Advances in Low-Level Jet Research and Future Prospects

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ABSTRACT

The low-level jet (LLJ) is closely related to severe rainfall events, air pollution, wind energy utilization, aviation safety, sandstorms, forest fire, and other weather and climate phenomena. Therefore, it has attracted considerable attention since its discovery. Scientists have carried out many studies on LLJs and made significant achievements during the past five or six decades. This article summarizes and assesses the current knowledge on this subject, and focuses in particular on three aspects: 1) LLJ classification, definition, distribution, and structure; 2) LLJ formation and evolutionary mechanisms; and 3) relationships between LLJ and rainfall, as well as other interdisciplinary fields. After comparing the status of LLJ research at home (China) and abroad, we then discuss the shortcomings of LLJ research in China. We suggest that this includes: coarse definitions of the LLJ, lack of observations and inadequate quality control, few thorough explorations of LLJ characteristics and formation mechanisms, and limited studies in interdisciplinary fields. The future prospects for several LLJ research avenues are also speculated.

Key words: low-level jet, structural and evolutionary mechanisms, rainfall, interdisciplinary research

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1. Introduction

In the context of global climate change, extreme weather and climate events show an obvious increase in both frequency and intensity. As a result, both meteorological and geological disasters, such as flooding and mudslides, which are closely associated with extreme rainfall, are causing serious damage to human lives and properties (IPCC, 2007). The low-level jet (LLJ) provides favorable background circulation and abundant water vapor for extreme rainfall events, and has therefore attracted widespread attention in the research community since the 1930s, with scientists having carried out a large amount of studies on LLJ since the 1950s in particular. The LLJ is widely distributed across each continent of the earth, such as North and South America, Africa, Asia, Oceania, and Antarctica (Stensrud, 1996). Goualt (1938) and Farquharson (1939) were among the first to discover African LLJ events in the late 1930s. Means (1952) used the concept of LLJ in his work on thunderstorms over the central area of the United States, and found that the LLJ plays an important role in squall lines and other extreme weather events. Blackadar (1957), Bonner (1968), and Uccellini and Johnson (1979) all carried out extensive research on LLJ formation and evolution, LLJ distribution and structure, as well as the relationships between LLJ and other weather and climate phenomena over North America. Similarly, Findlater (1969, 1977) completed a series of observational analyses on the characteristics of the Somali jet and its relationship with summer monsoonal rainfall

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in western India. Meanwhile, since the 1980s, Chinese scientists have focused on analyzing the relationship between LLJ and rainstorms, and their findings have provided useful reference for heavy rainfall prediction in South China (e.g., Tao et al., 1980; Yu et al., 1983).

Generally, the LLJ is regarded as a fast-moving ribbon of air with wind speed greater than 12 m s^{-1} in the boundary layer or the lower troposphere (usually below 700 hPa). Conventional sounding observations only include twice-daily measurements, and their spatial distribution is uneven. Therefore, it is hard to capture all LLJ events and obtain detailed information on LLJ evolutionary processes, especially for stronger LLJs (Mitchell et al., 1995). In view of this fact, most LLJ studies are based on rawinsondes. For example, with 6-hourly rawinsonde and hourly wind profiler observations, Bonner (1968) and Mitchell et al. (1995) each presented the geographical distribution of the Great Plains LLJ over North America, its seasonal activities, horizontal and vertical structures, and diurnal variation characteristics, and were able to conclude the climatology of the warm season Great Plains LLJ. Arritt et al. (1997) investigated anomalous LLJ activities and their contributions to the 1993 summer flood in America through high-resolution hourly wind observations from the National Oceanic and Atmospheric Administration (NOAA) Profiler Network. In order to study the environmental configuration of the LLJ, scientists have used regular weather observations (Chen and Yu, 1988). However, these observations rarely match each other in terms of observation time and location, so errors will inevitably arise. In addition, single-point rawinsonde measurements cannot capture horizontal shear and environmental conditions (Chen et al., 2005). High-resolution reanalysis data provide powerful support for detailed LLJ analysis. For example, using such data, Higgins et al. (1997) and Weaver and Nigam (2008) respectively examined the effects of the Great Plains LLJ on summer rainfall and water vapor transport, and the influence of the North Atlantic Oscillation and El Niño–Southern Oscillation on seasonal and annual variations of the LLJ and the subsequent adjustments of regional hydroclimate. Furthermore, a vast field campaign, the "South America LLJ Experiment", was carried out in the period 2002–2003 aimed at understanding the role of the LLJ in moisture and energy exchange between the tropics and extratropics and related aspects of regional hydrology, climate, and climate variability (Vera et al., 2006).

