at 0800 BJT (2000 BJT). (b–h) Differences in occurrence ratios of BLJs and SLLJs between 0800 and 2000 BJT across seven subregions: Northwest China (NWC), North China (NC), Northeast China (NEC), Tibetan Plateau (TP), Central China (CC), Southwest China (SWC), and South China (SC).

5. Discussion and conclusion

This study investigates two types of LLJs—namely, BLJs and SLLJs—across China during the warm season (2008–2017), using high-vertical-resolution radiosonde observations. Their spatiotemporal characteristics and synoptic backgrounds were systematically compared.

Overall, LLJs occur most frequently over Northeast and South China. BLJs are predominantly found over the Northeast Plain, between the Tibetan Plateau and Tarim Basin, and near Hainan Island, reflecting the combined influence of the Holton mechanism, orographic blocking, and channeling. In contrast, SLLJs are mainly distributed across South and Southwest China, where they are strongly linked to warm-season synoptic systems such as the mei-yu front, the Southwest Vortex, the WPSH, and monsoonal flows.

The vertical structure of LLJs shows a primary occurrence peak at ~ 0.7 km AGL and a secondary peak at ~ 1.9 km. BLJs and SLLJs exhibit average wind speed maxima of ~ 13 m s $^{-1}$ at 0.7 km and 2.5 km AGL, respectively. A distinct double-peak vertical distribution of LLJ occurrence is evident in several regions, including the Tibetan Plateau, Northwest China, North China, Central China, and South China during the pre-summer rainy season. The features highlight the influence of both topography and weather processes on LLJ vertical variability.

Wind direction patterns further underscore regional contrasts. Southwesterly LLJs dominate the eastern plain of China under monsoon circulation, while northwesterly LLJs prevail in western mountainous regions

under the influence of westerlies and terrain. Regionally, southwesterlies dominate in South and Central China and in BLJs over Northeast and Southwest China, whereas northwesterlies are typical of LLJs in Northwest China and the Tibetan Plateau, as well as of SLLJs in North and Northeast China.

The diurnal cycles reveal strong latitudinal dependence. LLJs occur more frequently in the early morning (0800 BJT) across Central, Southwest, and South China, but in the early evening (2000 BJT) in Northeast China. This latitudinal dependence is consistent with the Blackadar mechanism, where inertial oscillation periods vary with latitude. The earlier onset of BLJs in North China may also reflect additional contributions from the Holton mechanism.

Both BLJs and SLLJs are often accompanied by large-scale synoptic systems. In Northeast China, the Northeast Cold Vortex strongly modulates both types, with its position governing jet wind directions. In South China, SLLJs are more closely related to the WPSH and monsoon flows, resulting in a more westerly wind component compared with BLJs. In Southwest China, southwesterly BLJs develop along the southeastern flank of the southwest vortex, while southeasterlies on its northeastern side influence BLJs in Central China.

This study provides the first detailed observational climatology that distinguishes between BLJs and SLLJs across China using high-resolution nationwide radiosonde data. Relative to previous studies, it refines the spatial, vertical, and temporal characteristics of both jet types, clarifies their distinct synoptic environments, and provides an

observation-based benchmark for evaluating results derived from reanalysis data and numerical simulations, which are subject to uncertainties arising from model parameterization or data assimilation. However, it does not quantify their direct impacts on precipitation at the national scale, nor fully examine their formation mechanisms. Future work will focus on linking BLJ and SLLJ activity to rainfall variability in representative regions of China and further explore the processes driving their development.

Funding

This study was supported by the National Key Research and Development Program of China [grant number 2024YFC3013003], the Heavy Rainfall Research Foundation of China [grant number BYKJ2024Z01], the National Natural Science Foundation of China [grant numbers 42475002 and 42475003], the Innovation Group Project of the Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) [grant numbers SML2024SP035, SML2024SP012, and 311024001], the Guangdong Basic and Applied Basic Research Foundation [grant numbers 2025A1515011974, 2024A1515510005, and 2020B0301030004], and the Key Innovation Team of the China Meteorological Administration [grant number CMA2023ZD08].

