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Key Points:

- The Dongting-Poyang Lake region frequently experiences two types of boundary-layer jets linked to heavy rain: southerly and northeasterly
- Inertial oscillation drives nocturnal southerly jets and exit-region rainfall, while suppressing daytime winds and precipitation
- Northeasterly jet rain results from moisture transport by boundary-layer northerly and overlying southerly, combined with terrain lift

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Characteristics, Mechanisms, and Rainfall Impacts of Warm-Season Boundary-Layer Jets in the Dongting-Poyang Lake Region, South of the Middle Reach of the Yangtze River, China

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Abstract Boundary-layer (BL) jets (BLJs) exhibit significant diurnal variations and can strongly influence precipitation. The Dongting-Poyang Lake region of China experiences frequent BLJs and heavy rainfall, yet systematic studies remain limited. This study investigates southerly and northeasterly BLJs (SBLJs and NEBLJs) in the region, focusing on their spatiotemporal distributions, formation, and precipitation impacts. SBLJs occur most frequently in summer, characterized by strong, deep south–southwesterly flows with warm advection. SBLJs peak around 02:00 Beijing Time (BJT) and weaken after sunrise as the mixed BL develops, with a typical duration of 1–9 hr. NEBLJs occur mainly in spring and fall, featuring strong but shallow northeasterly flows. NEBLJs peak around 22:00 BJT, show weaker diurnal variability, with a higher proportion of long-duration cases persisting into daytime. Daily-mean BLJ winds depend on synoptic patterns, while nocturnal intensification is dominated by BL inertial oscillations. Daytime mixing weakens BL winds, and reduced nighttime friction enables inertial oscillations to strengthen BL flows. Differences in seasons, thermodynamic conditions, and BL depth modulate inertial oscillation phases. This causes NEBLJs to peak ~4 hr earlier than SBLJs. SBLJ-associated precipitation concentrates at the jet exit region and peaks during pre-dawn to early morning. Nocturnal BLJ strengthening enhances moisture flux and convergence to favor rainfall, while daytime deviation winds suppress precipitation. NEBLJ precipitation occurs at the jet exit during pre-dawn to early morning and on its left side in early evening. Of these, exit-region rainfall results from moisture transport by BL northerly and overlying southerly, combined with terrain-induced lift.

Plain Language Summary The Dongting-Poyang Lake region in China, south of the middle reach of the Yangtze River, often experiences two types of boundary-layer jets that strongly influence rainfall. One type of jet blows from the south or southwest, mainly in summer, peaking around 02:00 Beijing Time, then weakening after sunrise as the mixed boundary-layer develops. The second type originates from the northeast, usually in spring and autumn, and can last longer, sometimes persisting into the daytime. Nighttime strengthening of both jets is driven by boundary-layer inertial oscillations, while daytime mixing tends to weaken the winds. The northeast jets reach their strongest winds about 4 hr earlier than the southern jets, due to differences in season, thermal conditions, and boundary-layer depth. For the southerly jets, rainfall concentrates at the jet exit and peaks during the pre-dawn-to-early-morning hours, driven by nocturnal jet intensification that enhances moisture flux and convergence. For the northeasterly jets, the pre-dawn-to-early-morning rainfall peak near the jet exit results from moisture transport by boundary-layer northerlies combined with overlying southerlies, plus terrain-induced lifting. Understanding these wind jets and their effects on heavy rain over inland plains and mountainous regions is important for precipitation forecasting and disaster prevention.

1. Introduction

Low-level jets (LLJs) not only provide enhanced moisture transport but also induce diurnally varying geostrophic convergence and uplift in the jet exit region. Thereby, they modulate the diurnal peak, location, and intensity of precipitation (Fu et al., 2019; Xue et al., 2018). Based on their formation mechanisms and structural characteristics, LLJs can be categorized into boundary-layer (BL) jets (BLJs) and synoptic-scale LLJs (SLLJs)

(Banta, 2008). It is found that SLLJs remarkably influence the temporal and spatial distribution of BLJs (Wei et al., 2013). Nocturnal BLJs induced primarily by inertial oscillations (Blackadar, 1957) are crucial in forcing nocturnal precipitation (Xue et al., 2018; Y. Zhang et al., 2019). They enhance vertical shear between the BL and the free atmosphere, promote transport of warm-moist air, significantly increase moist static energy, and force convection and heavy rainfall near the jet exit region (Du & Chen, 2018; Su et al., 2025; Xue et al., 2018; Y. Zhang et al., 2019). About 74% of persistent heavy rainfall cases along the southern China coast are accompanied by southwesterly BLJs (X. Huang et al., 2022). Therefore, understanding the formation mechanisms of BLJs and their precipitation impacts is of great practical significance for improving heavy rainfall prediction.

The formation of BLJs is often attributed to inertial oscillations (Blackadar, 1957), as well as to influences from large-scale topography and land–sea baroclinicity (Burk & Thompson, 1996; Holton, 1967). Blackadar (1957) first proposed the BL inertial oscillation mechanism to explain the formation of nocturnal LLJs over the Southern Great Plains of the United States during summer. In his conceptual model, the rapid reduction of turbulent mixing after sunset disrupts the geostrophic balance within the BL, causing the wind vector to undergo a clockwise rotation that produces a supergeostrophic low-level wind maximum in the form of BLJ after mid-night (Du & Rotunno, 2014; Parish et al., 1988). Over land, the BL inertial oscillations, with the key signature of the clockwise rotation of the ageostrophic wind component are found in many parts of the world (Jiang et al., 2007; Van de Wiel et al., 2010). Holton (1967) attributed the nocturnal LLJs over the Great Plains region of the United States with large-scale sloping terrain to thermally driven diurnal oscillations. BL heating and cooling over the sloping terrain create horizontal buoyancy gradients and the development of up and downslope circulations and associated geostrophic adjustment. McNider and Pielke (1981) also found that mountain cooling, turbulence suppression, and inertial oscillation jointly govern nocturnal LLJ formation. Shapiro et al. (2016) developed a unified theory for the Great Plains nocturnal LLJs that combines the Blackadar inertial oscillation and the Holton buoyancy gradient mechanism. They found that the Holton mechanism by itself results in relatively weak wind maxima, but produces stronger jets when combined with the Blackadar mechanism. Jets that develop with both mechanisms were found to be generally consistent with observations and climatological analyses of the Great Plains LLJs. This suggests that both mechanisms can have their effects but the Blackadar inertial oscillation mechanism typically plays a more dominant role, especially in regions where terrain is relatively flat. Previous studies on BLJs in China have mainly focused on those in coastal areas and regions with large-scale topography. Over the coastal regions, BLJs are mainly driven by the inertial oscillation of ageostrophic winds, while large-scale sea-breeze circulations and land-sea thermal contrasts further amplify their nocturnal intensification (Dong et al., 2021; Du et al., 2015). In inland regions, for the well-known nocturnal precipitation peak in the Sichuan Basin, China, inertial-oscillation-enhanced BLJs form over the Yunnan-Guizhou Plateau, enter the semi-closed basin, and produce low-level convergence, resulting in this unique nocturnal rainfall peak. During the daytime, subgeostrophic BLJs draw air out from the basin, producing net divergence that suppresses precipitation within the basin (Y. Zhang et al., 2019). For Mei-yu frontal precipitation over the Yangtze-Huaihe river basins in China, Xue et al. (2018) emphasized the controlling role of BL inertial oscillations on precipitation diurnal variations. Similar to the Sichuan Basin, nocturnal supergeostrophic southwesterly BLJs produce strong net low-level convergence along the Mei-yu front, leading to an early-morning rainfall peak. During daytime, enhanced BL mixing generates subgeostrophic southerly flows and net divergence, suppressing rainfall at the Mei-yu front.

The Yangtze River basin is among the regions within China that experience the highest risks of extreme rainfall and flooding, where precipitation is influenced by multi-scale systems with complex mechanisms (G. Chen et al., 2019; Guan et al., 2020; H. L. Zhang et al., 2024). Historically, many heavy rainfall events in the mid-lower reaches of the Yangtze River, such as those in early July 2016, late May 2019, and early July 2020, had rainfall concentrated over the Dongting and Poyang Lakes and the surrounding lowlands (red dashed box in Figure 1, hereafter referred to as the DP-Lake region), and all these events were accompanied by BLJs (Y. Chen et al., 2020; Gou & Chen, 2020; Z. Huang et al., 2021). Statistical analyses further indicate that the DP-Lake region exhibits a high frequency of BLJs (Cui et al., 2023). Meanwhile, the region is characterized by mesoscale mountains, river basins, and dense river-lake networks (Figure 1). This raises the question of whether the dominant formation mechanisms, diurnal variations, and precipitation impacts of BLJs in the DP-Lake region differ from those in other areas of China.

Most prior BLJ studies in China dealt with southerly BLJs only (Du & Chen, 2019; Zhi et al., 2022). However, recent studies have revealed that heavy rainfall events over southern China are also frequently accompanied by northeasterly BLJs (D. Hu et al., 2025; Wang, Cui, et al., 2022). Northeasterly BLJs can directly transport

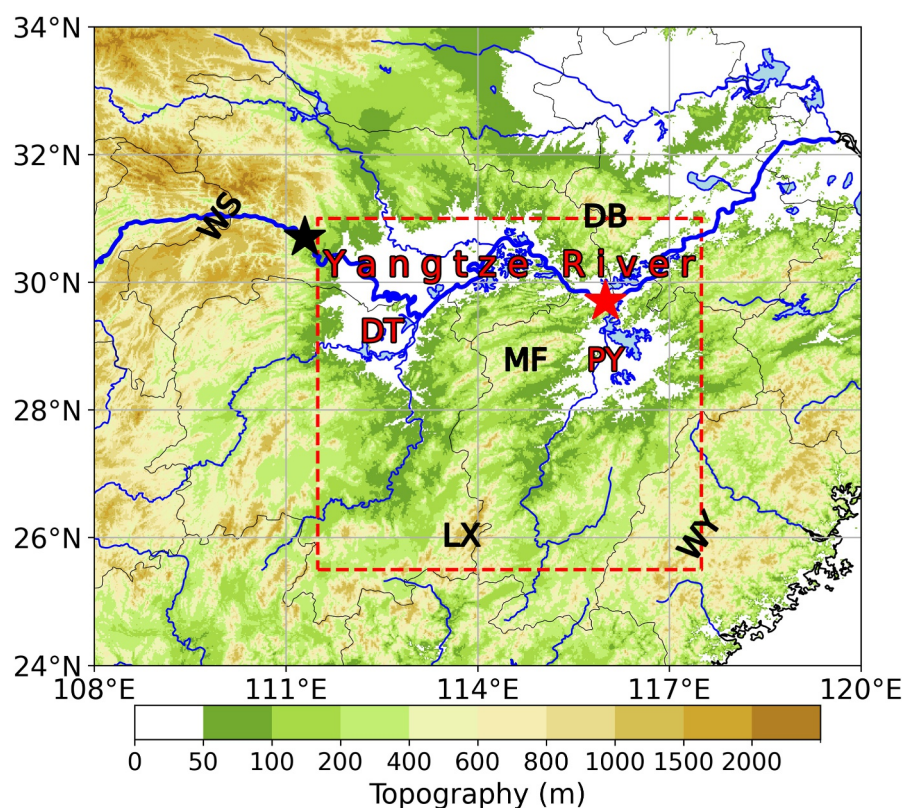


Figure 1. Topography (shading, m), major rivers (dark blue, with the thickest line representing the Yangtze River), and lakes (light blue) in eastern and central China. Gray lines represent provincial boundaries. Black labels WS, DB, MF, LX, and WY mark the locations of the Wushan, Dabie, Mufu, Luoxiao, and Wuyi Mountains, respectively. Red labels DT and PY indicate Dongting Lake and Poyang Lake, respectively. The red dashed rectangle outlines the DP-Lake region. The middle reach of the Yangtze River, extending from Yichang (black star) to Hukou (red star), is also indicated.

moisture from the coastal ocean into the inland areas of southern China, where local terrain-enhanced convergence promotes uplift and rainfall formation (He et al., 2020, 2023). Systematic studies of northeasterly BLJs remain limited, leaving their key characteristics and impacts on regional rainfall poorly understood.

This study first examines the climatology and establishes appropriate criteria for identifying and classifying BLJs in the DP-Lake region during the extended warm season (April–October), then addresses the following questions: (1) What are the primary BLJ types in the DP-Lake region, and what are their spatiotemporal distributions and structural characteristics? (2) How do the formation mechanisms and diurnal variation patterns differ among different BLJ types in the region? (3) How do the BLJs influence regional precipitation? We conduct the study by using the ECMWF fifth-generation global reanalysis (ERA5) data set (Hersbach et al., 2020) and hourly rain gauge data over a 20-year period.

The remainder of this paper is organized as follows. Section 2 describes the data and methodology, discusses the definition and classification criteria for BLJs. Section 3 presents the results, covering (a) statistical characteristics of BLJs in the DP-Lake region, (b) formation and diurnal mechanisms from the perspectives of synoptic systems and inertial oscillations, and (c) impacts of southerly and northeasterly BLJs on rainfall distribution and diurnal variations. The final section provides a summary and discussion.

2. Data and Methods

2.1. Data

In this study, we focus on LLJs and precipitation during the warm season (April–October) from 2001 to 2021 within the DP-Lake region (111.5°–117.5°E, 25.5°–31°N), situated south of the middle Yangtze River basin. This study employs two primary data sets to analyze LLJs and precipitation over the DP-Lake region: hourly rain

gauge data from the national meteorological observation stations of China, and the ERA5 data set that has a spatial resolution of $0.25^\circ \times 0.25^\circ$ and an hourly temporal resolution (Hersbach et al., 2023). Pressure-level variables (horizontal wind components u and v , temperature, specific humidity, and geopotential height) and single-level variables (surface downward shortwave radiation and BL height) from ERA5 are employed to characterize BLJs and the associated environmental conditions. Previous evaluations have demonstrated that ERA5 data have good capability in reproducing the low-level wind fields over China, effectively capturing the fine structure and diurnal variations of the BLJ (Du & Yi, 2025; Li & Du, 2021).