During the past half-century, LLJ studies have covered many aspects, including the structural and evolutionary characteristics (Bonner, 1968; Findlater, 1969; Chen et al., 2005), formation and development mechanisms (Blackadar, 1957; Holton, 1967; Uccellini and Johnson, 1979; Pan et al., 2004), and LLJ relationship with rainfall and other weather and climate phenomena (Tao et al., 1979; Higgins et al., 1997; Saulo et al., 2007). The research methods have evolved from observational analysis at the very beginning, to theoretical studies, and more recently to numerical experimental investigations (Holton, 1967; Mitchell et al., 1995; Ting and Wang, 2006). The mesoscale numerical model is the most widely used tool, as it can not only provide high spatial and temporal resolution data for LLJ research, but also examine the already existing LLJ formation theories and further explore the possible influencing mechanisms through numerical sensitivity experiments. For example, Pan et al. (2004) and Zhang et al. (2006) conducted studies concerning the influence of topography, land surface heat flux, and land-sea contrast on the formation and evolution of the Rocky Mountains and Appalachian Mountains LLJs with mesoscale models so as to quantify the relative roles of the above factors. In addition, Qian et al. (2004) and Zhao (2012) respectively analyzed the interactions between precipitation-related latent heat release and LLJ development, and the local topographical effects on the LLJ during the Meiyu season in South China.

The relationship between LLJ and strong precipitation has been intensively studied during the past several decades. The findings have been effective in increasing the precision of rainfall prediction (Tao et al., 1980), and enhanced our understanding of extreme rainfall and flooding events, which provides the scientific basis for the prediction and prevention of such disastrous events. In addition to precipitation, the

LLJ is closely related to air pollution, wind energy utilization, aviation safety, sandstorm transport, and forest fire (Uccellini, 1980; Liechti and Schaller, 1999; Archer and Jacobson, 2005). As these relationships have come to light, more and more attention has been paid to corresponding studies in these fields by natural and social scientists. Hence, LLJ research has both theoretical and practical meanings.

At present, information regarding the LLJ over mainland China is inadequate, and our knowledge on LLJ-related events is limited (Sai and Miao, 2012). Meanwhile, most Chinese scientists have focused on the relationship between LLJ and precipitation, and the lack of observations or difficulties in data sharing have resulted in relatively few studies on LLJ structural and evolutionary mechanisms. Therefore, many more studies are still needed to understand this important weather phenomenon. In fact, in recent years, the amount of observations has increased, which provides an ever-improving and favorable platform for LLJ research. However, before we embark on such research, a detailed review of LLJ-related studies from both home and abroad is useful. Accordingly, in the present paper, we focus on reviewing three major aspects of LLJ research: LLJ classification, definition, distribution, and structure; LLJ formation and evolutionary mechanisms; and the relationships between LLJ and rainfall as well as other interdisciplinary fields. Finally, we discuss the shortcomings of LLJ studies in China and speculate on the future prospects of several LLJ research avenues.

2. LLJ classification, definition, distribution, and structure

2.1 LLJ classification and definition

Based on the maximum wind speed height, the LLJ can be divided into the free atmosphere LLJ (850–600 hPa) and the boundary layer LLJ (below 850 hPa or 1500 m) (Sai and Miao, 2012). Free atmosphere LLJs always appear with synoptic systems, e.g., the strong baroclinic LLJ at the edges of the tropical cyclone or the southwest vortex east of the Sichuan basin, and the LLJ in local circulation resulting from strong convection. Boundary layer LLJs include both the less-baroclinic jets without obvious synoptic systems, and those jets accompanying rainstorms over the transition zone between high and low pressure systems, such as the LLJ east of the Rocky Mountains and the Somali jet in East Africa. Of course, according to the coverage area of strong winds, the LLJ can also be divided into large-scale, synoptic-scale, and mesoscale jets (Yu, 1986). We do not discuss each type of LLJ in this paper, but review their general characteristics and formation mechanisms.