Acknowledgments

The authors would like to thank the high-performance computing support from the School of Atmospheric Science of Sun Yat-sen University.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.aosl.2026.100791](https://doi.org/10.1016/j.aosl.2026.100791).

References

- Blackadar, A.K., 1957. Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bull. Am. Meteorol. Soc.* 38 (5), 283–290. doi:[10.1175/1520-0477-38.5.283](https://doi.org/10.1175/1520-0477-38.5.283).
- Bonner, W.D., 1968. Climatology of the low level jet. *Mon. Wea. Rev.* 96 (12), 833–850. doi:[10.1175/1520-0493\(1968\)096%3C0833:COTLLJ%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1968)096%3C0833:COTLLJ%3E2.0.CO;2).
- Chen, G.T.J., Wang, C.C., Lin, L.F., 2006. A diagnostic study of a retreating Mei-Yu front and the accompanying low-level jet formation and intensification. *Mon. Wea. Rev.* 134 (3), 874–896. doi:[10.1175/MWR3099.1](https://doi.org/10.1175/MWR3099.1).
- Chen, Q., 1982. The instability of the gravity-inertia wave and its relation to low-level jet and heavy rainfall. *J. Meteorol. Soc. Japan Ser. II* 60 (5), 1041–1057. doi:[10.2151/jmsj1965.60.5.1041](https://doi.org/10.2151/jmsj1965.60.5.1041).
- Chen, X.A., Chen, Y.L., 1995. Development of low-level jets during TAMEX. *Mon. Wea. Rev.* 123 (6), 1695–1719. doi:[10.1175/1520-0493\(1995\)123%3C1695:DOLLJD%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1995)123%3C1695:DOLLJD%3E2.0.CO;2).
- Chen, Y., Ma, W., He, J., Zhao, W., Sun, M., Ma, Y., 2025. Contrasting mechanisms of cross-regional heavy precipitation induced by an eastward-moving Tibetan Plateau vortex: Dynamical dominance versus thermodynamic maintenance. *Atmos. Res.*, 108634. doi:[10.1016/j.atmosres.2025.108634](https://doi.org/10.1016/j.atmosres.2025.108634).
- Chen, Y.L., Chen, X.A., Zhang, Y.X., 1994. A diagnostic study of the low-level jet during TAMEX IOP 5. *Mon. Wea. Rev.* 122 (10), 2257–2284. doi:[10.1175/1520-0493\(1994\)122%3C2257:ADSOTL%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1994)122%3C2257:ADSOTL%3E2.0.CO;2).
- Chen, Y.L., Tu, C.C., Hsiao, F., Chen, C.S., Lin, P.L., Lin, P.H., 2022. An overview of low-level jets (LLJs) and their roles in heavy rainfall over the Taiwan area during the early summer rainy season. *Meteorology* 1 (1), 64–112. doi:[10.3390/meteorology1010006](https://doi.org/10.3390/meteorology1010006).
- Cui, C., Zhou, W., Yang, H., Wang, Xiaokang, Deng, Y., Wang, Xiaofang, Xu, G., Wang, J., 2023. Analysis of the characteristics of the low-level jets in the middle reaches of the Yangtze River during the Mei-yu Season. *Adv. Atmos. Sci.* 40 (4), 711–724. doi:[10.1007/s00376-022-2107-1](https://doi.org/10.1007/s00376-022-2107-1).