We noticed that the low-level wind fields in ERA5 exhibit a pronounced weakening from 17:00 to 18:00 BJT (=UTC + 8 hr) and from 05:00 to 06:00 BJT. Similar behaviors have been reported by previous studies (G. Chen et al., 2021; Liu et al., 2023; Xu et al., 2021), which have been attributed to the assimilation scheme employed in ERA5. The ERA5 4DVar system uses a 12 hr data assimilation window, with observational data assimilated from 09:00 to 21:00 UTC (inclusive) and from 21:00 to 09:00 UTC (inclusive) of the following day. Therefore, the 09:00 and 10:00 UTC (17:00 and 18:00 BJT) fields, and the 21:00 and 22:00 UTC (05:00 and 06:00 BJT) fields come from two different 4DVar data assimilation cycles (Hersbach et al., 2020), leading to apparent discontinuities across the pairs of times. To mitigate this issue, when presenting the hodographs of hourly winds (Figures 8, 14b, and 14c) using ERA5 data, values at 10:00 UTC (18:00 BJT) and 22:00 UTC (06:00 BJT) are replaced by the averages of the preceding and following hours to ensure data continuity.

2.2. Definition and Identification Criteria of BLJs

2.2.1. Major Low-Level Wind Patterns

BLJs are often found to peak at around 925 hPa (T. Chen et al., 2024). Based on the daily mean ERA5 925 hPa wind fields during the warm seasons of 2001–2021, hierarchical clustering is performed by treating each daily wind field within the DP-Lake region as a single sample. Consequently, the distance metric measures dissimilarities between complete wind-field patterns, ensuring that the resulting clusters represent distinct circulation regimes. Hierarchical clustering is an agglomerative, iterative approach that begins with each observation forming its own singleton cluster (Y. Hu et al., 2019; Ratto et al., 2014). At each subsequent step, all possible pairs of clusters are evaluated using Ward's distance, which measures the increase in the total within-cluster sum of squares (ESS) that would result from merging the two clusters. The clustering process proceeds iteratively, combining clusters in a manner that minimizes the increase in within-cluster variance. The procedure is typically terminated when a pronounced “jump” in the minimum Ward distance is observed, indicating that two clusters with substantially different characteristics have been merged; thus, the optimal clustering solution is taken from the previous step. The method groups data points by minimizing the total within-cluster variance at each step, producing compact and well-separated clusters. It relies on standardized Euclidean distances to ensure statistical robustness and meaningful separation, making it suitable for analyses that require interpretable and homogeneous clusters.

Hierarchical cluster analysis identifies an objective optimal cluster number of two, which captures the primary contrast between southerly and northeasterly low-level winds. To explore the disparate effects of different BLJ patterns on precipitation, we further examined the clustering dendrogram (figure omitted). At a Ward distance of around 1,500, the low-level wind fields over the DP-Lake region (outlined by the purple boxes in Figure 1) can be classified into four categories (Figure 2), ranked by frequency: weak easterly-northeasterly winds (1,491 days, Type 1), strong southerly-southwesterly winds (1,362 days, Type 2), southerly and northeasterly winds (891 days, Type 3), and strong northeasterly winds (750 days, Type 4). Each circulation type corresponds to distinct pressure distributions, where the winds generally follow the isobars, with high pressure on the right and a certain degree of deflection toward the low-pressure side in the presence of BL friction. Therefore, during the warm season, the DP-Lake region frequently experiences two dominant low-level wind patterns: Type 2 with prevailing southerly-southwesterly winds and Type 4 with prevailing northeasterly winds, together account for approximately 47% of all warm-season days. Types 1 and 3 in the other two clusters have much weaker winds in the DP-Lake region.

2.2.2. Definition and Sample Sets of BLJs

BLJs are characterized by vertical jet-shaped wind profiles, with a local wind speed maximum within a certain layer above the surface which exceeds that of an overlying layer. For statistical purposes, we define the following criteria for BLJs and their associated characteristics occurring within the two dominant types of flows identified

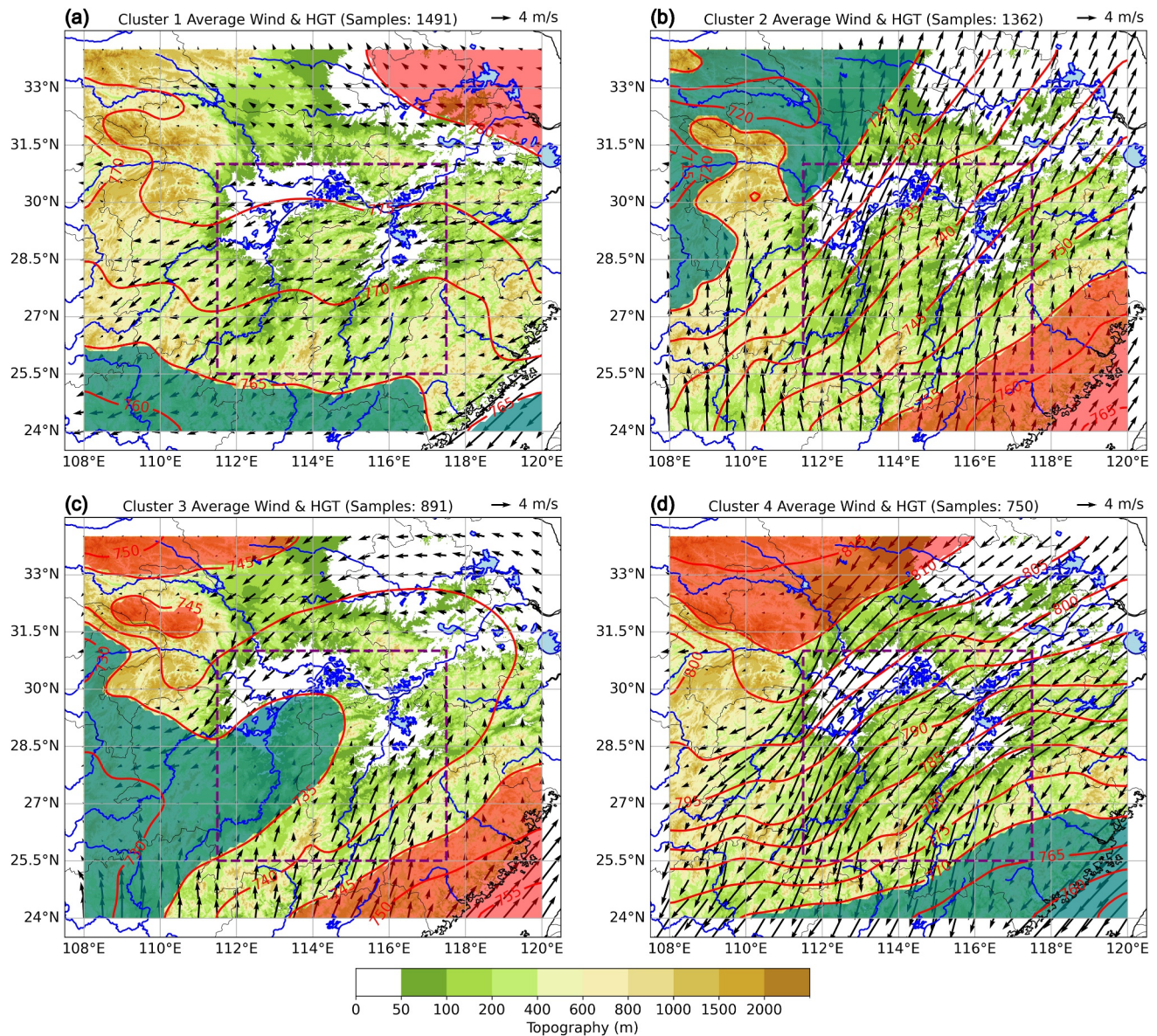


Figure 2. Hierarchical clustering results of daily mean 925-hPa wind fields during the warm season (April–October) for 2001–2021, derived from ERA5 reanalysis. Composite wind speed and direction for the four clusters are shown by vectors. Geopotential height fields are indicated by red solid contours, with teal-blue and red shading representing low- and high-pressure areas, respectively. Purple dashed boxes outline the DP-Lake region. Green and yellow shading denotes terrain elevation. Dark blue lines indicate rivers, light blue shading denotes lakes, and gray lines represent provincial boundaries.

for the DP-Lake region earlier. These criteria are established with reference to the definition proposed by Du et al. (2014).

BLJ points: Grid points at 925 hPa where wind speed $\geq 10 \text{ m s}^{-1}$, and the wind is from south-southwest (157.5° – 247.5°) for southerly BLJ (SBLJ) or from northeast (0° – 90°) for northeasterly BLJ (NEBLJ), with the speed exceeding that of the overlying (900–700 hPa) layers by more than 3 m s^{-1} .

BLJ events: Time points at which more than 25% of grid points within the DP-Lake region meet the BLJ point criteria. Sensitivity tests using different area percentage thresholds confirm that the results are robust to the threshold choice. These events are further classified as SBLJ events or NEBLJ events according to the dominant wind direction.

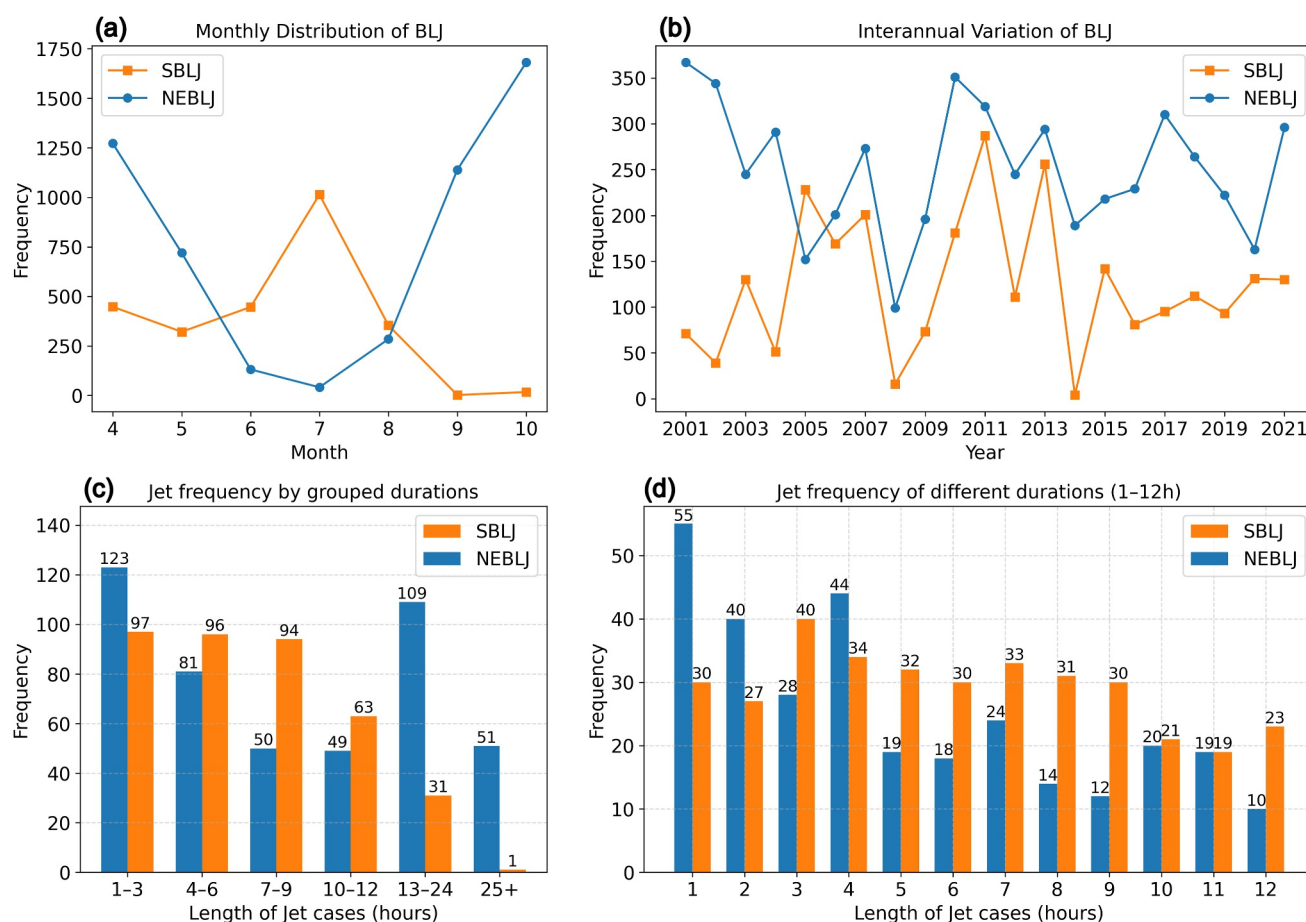


Figure 3. (a) Monthly distribution and (b) interannual variations of SBLJ and NEBLJ events in the DP-Lake region. (c, d) Frequency distribution of durations for SBLJ and NEBLJ cases in the region.

BLJ cases: BLJ events that are continuous in time are grouped into a single BLJ case, with the first time point marking the start, and the last time point marking the end; the difference between them defines the duration of case.

BLJ days: For each BLJ event, the BLJ day is defined by expanding ± 12 hr around the central time of the event. Thus, a BLJ day is centered on the event rather than on the calendar day and may cross day boundaries.

Times potentially influenced by tropical cyclones are excluded using the Chinese Meteorological Administration (CMA) Best Track data set, provided by the CMA Tropical Cyclone Data Center. For each time, the influence of a cyclone is assessed based on its center location and intensity. When the occurrence of a tropical cyclone coincides with a BLJ event, and the cyclone's influence area overlaps with the DP-Lake region, the event is considered potentially affected by the cyclone and thus removed from the sample set.

Following these definitions and procedures, two types of sample sets are established for the DP-Lake region during 2001–2021: the BLJ event sample set and the BLJ day sample set. The event sample set comprises all times associated with BLJ occurrences and is used to examine the intrinsic characteristics of the jets. The BLJ day sample set is constructed by compiling all BLJ days associated with the identified events, and the resulting time series consists of the consecutive hourly times within each event-centered BLJ day for examining the diurnal variations of BLJs.