So far, there is no universally accepted LLJ definition because of the differences in LLJ height, coverage area, maximum wind speed, horizontal and vertical shears, and so on. Bonner (1968) set three criteria for an LLJ based on the maximum wind speed and vertical shear. Criterion 1 (2, 3) is that the wind at the level of maximum wind must equal to or exceed 12 (16, 20) m s^{-1} and must decrease by at least 6 (8, 10) m s^{-1} to the next highest level with minimum wind or to the 3-km level, whichever is lower. This definition is extensively accepted in both North and South American LLJ research (Higgins et al., 1997; Pan et al., 2004; Vera et al., 2006). Besides, scientists also set different limitations for LLJ maximum wind speed and its height, and vertical shear, based on topographical distribution and background circulation conditions. For example, the vertical jet-like structures in the lowest 1.5 km were identified with positive shear below and negative shear above at 300-m height intervals in Zhang et al. (2006). Such a broad definition of LLJ is necessary because a single station is unable to frequently capture the core of LLJs.

Following the LLJ criteria of Bonner (1968), Chen et al. (2005) relaxed the height of maximum wind speed up to 600 hPa. With this definition, the sounding data in their study showed a double-peak structure, with a primary maximum at 900–925 hPa and a secondary maximum at 825–850 hPa. Over Taiwan, the primary LLJ wind speed maximum corresponds to barrier jets within the boundary layer due to terrain blocking, which has a higher frequency. The 850–700-hPa jets are movable and closely linked to Mei-yu-frontal heavy rainfall. Du et al. (2012) also found similar double-peak LLJs at Qingpu station (Shanghai) from the wind profiler radar data, which correspond to the 500–800-m boundary layer jet and 2100–2200-m synoptic system related LLJs. Before this, most studies on mainland China LLJs only set a limitation on the maximum wind speed at a certain pressure level because of the lower-resolution data and no restriction on vertical shears (e.g., Yu et al., 1983; Zhai et al., 1999; Xu et al., 2001; Qian et al., 2004).

Stensrud (1996) made a distinction between the LLJ and the low-level jet stream. He pointed out that the LLJ represents the air currents with obvious vertical shear, whereas no limit is given for the low-level jet stream (strong vertical shear is not necessary for it to exist), and this classification is accepted by most researchers. Zhang et al. (2007) compared the southwest LLJ and low-level southwesterly maximum wind over China and revealed their synoptic and climatological differences. Most LLJ research from abroad sets a limit on vertical shear to avoid confusion with low-level high-speed streams. The LLJ and low-level jet stream do show obvious differences in their distribution, horizontal and vertical structure, diurnal variations, formation mechanisms, as well as their effects on rainstorms. In this paper, unless otherwise stated, the LLJ refers to high-speed air currents with obvious vertical shear in both the boundary layer and the lower troposphere.

2.2 LLJ distribution and activity

The LLJ is widely spread over every continent of the earth, but tends to locate to the east of large mountains or in areas with land-sea contrast. It always lies along topographic or coastal lines. Stensrud (1996) prepared a hand-drawn map of LLJ distributions over the earth based on previously published data. Recently, Rife et al. (2010) produced a map of the global distribution of diurnally varying LLJs based on 40-km high-resolution hourly reanalysis data (Fig. 1). All the known nocturnal LLJs of Stensrud (1996) appear clearly in Fig. 1, and several newly identified areas of intense LLJ activity are also present, such as over the Tibet and the Tarim basin in China. The intensity of the LLJ in the Northern Hemisphere is in general stronger than that in the Southern Hemisphere due to a larger continental area.

LLJs occur throughout the year, but maintain a higher frequency during the warm season in each hemisphere, with greater intensity and coverage area (Findlater, 1977; Virji, 1981; Paegle et al., 1987). Using North America as an example, Weaver and Nigam (2008) found that the Great Plains LLJs are most active and strong in July according to 25-yr high-resolution reanalysis data. The LLJs over Southwest China show similar activities (Zhang et al., 2007). Meanwhile, LLJ activities are regulated by the large-scale climate background, showing distinctive annual variations (Weaver and Nigam, 2008). For example, the North American LLJ was found to have occurred more frequently during the period 2000–2002 than 1997–1999 under the simultaneous modulation of El Niño and the Pacific Decadal Oscillation (Song et al., 2005).