- Ding, Y.H., Chan, J.C.L., 2005. The East Asian summer monsoon: An overview. *Meteorol. Atmos. Phys.* 89 (1–4), 117–142. doi:[10.1007/s00703-005-0125-z](https://doi.org/10.1007/s00703-005-0125-z).
- Doubler, D.L., Winkler, J.A., Bian, X., Walters, C.K., Zhong, S., 2015. An NARR-derived climatology of southerly and northerly low-level jets over north America and coastal environs. *J. Appl. Meteorol. Climatol.* 54 (7), 1596–1619. doi:[10.1175/JAMC-D-14-0311.1](https://doi.org/10.1175/JAMC-D-14-0311.1).
- Du, Y., Chen, G., 2018. Heavy rainfall associated with double low-level jets over Southern China. Part I: ensemble-based analysis. *Mon. Wea. Rev.* 146 (11), 3827–3844. doi:[10.1175/MWR-D-18-0101.1](https://doi.org/10.1175/MWR-D-18-0101.1).
- Du, Y., Chen, G., 2019. Heavy rainfall associated with double low-level jets over southern China. Part II: convection initiation. *Mon. Wea. Rev.* 147 (2), 543–565. doi:[10.1175/MWR-D-18-0102.1](https://doi.org/10.1175/MWR-D-18-0102.1).
- Du, Y., Rotunno, R., 2014. A simple analytical model of the nocturnal low-level jet over the great plains of the United States. *J. Atmos. Sci.* 71 (10), 3674–3683. doi:[10.1175/JAS-D-14-0060.1](https://doi.org/10.1175/JAS-D-14-0060.1).
- Du, Y., Zhang, Q., Chen, Y., Zhao, Y., Wang, X., 2014. Numerical simulations of spatial distributions and diurnal variations of low-level jets in China during early summer. *J. Clim.* 27 (15), 5747–5767. doi:[10.1175/JCLI-D-13-00571.1](https://doi.org/10.1175/JCLI-D-13-00571.1).
- Du, Y., Zhang, Q., Ying, Y., Yang, Y., 2012. Characteristics of low-level jets in Shanghai during the 2008–2009 warm seasons as inferred from wind profiler radar data. *J. Meteor. Soc. Japan* 90 (6), 891–903. doi:[10.2151/jmsj.2012-603](https://doi.org/10.2151/jmsj.2012-603).
- Ferguson, C.R., 2022. Changes in great plains low-level jet structure and associated precipitation over the 20th century. *J. Geophys. Res.: Atmos.* 127 (3), e2021JD035859. doi:[10.1029/2021JD035859](https://doi.org/10.1029/2021JD035859).
- Fu, S.M., Mai, Z., Sun, J.H., Li, W.L., Ding, Y., Wang, Y.Q., 2019. Impacts of convective activity over the Tibetan Plateau on plateau vortex, southwest vortex, and downstream precipitation. *J. Atmos. Sci.* 76 (12), 3803–3830. doi:[10.1175/JAS-D-18-0331.1](https://doi.org/10.1175/JAS-D-18-0331.1).
- Fu, S., Sun, J., 2012. Circulation and eddy kinetic energy budget analyses on the evolution of a Northeast China cold vortex (NCCV) in May 2010. *J. Meteor. Soc. Japan Ser. II* 90 (4), 553–573. doi:[10.2151/jmsj.2012-408](https://doi.org/10.2151/jmsj.2012-408).
- Fu, S.M., Zhang, Y.C., Wang, H.J., Tang, H., Li, W.L., Sun, J.H., 2022. On the evolution of a long-lived mesoscale convective vortex that acted as a crucial condition for the extremely strong hourly precipitation in Zhengzhou. *J. Geophys. Res.: Atmos.* 127 (11), e2021JD036233. doi:[10.1029/2021JD036233](https://doi.org/10.1029/2021JD036233).