It should be noted that identifying LLJs with data at fixed pressure levels may fail to capture the real height of the jet core and underestimate vertical wind shear, hindering detailed analysis of the vertical structure of LLJs. Nevertheless, statistical analyses and typical heavy rainfall case studies focused on the middle and lower reaches of the Yangtze River further demonstrate that 925-hPa data can effectively characterize the high-frequency zones

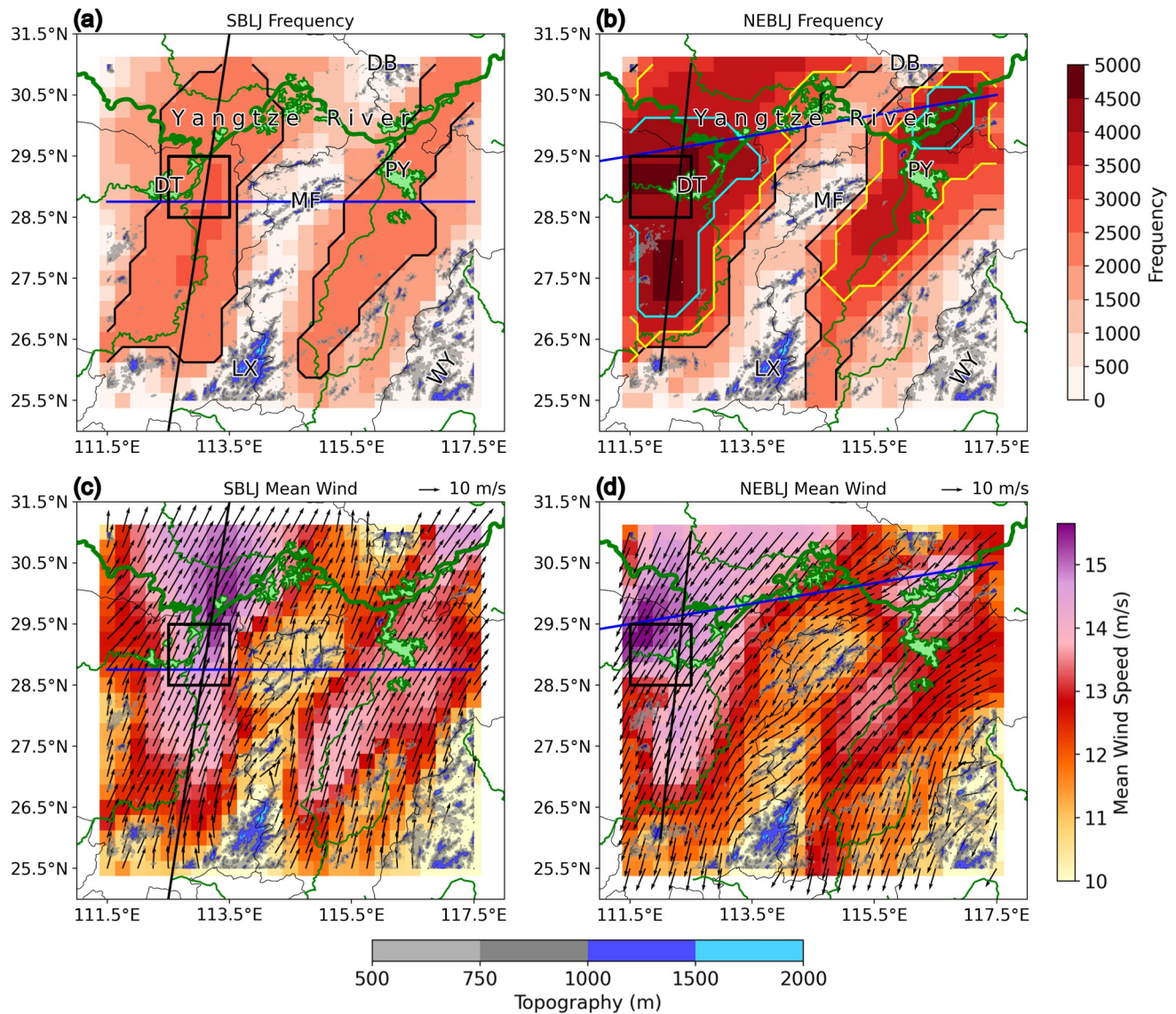


Figure 4. (a, b) Spatial distribution of BLJ points frequency (red shading), with black, yellow, and cyan contours denoting areas exceeding 2,000, 3,000, and 4,000 counts, respectively. (c, d) BLJ points average wind speed (yellow, red, and purple shading) and horizontal wind (vector) for (a, c) SBLJ and (b, d) NEBLJ events over the DP-Lake region at 925 hPa. Black and blue straight lines mark the along-jet and cross-jet sections, respectively. Black boxes outline the jet-core regions (SBLJ: 112.5°–113.5°E, 28.5°–29.5°N; NEBLJ: 111.5°–112.5°E, 28.5°–29.5°N). Gray and blue shading indicate terrain, green lines indicate rivers, and light-green shading indicates lakes. DT and PY denote Dongting Lake and Poyang Lake, respectively, while DB, MF, LX, and WY denote the Dabie, Mufu, Luoxiao, and Wuyi Mountains, respectively.

and diurnal variation features of BLJs. In addition, jet properties derived at this level generally agree with those obtained from adjacent standard isobaric levels (T. Chen et al., 2024; Tian et al., 2024; Wang, Cui, et al., 2022). Therefore, this study identifies boundary layer jets over the DP-Lake region using ERA5 925-hPa wind field data.

3. Results

3.1. Characteristics of SBLJs and NEBLJs

3.1.1. General Statistics

Table 1 summarizes the differences in the number of occurrences, wind speeds, and spatial coverage between the identified SBLJ and NEBLJ events over the DP-Lake region. Spatially, the “mean BLJ point coverage” refers to

Table 1

Statistical Characteristics of SBLJ and NEBLJ Events in the DP-Lake Region During the Warm Season From 2001 to 2021

	SBLJ	NEBLJ
Total BLJ events	2,601	5,268
Mean maximum wind speed (m s^{-1})	17.26	17.38
Area-mean wind speed (m s^{-1})	10.41	9.84
Mean BLJ point coverage (%)	37.5	39.1

the proportion of grid points within the DP-Lake region that meet the BLJ points' criteria during a given BLJ event, indicating the horizontal extent of a BLJ.

During the warm seasons from 2001 to 2021, NEBLJ events occur 5,268 times, approximately twice the number of SBLJ events. The two types of BLJ exhibit similar average maximum wind speeds (17.38 m s^{-1} for NEBLJs vs. 17.26 m s^{-1} for SBLJs). Compared with SBLJs, NEBLJ events feature a larger mean BLJ coverage (39.1% vs. 37.5%) but a smaller area-mean wind speed (9.84 m s^{-1} vs. 10.41 m s^{-1} for SBLJs). These suggest that NEBLJ events are more frequent and have broader spatial coverage, but weaker winds, indicating greater regional uniformity. In contrast, SBLJ events exhibit smaller spatial coverage but stronger area-mean winds.

Figures 3a and 3b illustrate the monthly distribution and interannual variations of the two BLJ types, respectively. In most years, SBLJs and NEBLJs exhibit positive interannual correlations (Figure 3b). Their monthly distribution patterns (Figure 3a), however, differ markedly: SBLJs primarily occur from April to August, with nearly half of all events concentrated in July. In contrast, NEBLJs mainly occur in April, May, September, and October, with October showing the highest number, therefore SBLJs and NEBLJs occur mostly in warmer and colder months, respectively.

The durations of the two types of BLJ cases (Figures 3c and 3d) also differ markedly. The SBLJ cases show a more concentrated distribution: approximately three-quarters of the cases last 1–9 hr, with similar numbers of ~30 cases across the duration range. The number of SBLJ cases with durations exceeding 10 hr decreases rapidly, with only one case lasting longer than 24 hr. In contrast, about one-fourth of NEBLJ cases last 1–3 hr (Figure 3c), with 1 hr cases being the most frequent (Figure 3d). However, NEBLJ cases lasting longer than 13 hr account for 30.4%, which is roughly 2.5 times the proportion of SBLJ cases with comparable durations (12.3%). Such statistics suggest that the SBLJs may be controlled more strongly by diurnal processes while NEBLJs may be associated with weather systems that have more variability.

3.1.2. Horizontal Distribution and Vertical Structure

In plan view (Figure 4), both jet types feature two high-frequency bands roughly aligned in the north–south direction. The two bands are separated by the Dabie Mountains (DB), Luoxiao Mountains (LX), and Mufu Mountains (MF). They are located over the Dongting and Poyang Lakes, as well as the river-valley areas to their south (Figures 1, 4a, and 4b). Because the total number of NEBLJ events is substantially larger than that of SBLJ events (5,268 vs. 2,601), NEBLJs exhibit higher BLJ-point frequencies (Figure 4b). Despite this difference, both types share a consistent spatial pattern: the western branch features higher frequencies and stronger winds, with the maximum mean wind speed of BLJ events exceeding 15 m s^{-1} , while the eastern branch shows a larger u -component of wind (Figures 4c and 4d). Influenced by the differences in prevailing wind directions, the centers of maximum wind speed show slight shifts between the two BLJ types: the SBLJ centers lie farther north, whereas the NEBLJ centers shift toward the southwest. Accordingly, by jointly considering both the maximum wind speed and the BLJ-point frequency, the jet-core regions for the two jet types are identified (indicated by the black boxes in Figure 4).

The mean vertical wind profiles over the jet-core region for BLJ events (Figures 5a and 5b) show that wind speed peaks at 925 hPa, with maximum values close to 15 m s^{-1} for both BLJ types. The meridional (v) wind component contributes most to the BLJ peak, while the u -component helps to increase the wind speed above the peak level somewhat. However, the vertical variations of wind direction differ markedly between the two types of BLJs. For SBLJs, the wind direction changes little with height (Figure 5a), changing only slightly from southerly near the surface to southwesterly at the 700 hPa level. In contrast, the NEBLJ wind direction changes a lot with height

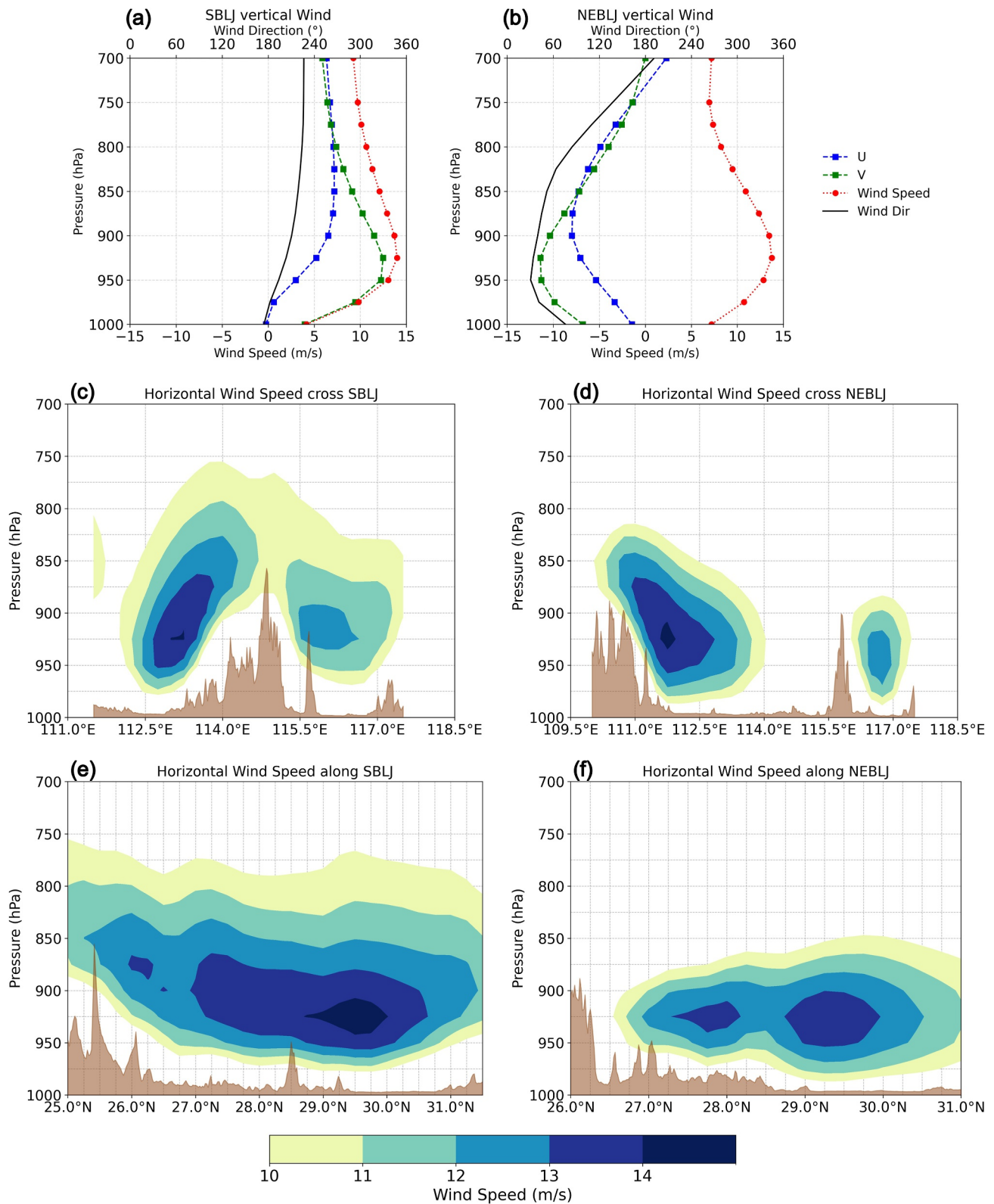


Figure 5. Area-averaged u and v wind components, wind speed, and wind direction values over the jet-core regions (black boxes in Figure 4) for (a) SBLJ and (b) NEBLJ events. Mean cross-jet (c, d; blue lines in Figure 4) and along-jet (e, f; black lines in Figure 4) sections of horizontal wind speed (shading) for (c, e) SBLJ and (d, f) NEBLJ events. Brown shading denotes terrain elevation.