2.3 LLJ structure

A significant jet core with large horizontal shear always exists at the horizontal level of the LLJ, which runs parallel to the topography or coastline. In North America, the LLJ mainly appears over the Great Plains to the east of the Rocky Mountains. Synoptic-scale low pressure systems always exist to the left of the LLJ and large-scale high pressure systems provide favorable background conditions to its right. The pressure gradient between high- and low-pressure systems leads to consistent increase of air currents (Figs. 2a and 2b of Rife et al., 2010). The LLJs to the east of the Tibetan Plateau, Africa, and the Andes Mountains in South America all show similar horizontal structure and synoptic configuration (Findlater, 1977; Vera et al., 2006; Zhang et al., 2007; Liu, 2012; Liu et al., 2012). Bonner (1968) conducted a systematic study of the LLJ horizontal structure with sounding data based on the LLJ coordinate system. His results indicated that divergence exists in the upstream side and convergence in the downstream side of LLJs. Thus, air stream should be sinking as it moves into the jet maximum, and then rising downstream from the jet, leading to an increased likelihood of nocturnal thun-

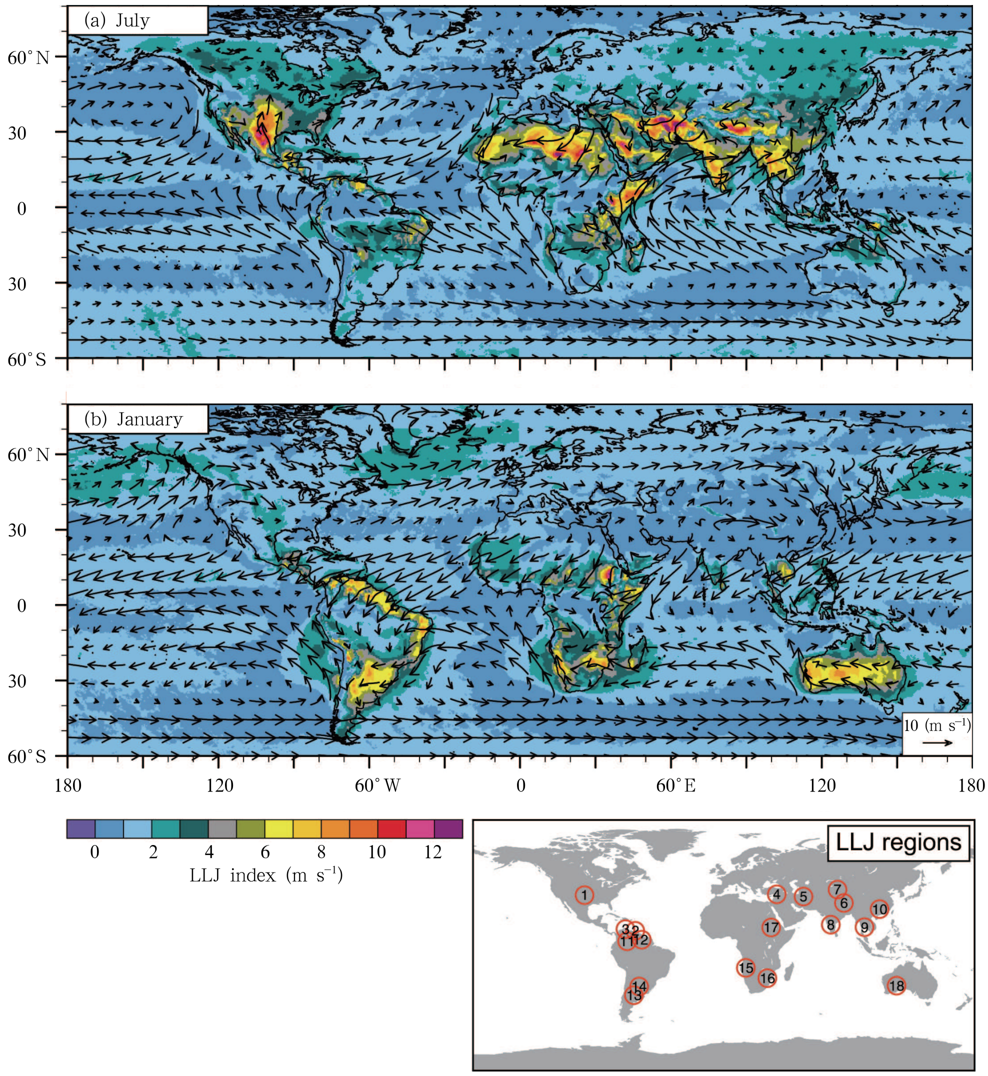