- Guo, J., Li, Y., Cohen, J.B., Li, J., Chen, D., Xu, H., Liu, L., Yin, J., Hu, K., Zhai, P., 2019. Shift in the temporal trend of boundary layer height in China using long-term (1979–2016) radiosonde data. *Geophys. Res. Lett.* 46 (11), 6080–6089. doi:[10.1029/2019GL082666](https://doi.org/10.1029/2019GL082666).
- He, M.Y., Liu, H.B., Wang, B., Zhang, D.L., 2016. A modeling study of a low-level jet along the Yun-Gui Plateau in south China. *J. Appl. Meteorol. Climatol.* 55 (1), 41–60. doi:[10.1175/JAMC-D-15-0067.1](https://doi.org/10.1175/JAMC-D-15-0067.1).
- Holton, J.R., 1967. The diurnal boundary layer wind oscillation above sloping terrain. *Tellus* 19 (2), 199–205. doi:[10.1111/j.2153-3490.1967.tb01473.x](https://doi.org/10.1111/j.2153-3490.1967.tb01473.x).
- Kong, H., Zhang, Q., Du, Y., Zhang, F., 2020. Characteristics of coastal low-level jets over Beibu Gulf, China, during the early warm season. *J. Geophys. Res.: Atmos.* 125 (14), e2019JD031918. doi:[10.1029/2019JD031918](https://doi.org/10.1029/2019JD031918).
- Li, D., Von Storch, H., Yin, B., Xu, Z., Qi, J., Wei, W., Guo, D., 2018. Low-Level Jets Over the Bohai Sea and Yellow Sea: climatology, variability, and the relationship with regional atmospheric circulations. *J. Geophys. Res.: Atmos.* 123 (10), 5240–5260. doi:[10.1029/2017JD027949](https://doi.org/10.1029/2017JD027949).
- Li, N., Guo, J., Wu, M., Zhang, F., Guo, X., Sun, Y., Zhang, Z., Liang, H., Chen, T., 2024. Low-level jet and its effect on the onset of summertime nocturnal rainfall in Beijing. *Geophys. Res. Lett.* 51 (20), e2024GL110840. doi:[10.1029/2024GL110840](https://doi.org/10.1029/2024GL110840).
- Liang, Z., Fovell, R.G., Liu, Y., 2019. Observational analysis of the characteristics of the synoptic situation and evolution of the organized warm-sector rainfall in the coastal region of South China in the pre-summer rainy season. *Atmosphere* 10 (11), 722. doi:[10.3390/atmos10110722](https://doi.org/10.3390/atmos10110722).
- Lima, D.C.A., Soares, P.M.M., Nogueira, M., Semedo, A., 2022. Global coastal LOW-LEVEL winds revisited through the new ERA5 reanalysis. *Int. J. Climatol.* 42 (9), 4491–4507. doi:[10.1002/joc.7482](https://doi.org/10.1002/joc.7482).
- Lin, A., Li, C., Zheng, B., Gu, D., 2013. Variation characteristics of sustained torrential rain during the pre-flooding season in Guangdong and the associated circulation pattern. *Acta Meteor. Sinica* 71 (4), 628–642. doi:[10.1007/s13351-013-0507-y](https://doi.org/10.1007/s13351-013-0507-y).
- Liu, H., He, M., Wang, B., Zhang, Q., 2014. Advances in low-level jet research and future prospects. *J. Meteorol. Res.* 28 (1), 57–75. doi:[10.1007/s13351-014-3166-8](https://doi.org/10.1007/s13351-014-3166-8).