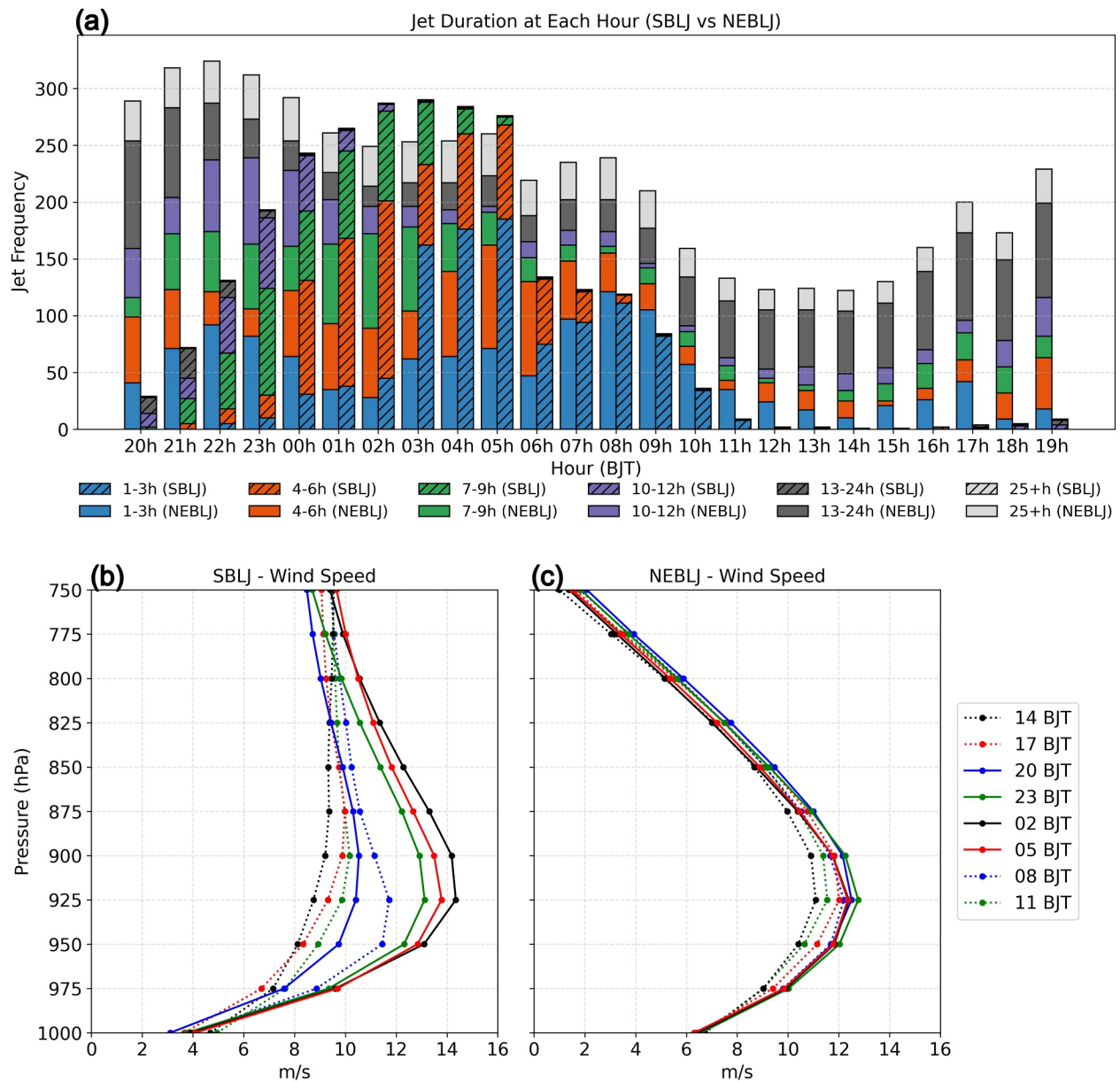


Figure 6. (a) Diurnal variations of BLJ event frequency and duration for the two BLJ types in the DP-Lake region. The total height of the hatched colored bars and shaded colored bars represents the hourly total frequency of SBLJ and NEBLJ events, respectively. (b) Diurnal variations of area-averaged wind speed profiles over the jet-core region (black boxes in Figure 4) for SBLJ and NEBLJ days.

(Figure 5b). Below 800 hPa, the flow is northeasterly, with the northerly component being the largest at 950 hPa. Above 800 hPa, the wind veers to southeasterly and then to southerly around 700 hPa. Therefore, during SBLJ events, the winds are dominantly southerly to southwesterly throughout the lower levels. In NEBLJ events, the winds change from northeasterly in the BL to southerly aloft, indicating that NEBLJs are shallower.

To further reveal the three-dimensional structure of BLJs, Figures 5c–5f present cross sections along and across the jet axes. As revealed by the vertical wind profiles, the SBLJs, which cross the Nanling Mountains (≈ 1 km, NL) into the DP-Lake region, are deeper, with the region of wind speed exceeding 10 m s^{-1} extending upward to slightly above 800 hPa, while the jet core ($> 14 \text{ m s}^{-1}$) remains near 925 hPa (Figures 5c and 5e). In contrast, the NEBLJs, which originate over the middle-lower Yangtze River plains, are largely confined below 850 hPa (Figures 5d and 5f). The cross-jet sections (Figures 5c and 5d) clearly show that both types of BLJs are influenced by topography and are separated into western and eastern branches.

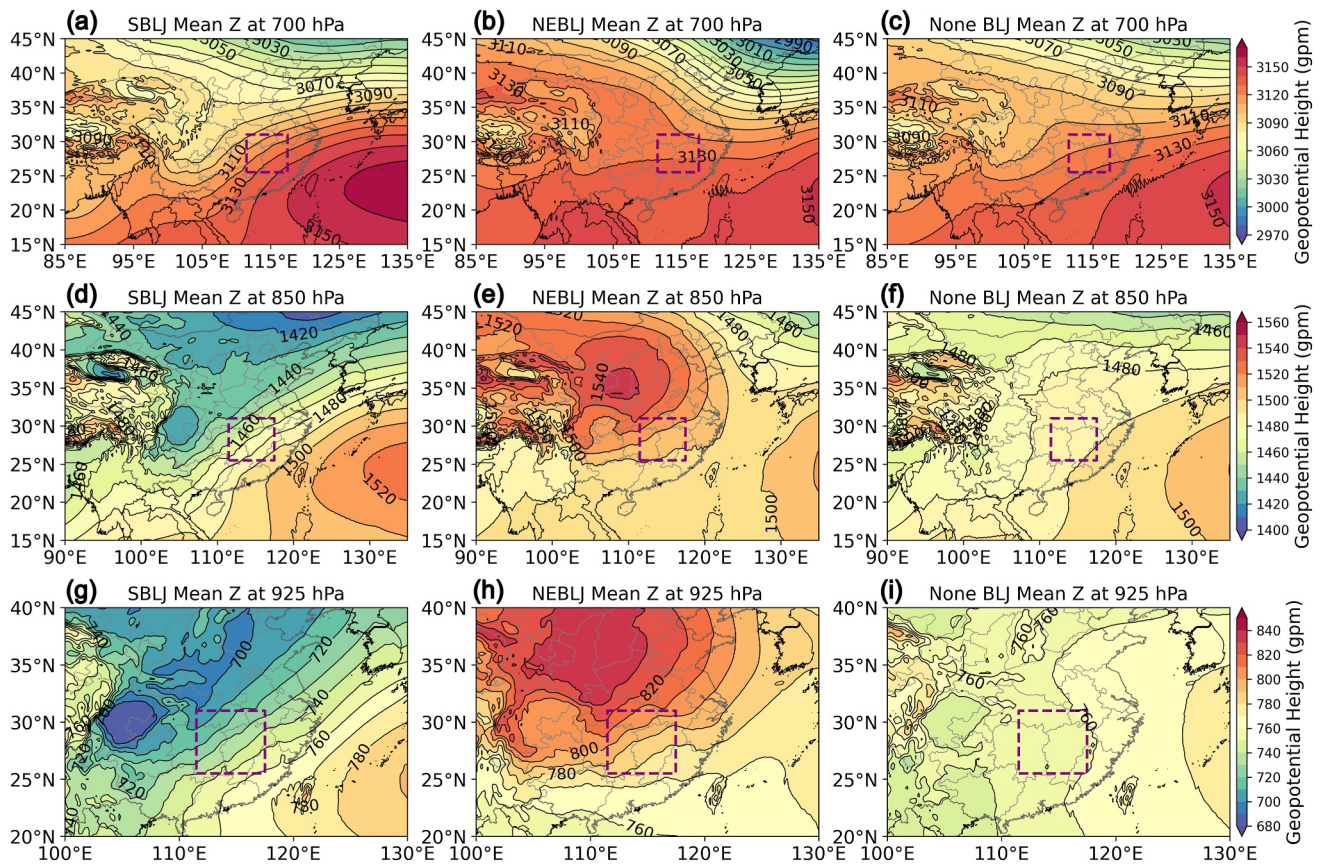


Figure 7. Distributions of geopotential height at (a–c) 700 hPa, (d–f) 850 hPa, and (g–i) 925 hPa averaged during (a, d, g) SBLJ and (b, e, h) NEBLJ events, and (c, f, i) non-jet periods. The purple dashed boxes denote the DP-Lake region. SBLJ and NEBLJ composites are averaged over all corresponding event times from 00:00 BJT on 1 April to 23:00 BJT on 31 October during 2001–2021, while non-jet periods represent all times within the same interval when no BLJ events are detected.

3.1.3. Diurnal Variations

Figure 6a shows the diurnal variations of SBLJ and NEBLJ event frequencies and durations. The total bar height at each time indicates the total number of BLJ events at that time, while the different colors indicate the number of BLJ events with different durations (in hours). SBLJs display a pronounced nocturnal peak (Figure 6a), with frequencies increasing from 29 events around 20:00 BJT to a maximum of 290 events around 03:00 BJT, and then decreasing rapidly after sunrise (06:00–07:00 BJT) to a minimum in the afternoon (12:00–16:00 BJT) when only 1–2 SBLJ events occur. There is clearly a pronounced nocturnal concentration of events during 00:00–05:00 BJT. Most SBLJ events are short-duration events (lasting ≤ 12 hr), with long-duration events (lasting ≥ 13 hr) accounting for only 3.6% of all events. From 21:00 to 08:00 BJT, the duration of BLJ events gradually shortens: the proportion of 1–6 hr events increases from 6.9% to 99.2%, whereas the number of long-duration events sharply decreases from 27 to just 1. This is likely because most SBLJs are not able to persist after sunrise, when enhanced daytime BL turbulent mixing destroys the jets; nocturnal SBLJs that form late are therefore short-lived.

In contrast, NEBLJs exhibit much weaker diurnal variations in occurrence frequency, featuring an earlier nocturnal peak (Figure 6a). The frequency of NEBLJs begins to increase in the late afternoon, reaching its peak in late evening at 22:00 BJT with a maximum of 324 events. It then gradually decreases throughout the night, with a secondary peak of 239 events at 08:00 BJT after sunrise, before declining to a minimum at 14:00 BJT with 122 events. Correspondingly, long-duration events account for 34.8% of all NEBLJ events, far exceeding the 3.6% for SBLJs. During 11:00–18:00 BJT, long-duration events make up more than 50% of all events in the period, indicating that NEBLJs are likely more strongly influenced by larger-scale systems.

The diurnal variations of BLJ wind speed, averaged over the jet-core region, closely follow the frequency variation patterns. For SBLJs (Figure 6b), wind speed increases markedly after 20:00 BJT and peaks around 02:00

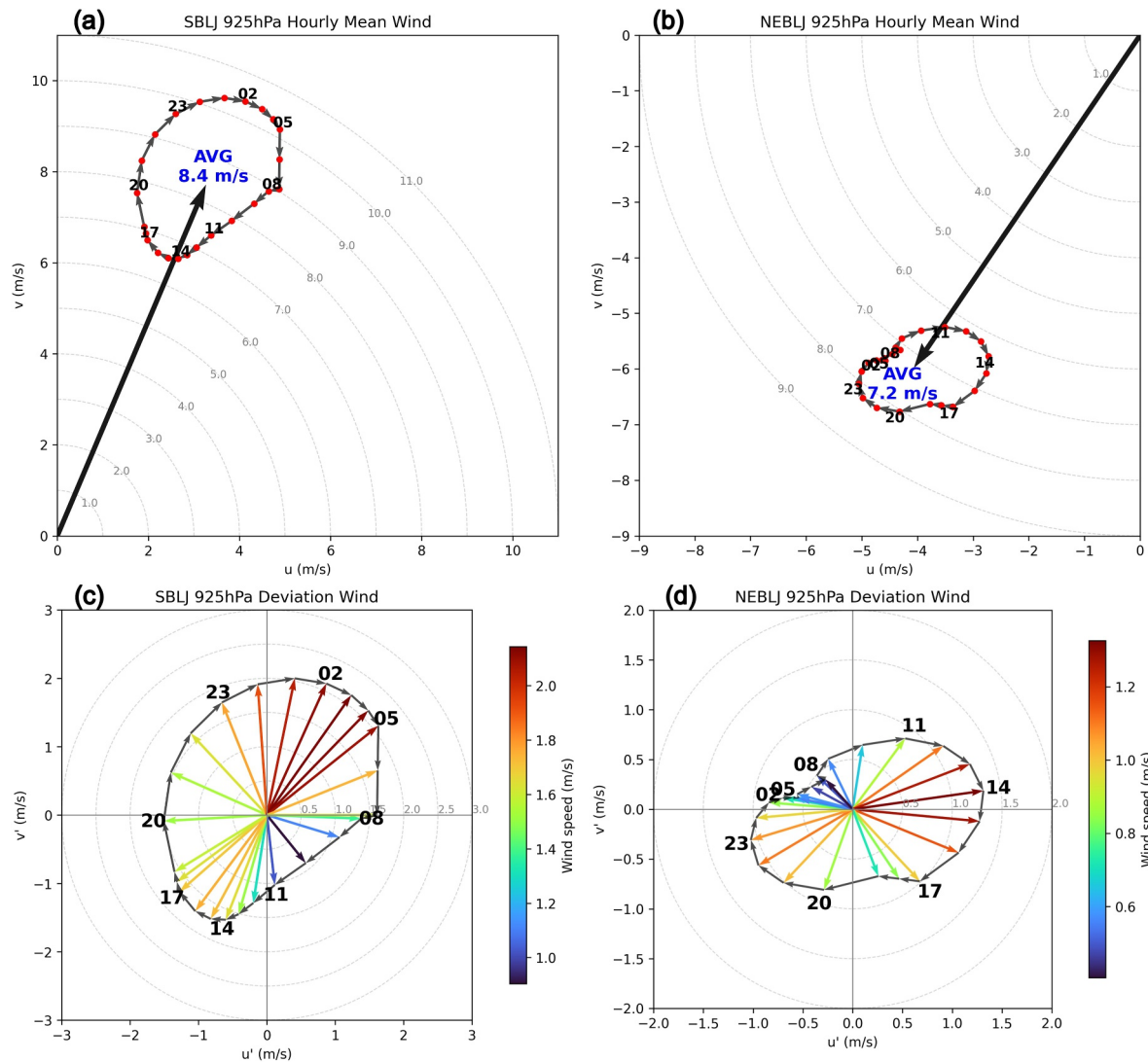


Figure 8. Hodographs of average hourly (a, b) total winds and (c, d) deviation winds from the daily mean at 925 hPa, averaged over the DP-Lake regions, on (a, c) SBLJ and (b, d) NEBLJ days. Values at 18:00 and 06:00 BJT are replaced by the averages of the preceding and following hours to ensure data continuity.

BJT. Thereafter, it decreases steadily, reaching a minimum in the early afternoon. The altitude of maximum wind speed also varies somewhat: with daytime maxima occurring at higher levels (between 875 and 900 hPa) and nocturnal maxima at lower levels (at around 925 hPa). This behavior is indicative of nocturnal inertial oscillations, whereby BL flows that are decelerated by daytime surface friction and vertical turbulent mixing are reaccelerated at night, producing supergeostrophic winds.