Fig. 1. Mean nocturnal LLJ (NLLJ) index (shaded) and 500-m above-ground-level (AGL) winds (arrows) at local midnight in the period 1985–2005 for (a) July and (b) January, calculated from CFDDA hourly analyses. The inset shows the locations of NLLJs analyzed for the study. This figure is taken from Rife et al. (2010).

derstorms in the downstream section of the jet. In China, the LLJs south of the Yangtze River basin show similar structures; namely, highly warm and moist rising air stream and intense convergence to the left side of the jet, and always accompanied by rainstorms (Tao et al., 1980).

In the vertical direction, the wind profile has typical jet-like characteristics, with maximum wind and strong vertical shear. We take North America as an example: the wind maximum (> 16 m s^{-1}) appears between 250 and 1000 m and then quickly decreases to 6 m s^{-1} at 3000 m (Fig. 2c). The above vertical structure is continuously found in areas with frequent LLJ activity (Findlater, 1977). As mentioned earlier, Chen et al. (2005) and Du et al. (2012) found double-peak LLJs in Taiwan and Shanghai, corresponding to boundary layer and synoptic-scale jets. Because of the close relationship with synoptic system forcing, the synoptic-scale LLJ appears much higher (850–800 hPa). In fact, the two kinds of jets are ubiquitous (Stensrud, 1996). Tao et al. (1980) pointed out that different scale LLJs are not isolated; most studies show only one jet peak because they choose different LLJ criteria.