- Liu, X., Chen, G., Zhang, S., Du, Y., 2023. Formation of low-level jets over southern China in the Mei-Yu season. *Adv. Atmos. Sci.* 40 (10), 1731–1748. doi:[10.1007/s00376-023-2358-5](https://doi.org/10.1007/s00376-023-2358-5).
- Liu, H.B., Wang, B., 2012. Low-level jets over southeast China: The warm season climatology of the summer of 2003. *Atmos. Ocean. Sci. Lett.* 5 (5), 394–400. doi:[10.1080/16742834.2012.11447017](https://doi.org/10.1080/16742834.2012.11447017).
- Lu, P., Zheng, W., Li, Y., 2020. Comparison of the movement and vertical structures of two types of the southwest vortex. *Meteorol. Atmos. Phys.* 132 (4), 571–581. doi:[10.1007/s00703-019-00707-3](https://doi.org/10.1007/s00703-019-00707-3).
- Luiz, E.W., Fiedler, S., 2024. Global climatology of low-level-jets: Occurrence, characteristics, and meteorological drivers. *J. Geophys. Res.: Atmos.* 129 (9), e2023JD040262. doi:[10.1029/2023JD040262](https://doi.org/10.1029/2023JD040262).
- Luo, Y., Du, Y., 2023. The roles of low-level jets in “21·7” Henan extremely persistent heavy rainfall event. *Adv. Atmos. Sci.* 40 (3), 350–373. doi:[10.1007/s00376-022-2026-1](https://doi.org/10.1007/s00376-022-2026-1).
- Ma, T., Liu, Y.M., Wu, G.X., Mao, J.Y., Zhang, G.S., 2020. Effect of potential vorticity on the formation, development, and eastward movement of a Tibetan Plateau vortex and its influence on downstream precipitation. *Chin. J. Atmos. Sci.* 44 (3), 472–486. doi:[10.1007/s00376-021-1027-9](https://doi.org/10.1007/s00376-021-1027-9).
- Miao, Y., Guo, J., Liu, S., Wei, W., Zhang, G., Lin, Y., Zhai, P., 2018. The climatology of low-level jet in Beijing and Guangzhou, China. *J. Geophys. Res.: Atmos.* 123 (5), 2816–2830. doi:[10.1002/2017JD027321](https://doi.org/10.1002/2017JD027321).
- Monaghan, A.J., Rife, D.L., Pinto, J.O., Davis, C.A., Hannan, J.R., 2010. Global precipitation extremes associated with diurnally varying low-level jets. *J. Clim.* 23 (19), 5065–5084. doi:[10.1175/2010JCLI3515.1](https://doi.org/10.1175/2010JCLI3515.1).
- Nicolini, M., Salio, P., Ulke, G., Marengo, J., Douglas, M., Paegle, J., Zipser, E., 2004. South American low-level jet diurnal cycle and three-dimensional structure. *Clivar. Exchang.* 9 (1), 6–9. doi:[10.1175/bams-87-1-63](https://doi.org/10.1175/bams-87-1-63).
- Pu, B., Dickinson, R.E., 2014. Diurnal spatial variability of Great Plains summer precipitation related to the dynamics of the low-level jet. *J. Atmos. Sci.* 71 (5), 1807–1817. doi:[10.1175/JAS-D-13-0243.1](https://doi.org/10.1175/JAS-D-13-0243.1).
- Ranjha, R., Svensson, G., Tjernström, M., Semedo, A., 2013. Global distribution and seasonal variability of coastal low-level jets derived from ERA-Interim reanalysis. *Tellus A: Dyn. Meteorol. Oceanogr.* 65 (1), 20412. doi:[10.3402/tellusa.v65i0.20412](https://doi.org/10.3402/tellusa.v65i0.20412).