NEBLJs exhibit quite different patterns in both the timing and altitude of maximum wind speed (Figure 6c). The level of maximum wind speed over the jet-core region remains consistently near 925 hPa throughout the diurnal cycle, while wind speed decreases to close to zero at 750 hPa. The wind speed near 925 hPa reaches its minimum around 14:00 BJT, increases markedly by 17:00 BJT, and then reaches its peak value around 23:00 BJT. The NEBLJs reach their daily speed maximum about 3 hr earlier than SBLJs, similar to the phase difference in occurrence frequencies discussed earlier. The difference in the diurnal phases of the two types of BLJs will be discussed further later.

Overall, SBLJ events occur primarily during the summer months and typically last for 1–9 hr. The BL and lower troposphere during SBLJ events are dominated by southerly–southwesterly flows. In contrast, NEBLJ events occur more frequently and peak in spring and fall, with a larger proportion of NEBLJ cases lasting ≤ 3 hr or

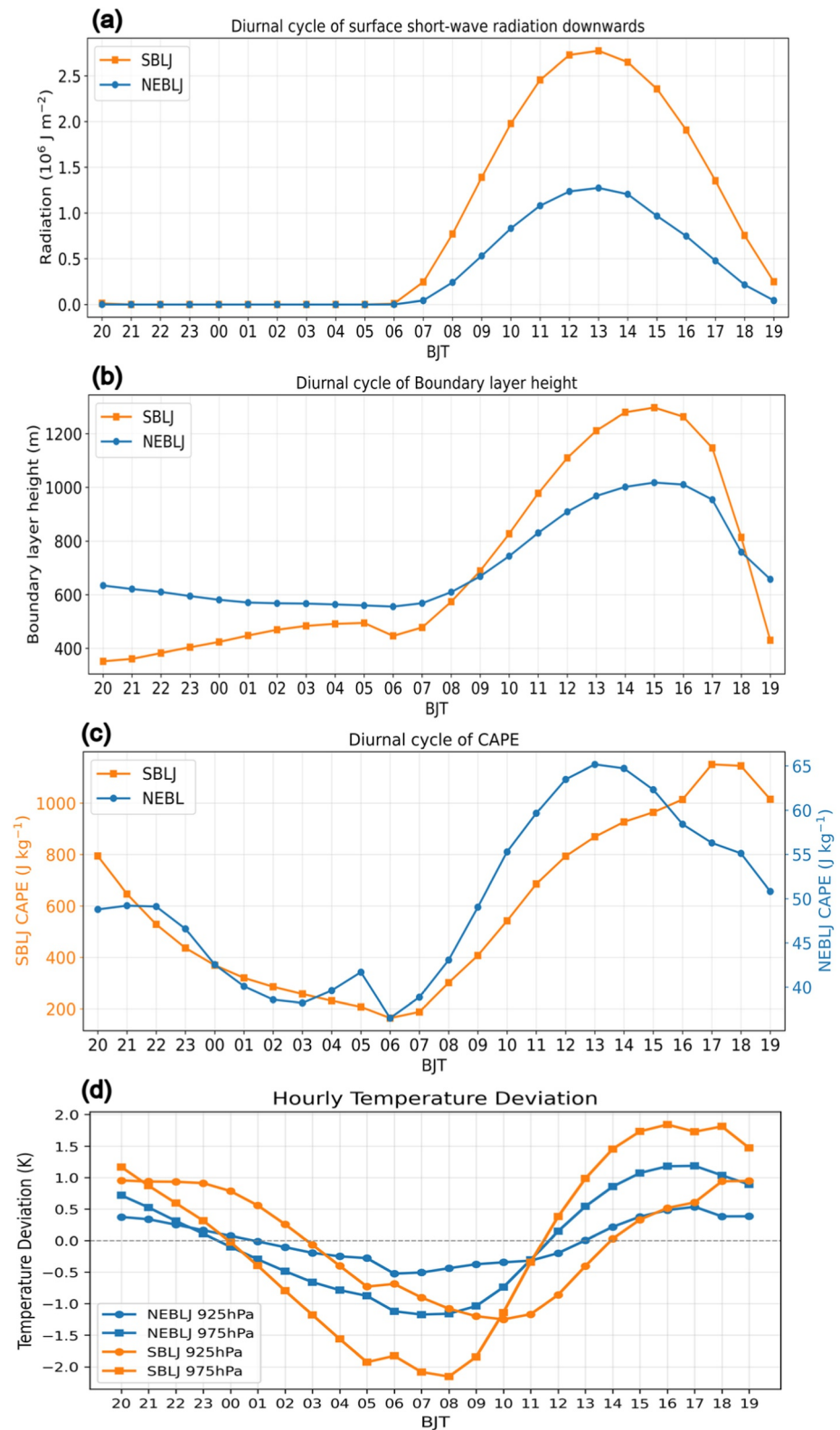


Figure 9. Diurnal variations of (a) downward shortwave radiation at the surface, (b) BL height, (c) convective available potential energy at the surface, and (d) hourly temperature anomalies (hourly temperature minus daily mean temperature) at 925 hPa and 975 hPa, averaged over jet-core regions on SBLJ and NEBLJ days.

≥ 13 hr. Unlike SBLJs, NEBLJs feature northeasterly flows largely confined within the BL, above which the flow quickly veers to southeasterly. Both types of jets exhibit east and west double jet cores, with the western branch occurring more frequently and characterized by stronger winds and greater vertical depth.

The SBLJ events show pronounced diurnal variability in both frequency and wind speed, with a distinct nocturnal peak around 03:00 BJT, accompanied by a nighttime lowering of the maximum wind-speed height and a rapid weakening after sunrise. By contrast, NEBLJ events exhibit much weaker diurnal variability. Both BLJ frequency and wind speed peak before midnight, but a substantial number of long-duration cases persist throughout the daytime. It is worth noting that the abrupt frequency declines around 06:00 and 18:00 BJT may be spurious features arising from the ERA5 assimilation cycle, rather than reflecting real meteorological signals. Taken together, the two jet types exhibit significant differences in their spatiotemporal and diurnal characteristics, which will be examined further in the next section.

3.2. Formation and Diurnal Variation Mechanisms of SBLJs and NEBLJs

3.2.1. Dominant Synoptic Systems and Mean Winds

The mean direction and intensity of BLJs are mostly controlled by horizontal pressure gradients associated with high- and low-pressure systems such as the subtropical high, low vortices and frontal systems (Luo & Du, 2022; Xue et al., 2018). Figure 7 shows the mean geopotential height at 925, 850, and 700 hPa during SBLJs, NEBLJs, and non-BLJ periods.

During SBLJ events (Figures 7a, 7d, and 7g), the patterns at different pressure levels are broadly similar, with southeastern China dominated by a high-pressure system, while a low-pressure system prevails over the west and north. Compared with non-jet periods, a key difference is the intensified low-pressure system to the northwest of the DP-Lake region at 850 hPa and below. This stronger high–low pressure contrast forms a pronounced zone of dense isobars oriented southwest–northeast, consistent with the characteristics of the Mei-yu front (Wang et al., 2019; Wang, Zhou, et al., 2022). The DP-Lake region lies within the dense isobars belt, where the pressure gradient force points from southeast to northwest, resulting in south–southwesterly flows (Figure 8a) that are balanced by pressure gradient, Coriolis, and frictional forces.

In contrast, during NEBLJ events (Figures 7b, 7e, and 7h), the pressure patterns at 700 hPa show little variation compared with those during SBLJ events or non-jet periods, except for a markedly reduced pressure gradient, which corresponds to the minimum wind speed at this level in the vertical wind profile. At 850 hPa and below, the patterns differ significantly from those during SBLJ events, with a high-pressure system situated over northern China and a low-pressure center over the southern coast of China. The DP-Lake region lies within a southwest–northeast zone of dense isobars, with the pressure gradient force directed from northwest to southeast, producing northeasterly flows (Figure 8b) under the three-force balance. For the non-jet periods (Figures 7c, 7f, and 7i), the pressure gradient is generally weak.

3.2.2. Inertial Oscillations and Diurnal Variations of Perturbation Winds

Figures 8a–8d show the diurnal variations of hourly mean total wind at 925 hPa and the departures of hourly total winds from the daily mean. The fields are averaged over all SBLJ and NEBLJ days (as defined in Section 2.2.2) and across the DP-Lake region. The two BLJ types differ markedly in both wind intensity and diurnal phase: SBLJ days are characterized by stronger total winds and larger departures from the daily mean, whereas NEBLJ days feature weaker winds, smaller departures, with a diurnal phase about 4 hr earlier. Specifically, the daily mean wind speed on SBLJ days is 8.4 m s^{-1} (the long black vector in Figure 8a) with a south–southwesterly direction, consistent with the typical pressure pattern during SBLJ events. At around 02:00–03:00 BJT, the deviation winds reach their maximum magnitude and align with the mean wind vector (Figures 8a and 8c), producing the peak in total wind speed. On NEBLJ days, the daily mean wind is northeasterly at 7.2 m s^{-1} (long black vector in Figure 8b). The deviation winds align with the mean wind vector during 21:00–22:00 BJT (Figures 8b and 8d), generating the peak in total wind and the corresponding peak frequency at the time.

A further comparison shows that the strongest hourly total winds on SBLJ days (at $\sim 02:00$ BJT) exceeds the weakest wind speed (at 15:00 BJT) by 3.8 m s^{-1} on average, whereas the wind speed range for NEBLJs is only 2.0 m s^{-1} (between 22:00 and 12:00 BJT). The large deviation wind speeds and the strong diurnal amplitude of the total winds during SBLJ days are key contributors to the pronounced nocturnal intensification of SBLJs. We note

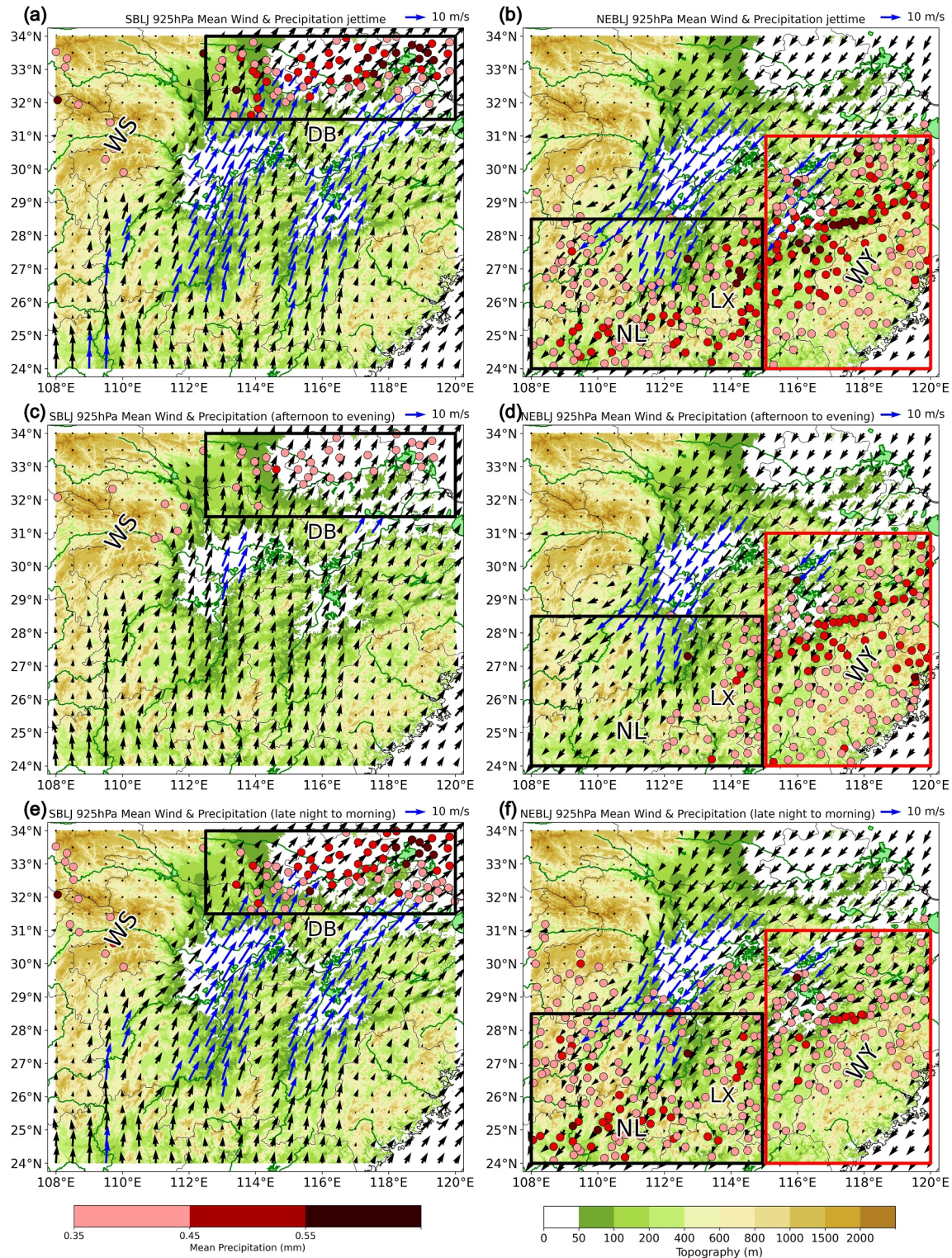


Figure 10. Mean wind fields (vectors) at 925 hPa and hourly precipitation at stations exceeding 0.35 mm (red dots) are shown for (a) SBLJ and (b) NEBLJ events, and for different time periods: 12:00–23:00 BJT (afternoon to evening) for (c) SBLJ and (d) NEBLJ days, and 00:00–11:00 BJT (late night to morning) for (e) SBLJ and (f) NEBLJ days. Topography is indicated by color shading.