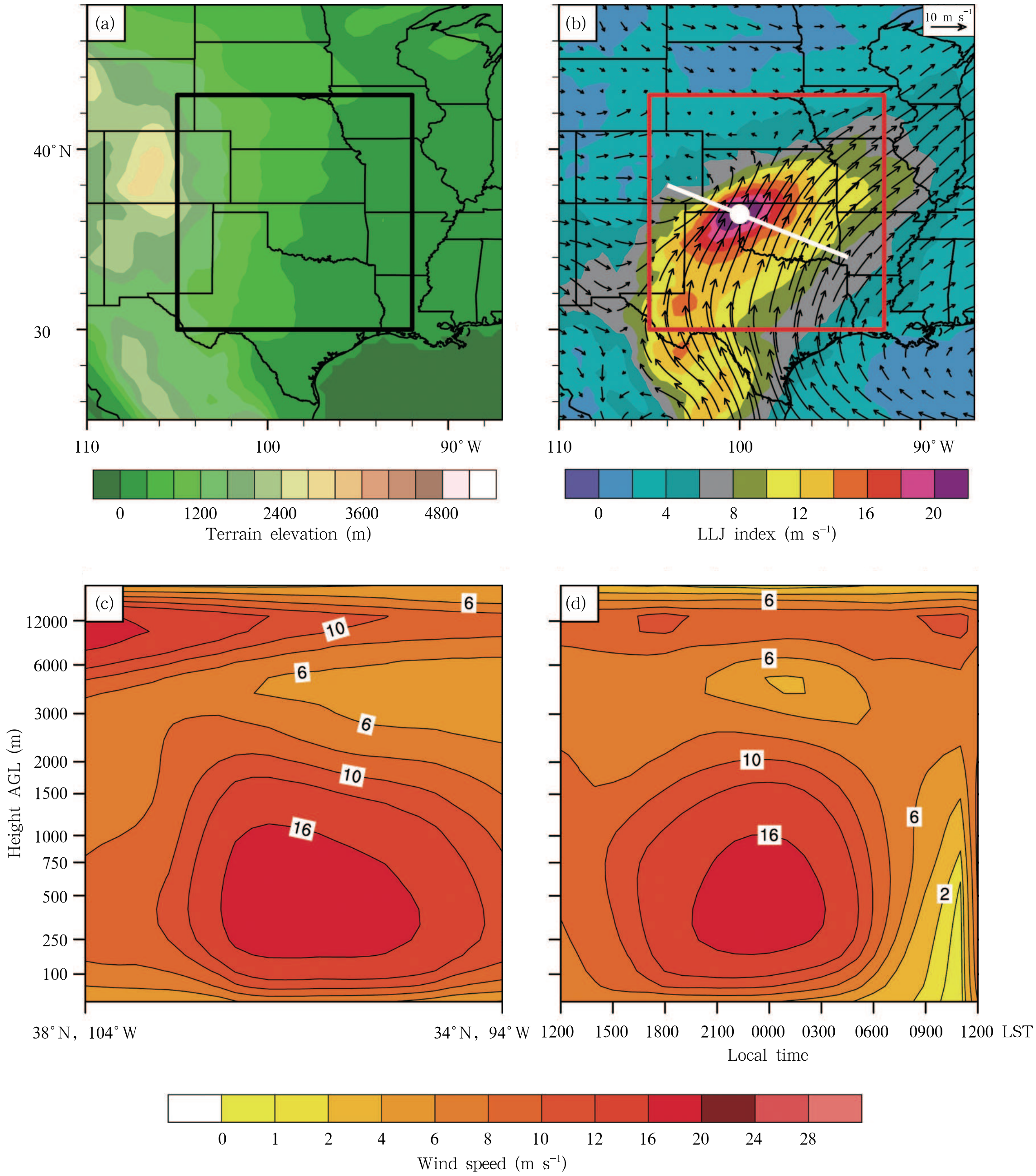

Fig. 2. Composite characteristics for strong (⩾ 90th percentile) NLLJ events for the Great Plains region (site 1 in Fig. 1) for July 1985–2005. (a) Terrain elevation within the region (meters MSL) and (b) mean NLLJ index (shaded) and 500-m AGL winds (arrows). The thick white line denotes the location of the cross-section shown in (c), and the white circle denotes the point at or near the jet core, and marks the location of the time-height plot shown in (d). (c) Cross-section of the mean wind speed along the white line in (b). (d) Mean time-height evolution of wind speed within the jet core, denoted by the white circle in (b). This figure is taken from Rife et al. (2010).

2.4 Diurnal variation

In the early 1930s, Goualt (1938) and Farquharson (1939) noticed nocturnal intense wind events; and then Gifford (1952), Lettau (1954), and Blackadar (1955) further proved the existence of this phenomenon. The United States of America first carried out a field experiment aimed at boundary layer winds, and Hoecker (1963) demonstrated the detailed diurnal variation of the LLJ with hourly observation data. The wind speed increased and reached its maximum at 0500 CST (Central Standard Time), and then it weakened after sunrise with the well-organized jet core separating into several centers. After sunset, the wind strengthened and recovered into a complete jet core at 2300 CST (Hoecker, 1963). Diurnal variation characteristics of LLJs are widely observed in areas with frequent LLJ activity. Although differences exist in the LLJ onset time, maximum wind speed, and jet core height over different areas, the wind speeds on average all reach their maximum at midnight to early morning and minimum around noon time (Figs. 2d and 3a). In addition, the LLJ maximum wind presents a distinct clockwise rotation during the whole day (Fig. 3). In view of this diurnal cycle, Blackadar (1957) and Holton (1967) each proposed explanations based on inertial oscillation theory and attributed it to upslope and downslope winds caused by the day-and-night radiation difference. Furthermore, Bonner and Paegle (1970) found that the veering of thermal winds due to the differences between topographic and atmospheric thermal characteristics can also affect the diurnal variation of the LLJ. Related research is reviewed in detail in Section 3.