- Rife, D.L., Pinto, J.O., Monaghan, A.J., Davis, C.A., Hannan, J.R., 2010. Global distribution and characteristics of diurnally varying low-level jets. *J. Clim.* 23 (19), 5041–5064. doi:[10.1175/2010JCLI3514.1](https://doi.org/10.1175/2010JCLI3514.1).
- Shapiro, A., Fedorovich, E., Rahimi, S., 2016. A unified theory for the great plains nocturnal low-level jet. *J. Atmos. Sci.* 73 (8), 3037–3057. doi:[10.1175/JAS-D-15-0307.1](https://doi.org/10.1175/JAS-D-15-0307.1).
- Shu, H., Zhang, F., Du, Y., Wang, Y., Guo, H., Song, Z., Zhang, Q., 2024. Characteristics and formation mechanisms of low-level jets in northeastern China. *Adv. Atmos. Sci.* 41 (12), 2432–2445. doi:[10.1007/s00376-024-3209-8](https://doi.org/10.1007/s00376-024-3209-8).
- Stensrud, D.J., 1996. Importance of low-level jets to climate: A review. *J. Clim.* 1698–1711. doi:[10.1175/1520-0442\(1996\)009%3C1698:IOLLJT%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(1996)009%3C1698:IOLLJT%3E2.0.CO;2).
- Su, L., Hu, J., Du, Y., Li, J., Chen, G., 2025. Boundary-layer and low-level moisture fluxes during low-level jet events in south China and their relationship with early summer rainfall. *J. Clim.* 38 (7), 1691–1713. doi:[10.1175/JCLI-D-23-0561.1](https://doi.org/10.1175/JCLI-D-23-0561.1).
- Su, T., Li, Z., Kahn, R., 2018. Relationships between the planetary boundary layer height and surface pollutants derived from lidar observations over China: Regional pattern and influencing factors. *Atmos. Chem. Phys.* 18 (21), 15921–15935. doi:[10.5194/acp-18-15921-2018](https://doi.org/10.5194/acp-18-15921-2018).
- Sun, S., 1986. The relationship between large scale low level jet over east Asia and monsoon as well as cross-equatorial currents in summer. *Acta Meteorol. Sinica* 44 (1), 55–62. doi:[10.11676/qxxb1986.007](https://doi.org/10.11676/qxxb1986.007).
- Wang, D., Liang, Z., 2020. Spatio-temporal characteristics of boundary layer height derived from soundings. *J. Appl. Meteor. Sci.* 31, 447–459. doi:[10.1007/bf00120035](https://doi.org/10.1007/bf00120035).
- Wang, D., Zhang, Y., Huang, A., 2013. Climatic features of the south-westerly low-level jet over southeast China and its association with precipitation over east China. *Asia-Pac. J. Atmos. Sci.* 49 (3), 259–270. doi:[10.1007/s13143-013-0025-y](https://doi.org/10.1007/s13143-013-0025-y).
- Wang, Z., Gao, K., Zhai, G., 2003. A mesoscale numerical simulation of low level jet realted with the southwest vortex. *Chin. J. Atmos. Sci.* 27 (1), 75–85. doi:[10.1007/bf02915507](https://doi.org/10.1007/bf02915507).
- Whiteman, C.D., Bian, X., Zhong, S., 1997. Low-level jet climatology from enhanced rawinsonde observations at a site in the southern great plains. *J. Appl. Meteorol.* 36 (10), 1363–1376. doi:[10.1175/1520-0450\(1997\)036%3C1363:LLJCFE%3E2.0.CO;2](https://doi.org/10.1175/1520-0450(1997)036%3C1363:LLJCFE%3E2.0.CO;2).
- Yan, Y., Cai, X., Wang, X., Miao, Y., Song, Y., 2021. Low-level jet climatology of China derived from long-term radiosonde observations. *J. Geophys. Res.: Atmos.* 126 (20), e2021JD035323. doi:[10.1029/2021JD035323](https://doi.org/10.1029/2021JD035323).
- Yan, R.T., Deng, F.D., Xu, D.B., Mai, Z.N., 2024. Analysis of the occurrence rules of the moving-out vortex over the Qinghai-Xizang Plateau and the differences in the development mechanism of typical cases in warm seasons. *J. Arid Meteorol.* 42 (6), 910. doi:[10.1007/978-1-935704-19-5_41](https://doi.org/10.1007/978-1-935704-19-5_41).
- Zhang, L., Zhang, H., Cai, X., Song, Y., Mamtimin, A., He, Q., 2024. Physical mechanisms of deep convective boundary layer leading to dust emission in the Taklimakan Desert. *Geophys. Res. Lett.* 51 (10), e2024GL108521. doi:[10.1029/2024gl108521](https://doi.org/10.1029/2024gl108521).
- Zhao, P., Sun, J., Zhou, X., 2003. Mechanism of formation of low level jets in the South China Sea during spring and summer of 1998. *Chin. Sci. Bull.* 48 (12), 1265–1270. doi:[10.1007/BF03183949](https://doi.org/10.1007/BF03183949).
- Zhao, Y., 2012. Numerical investigation of a localized extremely heavy rainfall event in complex topographic area during midsummer. *Atmos. Res.* 113, 22–39. doi:[10.1016/j.atmosres.2012.04.018](https://doi.org/10.1016/j.atmosres.2012.04.018).
- Zhu, Y., 2012. Variations of the summer Somali and Australia cross-equatorial flows and the implications for the Asian summer monsoon. *Adv. Atmos. Sci.* 29 (3), 509–518. doi:[10.1007/s00376-011-1120-6](https://doi.org/10.1007/s00376-011-1120-6).