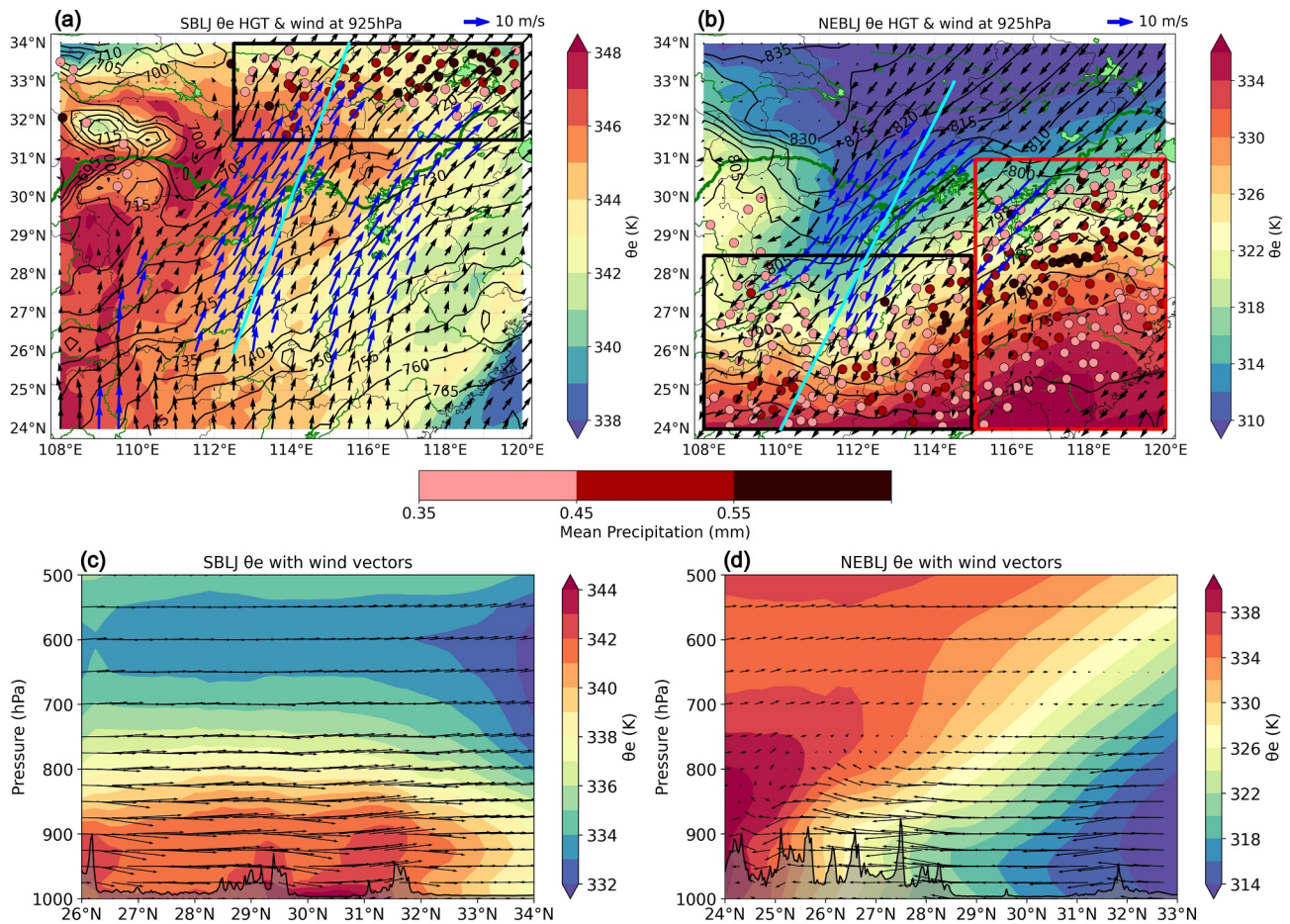


Figure 11. Mean equivalent potential temperature (θ_e ; shading), wind fields (vectors), geopotential height (black contours) at 925 hPa, and hourly precipitation at stations exceeding 0.35 mm (red dots) for (a) SBLJ and (b) NEBLJ events. The black boxes denote the BLJ-exit rainfall region, and red boxes denote the NEBLJ-left rainfall region. Latitude–height cross-sections of θ_e (shading), wind fields (v and $-w$), and terrain (semi-transparent tan shading) for (c) SBLJ and (d) NEBLJ events along the cyan line in panels (a) and (b).

that the ranges of wind speed variations on individual days should be significantly larger than that of mean values, due to the averaging effect.

A comparison of Figures 8a and 8b shows that the period during which the total wind falls below the daily mean spans 10:00–20:00 BJT for SBLJ days and 07:00–16:00 BJT for NEBLJ days, revealing a difference of about 3–4 hr. The possible reasons for such a difference are discussed below.

On SBLJ days that occur most frequently in summer months, during daytime, strong shortwave radiation reaching the surface (Figure 9a) helps create a deep mixed BL (Figure 9b). It, together with the continuous transport of warm and moist air into the DP-Lake region from the south by the low-level flow (Figures 11a and 11c), leads to a steady increase in convective available potential energy (CAPE) that reaches a regional mean maximum of $\sim 1,100 \text{ J kg}^{-1}$ at 17:00–18:00 BJT (Figure 9c). The strong BL mixing reduces jet-level wind speed, resulting in a minimum in the mean total wind speed around 15:00 BJT (Figure 8a). After sunset (18:00–19:00 BJT), surface radiative cooling sets in, leading to weakening of vertical turbulent exchange and decoupling of the BL flows from surface frictional effect. The effective removal of the frictional force causes the flows to lose the daytime three-force balance and accelerate forward, producing a nocturnal BLJ with a peak height near 925 hPa and a peak time around 02:00 BJT (Figure 6b). The deviation wind undergoes a clockwise rotation as shown in Figure 8c. These processes are explained by the inertial oscillation mechanism of nocturnal BLJs originally proposed by Blackadar (1957). In the past, this theory had mainly been applied to southerly LLJs.

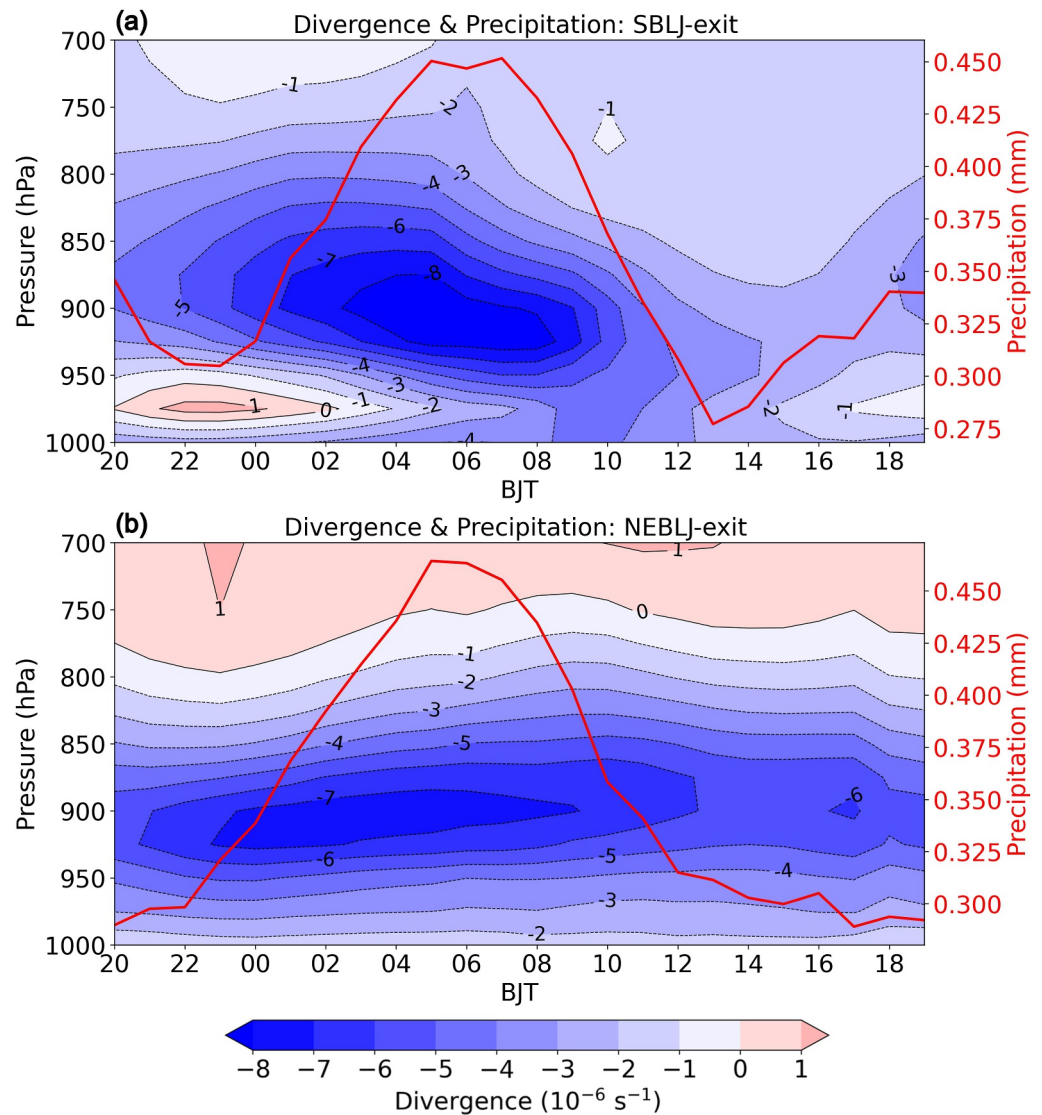


Figure 12. Vertical-time evolution of wind divergence (negative values indicate convergence) and hourly precipitation diurnal cycle (red lines), averaged over BLJ days for (a) the SBLJ-exit region and (b) the NEBLJ-exit region.

The NEBLJs occur more frequently in early spring and late fall (Figure 3a, showing peaks in April, September and October) while SBLJs peak in July. The earlier sunset on the NEBLJ days would cause earlier (by about 1 hr) decay of BL mixing and transition to nighttime BL, correspondingly an earlier phase of inertial oscillations. Second, the shortwave radiation (Figure 9a) and BL height (Figure 9b) during NEBLJ days are approximately one-half and three-quarters of those on SBLJ days, respectively. Moreover, the low-level northeasterly winds associated with NEBLJs transport colder air into the DP-Lake region (Figures 11b and 11d), resulting in CAPE values less than one-tenth of those on SBLJ days, with the CAPE on NEBLJ days peaking earlier at ~13:00 BJT (Figure 9c). The weaker BL mixing and shallower BL depth on NEBLJ days would imply easier and faster transition from daytime BL to nighttime BL, and the much earlier peak CAPE time also suggests the same.

The differences of hourly temperature anomalies between 925 and 975 hPa (Figure 9d) provides a quantitative explanation for the temporal differences in frictional decoupling and turbulent mixing within the BL between the two BLJ types. The 975 hPa level is more directly influenced by surface radiative heating, with both jet types exhibiting maximum positive temperature anomalies around 16:00 BJT. In contrast, the temperature at 925 hPa is strongly modulated by turbulent mixing. In SBLJ cases, the maximum positive anomaly at this level occurs between 19:00 and 22:00 BJT, lagging that at 975 hPa by approximately 4 hr. For NEBLJ cases, the maximum

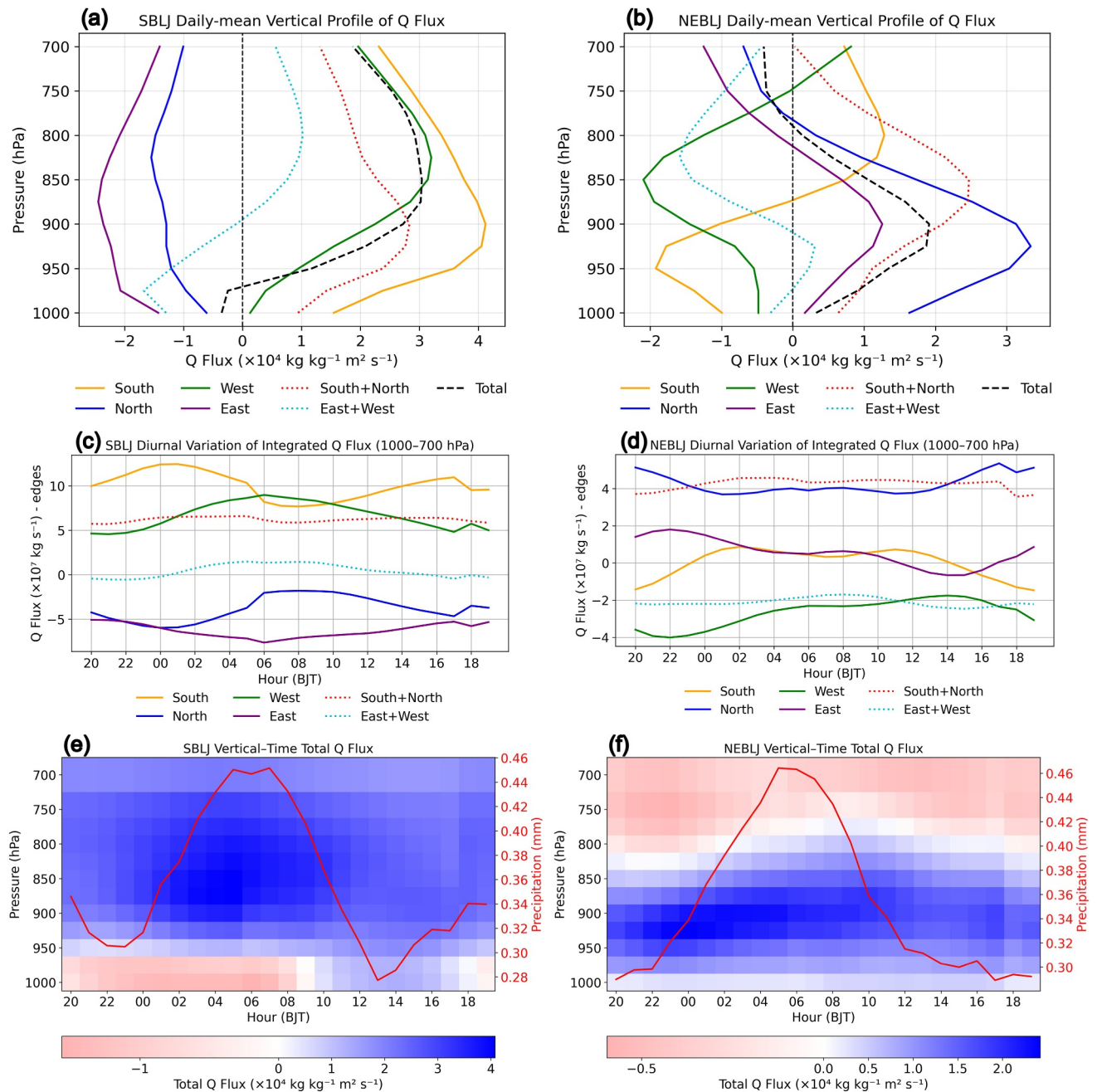


Figure 13. Vertical profiles of daily mean moisture flux across different boundaries over the (a) SBLJ-exit and (b) NEBLJ-exit regions. Diurnal variations of vertically integrated moisture flux at different boundaries over the (c) SBLJ-exit and (d) NEBLJ-exit regions. Diurnal variations of total boundary moisture flux over the (e) SBLJ-exit and (f) NEBLJ-exit regions.

occurs at 17:00 BJT, a lag of only 1 hr. The difference in lag times between the two jet types reflects their distinct BL turbulent mixing intensities. During NEBLJ events, weaker surface shortwave radiation and lower boundary layer height result in weaker turbulent mixing, which more readily permits the development of inertial oscillations and subsequent wind acceleration. The difference in lag time between the peak temperature anomalies at the two levels (1 hr vs. 4 hours) quantitatively explains why the diurnal peak of the NEBLJ occurs 3–4 hr earlier than that of the SBLJ.

In summary, differences in mean wind direction between SBLJs and NEBLJs are primarily governed by the spatial distribution of high- and low-pressure systems. Nocturnal jet formation is largely a result of strong

ageostrophic winds that develop at night through inertial oscillations after the reduction of frictional effects on the BL flow following sunset. Season differences and associated differences in surface heating, BL depth, and BL thermal energy affect the timing of daytime to nighttime BL transition and therefore the phase of diurnal inertial oscillations, which in turn determines the timing of peak jet frequency and intensity. As a result, the NEBLJs reach their diurnal maximum approximately 3–4 hr earlier than SBLJs do.

3.3. Impacts of SBLJs and NEBLJs on Precipitation

3.3.1. Differences in Precipitation Spatial Distribution and Causes

Figures 10 and 11 present the average wind fields, equivalent potential temperature θ_e , and hourly station precipitation exceeding 0.35 mm during SBLJ and NEBLJ events. The differences in precipitation between the two BLJ types can be summarized as follows. First, during SBLJ events, maximum precipitation occurs mainly in the jet exit region (hereafter referred to as the SBLJ-exit region) and ahead of the low-pressure trough (black boxes in Figures 10a, 10c, 10e, and 11a). In this region, convergence-induced ascent at the jet exit overlaps with trough-induced lifting, producing intense rainfall. In contrast, precipitation associated with NEBLJ events is more spatially dispersed, occurring both within the jet exit region (hereafter NEBLJ-exit region, black boxes in Figures 10b, 10d, 10f, and 11b) and on the left side of the jet (hereafter NEBLJ-left region, red boxes in Figures 10b, 10d, 10f, and 11b), in conjunction with an inverted low-pressure trough. Furthermore, the elevations of precipitation stations differ between the two BLJ types. SBLJ-related precipitation is concentrated in low-elevation areas embedded within warm advection (Figure 11a), whereas NEBLJ-related precipitation primarily occurs on hillsides or mountaintops near the frontal zone at the leading edge of cold advection (Figure 11b). The exit regions of both the eastern and western branches of NEBLJs are also where terrain rises in elevation, due to the presence of Wuyi (WY), Luoxiao (LX) and NanLing (NL) mountains. Second, diurnal variations affect the two types differently. For SBLJs, the main effect is on rainfall intensity; precipitation during the late-night-to-morning period is far stronger, consistent with the peak of nocturnal jets (Figure 10e). For NEBLJs, diurnal differences also manifest in spatial distribution: afternoon-to-evening rainfall is predominantly concentrated over the NEBLJ-left region (Figure 10d), whereas late-night-to-morning precipitation is stronger over the NEBLJ-exit region (Figure 10f).

The horizontal distribution and vertical structure of θ_e (Figure 11) indicate that atmospheric thermal energy is substantially higher during SBLJ events than NEBLJ events, consistent with the more than ten-fold difference in peak CAPE values between their jet-core regions (Figure 9c). During SBLJ events (Figure 11a), high- θ_e air is transported from the southwest by the jet streams. North of the Yangtze River, jet streams decelerate markedly and θ_e decreases rapidly. Precipitation mainly occurs in the jet exit regions north of the river, coinciding with the typical location of the Mei-yu front during late June–early July. In the along-jet vertical cross section (Figure 11c), θ_e is relatively uniform within the DP-Lake region, corresponding to nearly homogeneous low-level southerly–southwesterly winds (Figure 5a). Mountains at the terminus of the SBLJs (Figure 10a) further enhance convergence at the jet exit, producing a concentrated precipitation region.

For NEBLJ events, high θ_e exists to the south and southeast of the jets, while θ_e is lower at the jet core and north side, resulting in a strong cross- θ_e component in the flow (Figure 11b). Along the western branch of NEBLJs, vertical cross sections (Figure 11d) show dense θ_e contours sloping northward with height, indicating a cold-front structure, in which cold, dry air behind and below the frontal interface advances southward. At the leading edge of the jet, warm moist air is lifted by convergence and along the sloping frontal surface. The Nanling mountains (NL in Figure 10b) further block and lift the jet flow, and help enhance precipitation in the NEBLJ-exit region.

In summary, precipitation in the SBLJ-exit region develops against a synoptic background resembling the Mei-yu front, where relatively deep southerly BLJs transport warm, moist air. The wind convergence at the jet exit region is further enhanced by low-elevation mountains, generating a focused region of heavy rainfall.

In contrast, precipitation in the NEBLJ-exit region occurs under a cold-front–like synoptic pattern, with shallow northeasterly BLJs interacting with mid-elevation, large-scale terrain to lift warm, moist air from the south ahead of the cold front, producing precipitation. These processes will be examined further in the following section on diurnal precipitation variations. Additionally, precipitation in the NEBLJ-left region occurs over the northern slopes of the WY Mountains (Figure 10b) and its afternoon precipitation likely benefits from terrain-induced

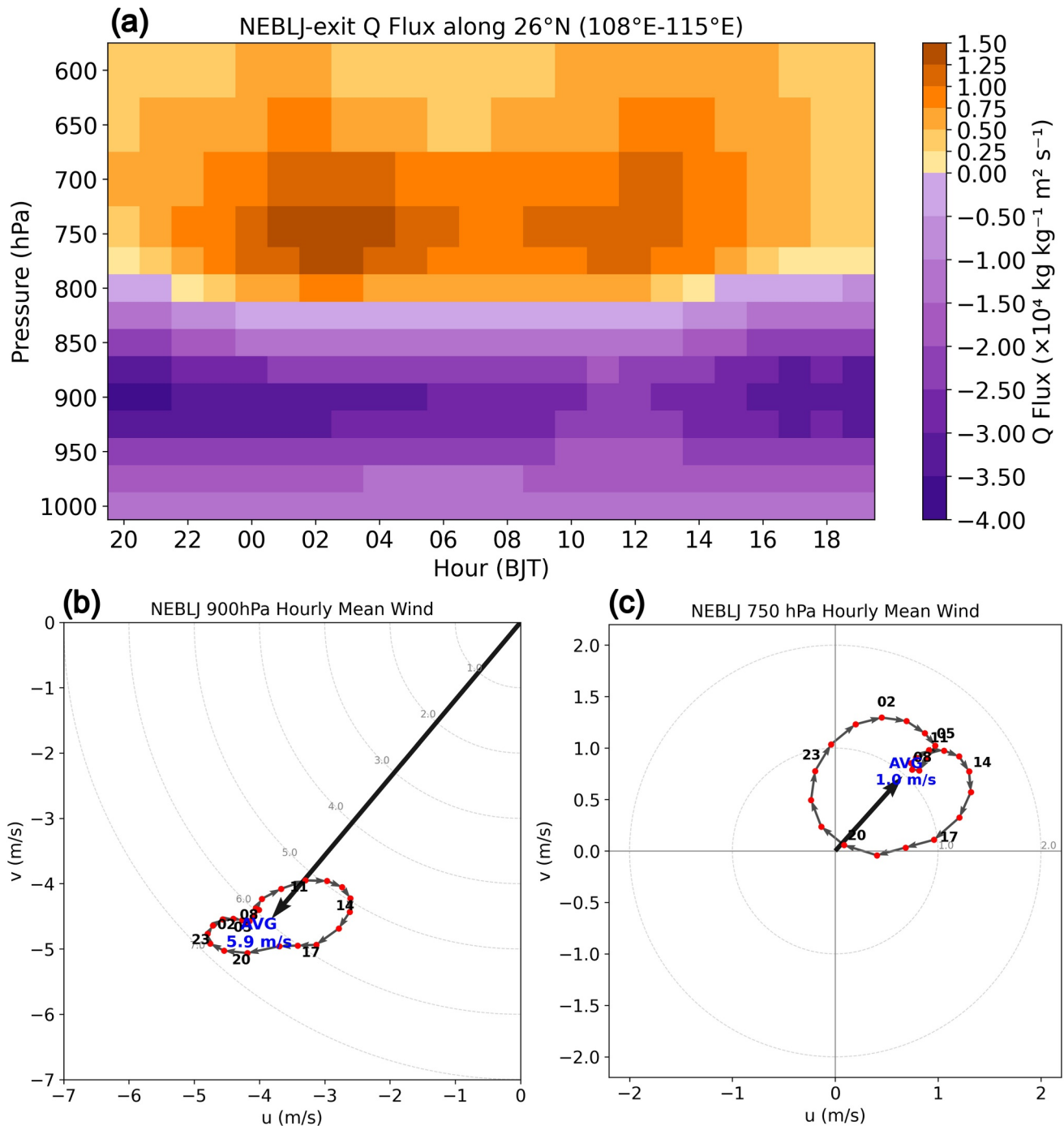


Figure 14. (a) Diurnal variations of boundary moisture flux along 26°N (108–115°E), positive values indicate south-to-north transport, and negative values indicate north-to-south transport. Hodographs of average hourly total winds at (b) 900 hPa and (c) 750 hPa over the NEBLJ-exit region on NEBLJ days. For panels (b) and (c), values at 18:00 and 06:00 BJT are replaced by the averages of the preceding and following hours to ensure data continuity.

thermal circulations. However, the relationship between this precipitation and the NEBLJ is unclear, and this study does not further analyze it.

3.3.2. Differences in Precipitation Diurnal Variation and Causes

Figure 12 shows the diurnal variations of hourly precipitation over the three precipitation regions identified in Figures 10a and 10b during SBLJ and NEBLJ events. In the two jet-exit regions, heavy precipitation

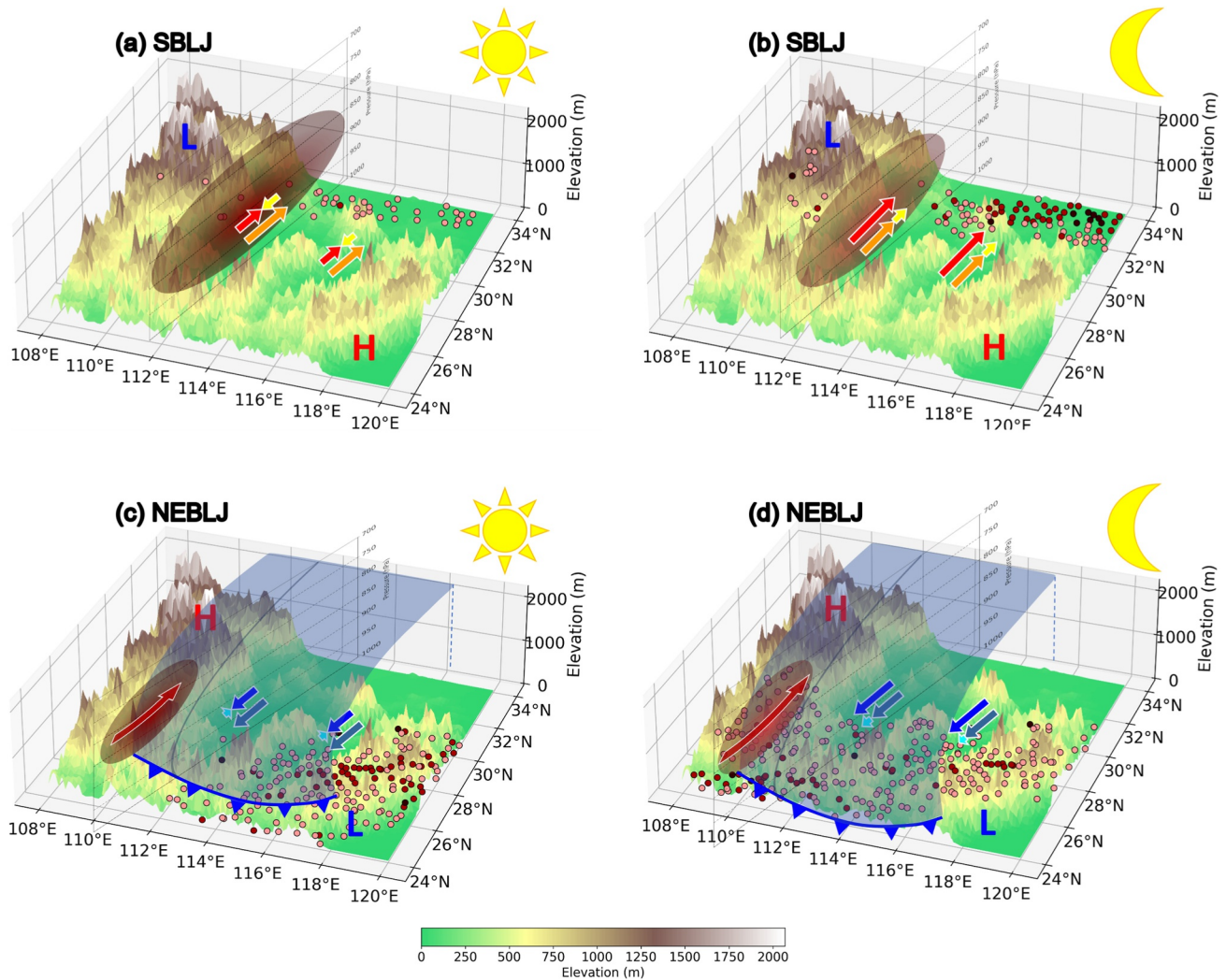


Figure 15. Conceptual models of the diurnal variations of SBLJs and NEBLJs and associated precipitation in the DP-Lake region. The wind fields include the daily mean winds, daytime/nighttime mean winds, and perturbation winds, represented by orange, red, and yellow arrows for the SBLJ, and by navy blue, blue, and cyan arrows for the NEBLJ. The symbols H and L denote the high- and low-pressure centers at 925 hPa, respectively. Hourly precipitation $\geq 0.35 \text{ mm hr}^{-1}$ is shown by red dots. Shaded colors indicate topography (m). In panels (c and d), the blue curve represents the frontal line at 925 hPa, with light-blue semi-transparent shading illustrating the frontal zone. Vertical cross sections highlight the cold front, cold air mass and northerly flow (all in blue), and the warm air mass and southerly flow (all in red).

predominantly occurs between 04:00 and 08:00 BJT, with NEBLJ precipitation peaking slightly earlier around 05:00–06:00 BJT and SBLJ precipitation slightly later around 05:00–07:00 BJT.

The diurnal variations of low-level wind convergence provide a direct explanation for the timing of rainfall. In the SBLJ-exit (Figure 12a) and NEBLJ-exit (Figure 12b) regions, the convergence cycle is largely governed by the evolution of the BLJs. Maximum convergence intensity is similar in both regions (-8 and $-7 \times 10^{-6} \text{ s}^{-1}$), with the strongest periods lasting from 02:00 to 08:00 BJT for SBLJs and 23:00–08:00 BJT for NEBLJs, spanning from the peak jet intensity to the end of the heavy precipitation period. The vertical structure of maximum convergence differs: in the SBLJ-exit region, the maximum convergence remains strong but its height gradually lowers from 875 to 925 hPa over time; in the NEBLJ-exit region, the maximum convergence is slightly lower in height. This difference primarily reflects the slightly higher SBLJ core and the nocturnal lowering of the maximum wind-speed level.

Consistent with the southerly–southwesterly wind direction from the surface to 700 hPa during SBLJ events over the DP-Lake region (Figure 5a), the vertical profiles of daily mean moisture flux in the SBLJ-exit precipitation region (Figure 13a) exhibit a coherent vertical structure within each boundary. Persistent inflow occurs along the

southern and western boundaries, while outflow occurs along the northern and eastern boundaries. The stronger, low-level meridional wind makes the southern and northern boundaries the dominant pathways for moisture transport. Moreover, given that the BLJ terminates between these two boundaries, inflow on the southern boundary exceeds outflow on the northern boundary, yielding a net positive moisture flux with a maximum approaching $3 \times 10^4 \text{ kg kg}^{-1} \text{ m}^{-2} \text{ s}^{-1}$. The meridional flux peaks near 800 hPa, with an amplitude roughly one-third of the zonal flux. Regarding diurnal variations (Figure 13c), southern and northern boundary fluxes peak earliest (around 00:00 BJT), while eastern and western boundary fluxes peak later (around 06:00 BJT), consistent with the diurnal cycle of wind (Figures 8a and 8c). The combined contributions of all four boundaries produce a regional moisture-flux maximum near 875 hPa between 02:00 and 08:00 BJT (Figure 13e), coinciding with the period of strongest convergence and the entire heavy-precipitation interval.

For NEBLJ events, the markedly variable wind directions (Figure 5b) result in a more complex vertical distribution of boundary moisture fluxes in the NEBLJ-exit region (Figure 13b). Below 800 hPa, the northern boundary provides the primary moisture inflow, peaking above $3 \times 10^4 \text{ kg kg}^{-1} \text{ m}^{-2} \text{ s}^{-1}$, while flux through the eastern boundary is roughly one-third of this magnitude. For both boundaries, inflow peaks between 925 and 900 hPa and switches to outflow above 800 hPa. The southern boundary shows outflow below 875 hPa but strong inflow above, with a maximum near 800 hPa comparable to that through the eastern boundary, indicating that southerly flow above the NEBLJs also brings in substantial moisture, contributing to precipitation. Rapid increases in outflow across the western boundary above 900 hPa, coupled with sharp reductions in inflow on the northern and eastern boundaries (where wind speeds decrease rapidly above the BLJ core; Figure 5b), confine effective moisture influx to layers below 800 hPa. Likewise, the diurnal variability of NEBLJ winds (Figures 8b and 8d) governs the temporal evolution of boundary moisture fluxes (Figure 13d): inflow along the northern boundary peaks earliest (17:00–20:00 BJT), the eastern boundary peaks around 22:00 BJT, and the southern boundary exhibits strong inflow between 02:00 and 12:00 BJT.

The zonal cross section along 26°N (Figure 14a) clearly shows southward moisture transport below 800 hPa, with a maximum near 900 hPa. The high-value period of moisture transport extends from 16:00 to 05:00 BJT the next day. The diurnal variations of the wind field at this level in the precipitation region (Figure 14b) resemble those of the NEBLJ over the DP-Lake region (Figure 8b), indicating that the NEBLJ exerts the primary control on moisture transport at this level. Moisture transport above 800 hPa is directed northward, peaking near 750 hPa between 00:00 and 05:00 BJT, driven by the diurnal variation of the southerly flow above the NEBLJ (Figure 14c). The combined effects produce a total moisture-flux maximum in the NEBLJ-exit region from 22:00 to 08:00 BJT. This period coincides with the strongest convergence and spans from the peak of jet intensity through the main precipitation interval.

In summary, the differences in the spatiotemporal distributions of precipitation between SBLJ and NEBLJ events can be attributed to differences and variations in low-level flow convergence and boundary moisture fluxes. For SBLJ events, precipitation in the exit region is primarily controlled by the BLJ-induced low-level wind convergence and moisture transport. Strong inflow from the southern boundary around midnight and from the western boundary pre-dawn, together with enhanced convergence during the late night to pre-dawn period, produces the pre-dawn to early-morning jet-exit heavy rainfall. The nocturnal intensification of the BLJ plays a key role in producing peak heavy precipitation from pre-dawn to early morning.

In contrast, although the precipitation peak in the NEBLJ-exit region occurs slightly earlier than that of the SBLJ, the underlying mechanisms are fundamentally different. During NEBLJ events, nocturnal moisture inflow is primarily dominated by the northern and eastern boundaries, while the southerly flow above the jet provides substantial moisture from late night to early morning. The combined effects of terrain and cold air lift the warm, moist air, while moisture transport and wind convergence are vertically superimposed, collectively generating heavy rainfall from pre-dawn to early morning.

Besides, the peak CAPE values differ by nearly an order of magnitude between the two types of BLJs (Figure 9c). Accordingly, it is reasonable to infer that the SBLJ is accompanied by more convective precipitation, while the NEBLJ is mostly associated with stratiform precipitation. Since convective precipitation systems generally develop rapidly, this feature reasonably explains our observational result. The wind speed peak of the SBLJ occurs later than that of the NEBLJ, yet their corresponding precipitation periods are similar.

Meanwhile, the afternoon moisture flux and wind convergence associated with both BLJ-exit regions decrease rapidly, particularly for the SBLJ, which exhibits more pronounced diurnal variations in BLJ frequency and wind speed. During this period, moisture flux and convergence drop to less than one-third of their nocturnal peaks, substantially reducing the forcing for precipitation in the BLJ-exit regions.

4. Summary and Discussion

Based on ERA5 reanalysis data and hourly precipitation observations during the extended warm season (April–October) from 2001 to 2021, this study systematically examines the spatiotemporal characteristics, formation mechanisms, and precipitation impacts of BLJs over the Dongting-Poyang Lake region. Hierarchical clustering combined with set BLJ identification criteria is applied. The main conclusions are summarized as follows.

Two distinct types of BLJs are identified over the DP-Lake region. SBLJs feature strong, deep southerly–southwesterly winds and occur most frequently in summer, primarily from late night to early morning (peaking around 02:00 BJT), with the jet-core height lowering to 925 hPa. SBLJs typically last 1–9 hr and weaken after sunrise as the daytime mixed boundary layer develops. In contrast, NEBLJs are characterized by strong but shallow northeasterly flow with stronger mean vertical wind shear. NEBLJs occur more frequently than SBLJs, mainly in spring and autumn, and peak around 22:00 BJT, with the jet core maintaining a constant height of 925 hPa throughout the day. They also exhibit a higher proportion of long-duration (≥ 13 hr) cases, many of which persist into the daytime, indicating weaker diurnal cycles and stronger association with synoptic systems.

The daily-mean winds of the two BLJ types are controlled by large-scale synoptic patterns, whereas inertial oscillation plays a key role in diurnal variations including nocturnal BLJ intensification. SBLJs occur with high pressure over the southeastern coast and low pressure over northwestern China, resulting in deep south–southwesterly flow crossing the Nanling Mountains into the DP-Lake region. In contrast, NEBLJs are controlled by northwestern highs and southern lows, producing shallow northeasterly flow originating from north of the Yangtze River basin often behind cold fronts. During daytime, BL mixing suppresses wind speeds, whereas after sunset, reduced surface friction allows BL winds to accelerate. Subjecting to the inertial oscillation mechanism, winds continue to strengthen beyond geostrophic balance, producing nocturnal BLJ maxima. Differences in seasonality, BL depth and the BL thermal conditions regulate the phase of inertial oscillation, resulting in the NEBLJ peak intensity occurring ~ 3 –4 hr earlier than that of SBLJs. Inertial oscillations drive wind speed to rise gradually after sunset, reach a peak at night, and then weaken after sunrise. Synoptic-scale forcing generally persists over a longer period, and its start and end times for modulating wind speed differ considerably across individual cases. As a result, the NEBLJs, which are largely affected by synoptic-scale forcing, shows weaker diurnal variation than the SBLJs primarily governed by local inertial oscillations.

The prominent diurnal variations in the intensities of the SBLJs and NEBLJs lead to clear diurnal variations in associated precipitation. The processes are summarized by the conceptual models shown in Figure 15. For SBLJs, rainfall is concentrated in the northern jet-exit region, driven primarily by warm-moist advection and convergence at the jet exit region. Daytime surface heating and the associated strong BL mixing weaken the BLJ (by mixing out the jet and making the BL flows sub-geostrophic), thereby suppressing flow convergence and rainfall in the jet exit region (Figure 15a). After sunset, with mixing reduced, inertial oscillations cause the BL flows to accelerate beyond geostrophic balance. The nighttime strengthening of SBLJs to peak intensity at 2–3 a.m. local time creates maximum moisture transport and exit-region convergence, and produces pre-dawn to early-morning heavy rainfall (Figure 15b). In contrast, NEBLJ-related precipitation occurs both in the jet-exit region and to its left, while both regions are occupied by major mountains. Similar to the SBLJ case, enhanced daytime BL mixing and the frictional effects weaken exit-region flow convergence, resulting in limited rainfall except near the cold front often at the leading edge of the NEBLJs. Most daytime rainfall instead occurs over the high terrain on the left side of the jet, driven by upslope flows associated with the mountain–plain thermal circulations, whose early evening peak is not clearly linked to the NEBLJs (Figure 15c). At night, the NEBLJs behind the cold front strengthen while the warm southerly flows south and above the NEBLJs also strengthen with the disappearance of BL mixing and the frictional effects. The accelerated NEBLJs encounter mountains at their exit region, as well as the moist air from the southerly flows, and creates enhanced rainfall from pre-dawn to early morning (Figure 15d).

In inland regions, BL inertial oscillations, as proposed by Blackadar (1957), remain the dominant mechanism controlling BLJ formation and evolution (Xue et al., 2018). Following this theory, BLJs over the Yangtze River

Basin are expected to peak from midnight to early morning. Consistent with this, Fu et al. (2019) reported a maximum BLJ at 05:00 LST on the windward side of the DB Mountains in the middle Yangtze River region. Our results similarly show that SBLJs occur most frequently between 00:00 and 05:00 BJT, consistent with theoretical expectations. The earlier peak of NEBLJs relative to SBLJs partly reflects seasonal differences and the corresponding variation in sunset times, broadly agreeing with Shu et al. (2024), who showed that earlier sunset in the cold season advances the phase of inertial oscillations. Interestingly, although the NEBLJ peak occurs ~4 hr earlier, precipitation at the jet-exit region for both BLJs still appears to peak at nearly the same time, pre-dawn to early morning. This may be explained by the warm, moist southerly flow aloft that overlies the NEBLJ core. This southerly flow exhibits a diurnal cycle closely resembling that of SBLJs and transports substantial moisture into the precipitation region from late night to early morning. This suggests that, although the NEBLJ itself attains its maximum intensity earlier in the night, the warm, moist southerly flow aloft, acting together with the NEBLJ, may still exert primary control over the timing of the precipitation peak.

Nocturnal BLJs are primarily governed by large-scale geostrophic flows and BL inertial oscillations on top of them. Mountainous terrain can further enhance ascent and moisture convergence in the jet-exit region, and strengthen the morning precipitation peak (Fu et al., 2019; Rao et al., 2022). In addition to this dynamical effect, mountains induce thermally driven upslope winds during the day and downslope winds at night, as well as up-drafts over high peaks. Typically, BL winds associated with mountain-plain circulations are much weaker than BLJs (Rampanelli et al., 2004); therefore, an evening precipitation peak dominated by mountain-plain thermal circulations is generally observed only over terrain away from the jet-exit region.

In addition, the double jet core structure of BLJs over the DP-Lake region is likely modulated by complex regional topography. Mechanical blocking and airflow splitting induced by mountains including the LX, MF and DB, together with the channeling effect across mountains and river valleys as well as modulation from local thermal circulations, collectively contribute to the formation of such dual-core structure. Further topographic sensitivity numerical simulations are required to clarify its dominant formation mechanisms.

In summary, this study reveals the occurrence, variability, and formation mechanisms of BLJs in the DP-Lake region and provides an assessment of their influence on precipitation over complex terrain from multiple perspectives. The study extends previous studies examining the effects of BLJ diurnal variations on precipitation in inland regions by examining and comparing northerly (equator-ward) BLJs against southerly (pole-ward) BLJs on which most earlier studies focus. Such studies can provide insights for improving diagnosis and forecasting of heavy precipitation in inland plains and mountainous areas. However, this study presents only climatologically averaged pictures, while individual cases, especially those of NEBLJs, can vary considerably from case to case. Future work should employ numerical simulations and sensitivity experiments to quantitatively explain the phase difference in inertial oscillation between SBLJs and NEBLJs, investigate the modulation effects of terrain with varying heights and scales on precipitation, evaluate the applicability of our findings to other similar inland lake-basin systems, and quantify the contribution of BLJs to early-morning heavy rainfall, thereby providing a reference for operational forecasting.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The ERA5 reanalysis data is available at <https://cds.climate.copernicus.eu/> (Hersbach et al., 2023). The precipitation data is provided by the National Meteorological Information Center of CMA (CMA, 2023). The global topography data set is obtained from NOAA National Centers for Environmental Information (NOAA, 2022). Typhoon data are obtained from the CMA Best Track data set provided by the Tropical Cyclone Data Center of CMA at <http://tcdata.typhoon.org.cn/en/index.html> (Lu et al., 2021; Ying et al., 2014).

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