Meteorological interest in the diurnal cycle of the LLJ lies in the fact that it is closely associated with the diurnal variation of precipitation. When the LLJ strengthens during nighttime, vertical shear increases and the wind becomes supergeostrophic. This leads to a less stable air column and is favorable for the development of convection. As a result, thunderstorms and rainstorms tend to develop or strengthen during nighttime (Tao et al., 1980). Higgins et al. (1997) pointed out that LLJ events are associated with enhanced precipitation over the northern central United States and the Great Plains and decreased precipitation along the Gulf Coast and East Coast. Because of the LLJ, in excess of 25% more precipitation falls over the Great Plains during the nighttime hours than during daytime hours in the warm season, and the overall moisture budget is considerable, with low-level inflow from the Gulf of Mexico increasing on average by more than 45% over nocturnal mean values. With the help of numerical simulation results, Liu (2012) found that the rainfall over the Yangtze-Huai River basin has double peaks; namely, rainfall is strongest in early morning and early evening, but weakest at noon and midnight. Meanwhile, the LLJ shows a diurnal cycle with intensification in the morning and weakening or disappearance around noon. The convergence resulting from the clockwise rotation of wind direction during this diurnal variation provides a reasonable explanation for the early morning rainfall peak over this region. The minimum rainfall downstream of the

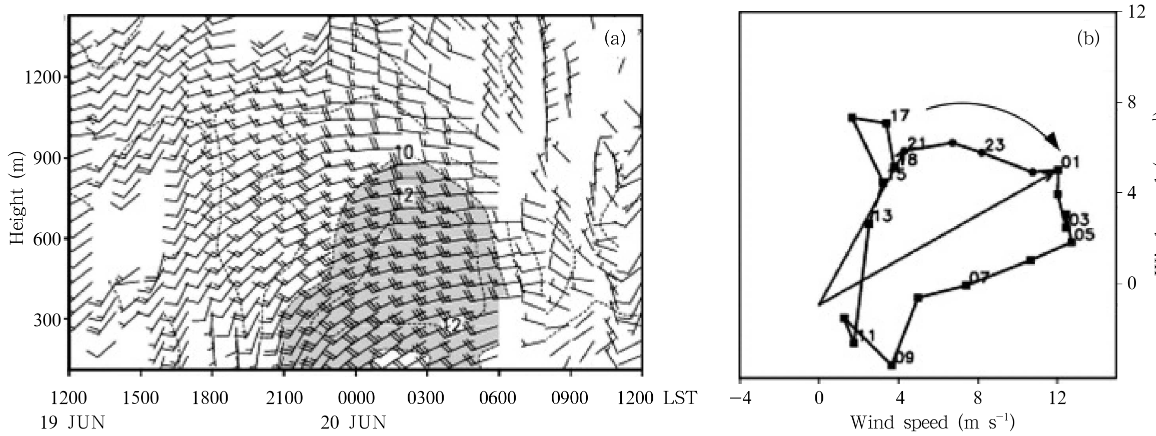

Fig. 3. (a) Time-height cross-section of horizontal wind and isotach (dotted; every 2 m s^{-1}) from the wind profiler observations at Fort Meade for the period 1200 LST (Local Standard Time) 19 June–1200 LST 20 June 2001. Shading denotes the layers of horizontal winds exceeding 10 m s^{-1}. A full barb is 5 m s^{-1}. (b) Hodograph at hourly intervals taken at 500 m AGL for the period 2100 LST 19 June–2000 LST 20 June 2001. The arrow denotes horizontal wind vectors given near sunset and at the time of peak magnitude. This figure is taken from Zhang et al. (2006).

Yangtze River basin is mainly caused by the eastward warm advection from the Tibetan Plateau, which inhibits local convection after noon (Chen, 2009). Xu and Chen (2013) also indicated that the LLJ forms 12 h prior to the occurrence of nocturnal rainstorms in northern Zhejiang Province.

3. Mechanisms of LLJ formation and evolution

Scientists have carried out a large amount of work on the above-described LLJ structural and evolutionary characteristics. In this section, we summarize five key aspects of the mechanisms of LLJ formation and evolution.

3.1 Inertial oscillation

Turbulent motion and boundary layer depth exhibit distinct diurnal variation as the solar radiation varies throughout the day. Vertical turbulent mixing weakens after sunset and a shallow inversion layer forms above the surface. The horizontal wind decouples from the land surface within the residual layer; that is, the wind is no longer affected by the surface friction. Therefore, the horizontal wind, which is subgeostrophic, will evolve into being geostrophic. Because of the combined effects between Coriolis force and inertial centrifugal force, an inertial oscillation appears under the interactions of these two forces with a periodicity of 17 h (Blackadar, 1957; Stensrud, 1996; Hao et al., 2001). Meanwhile, the wind field endures a transition from subgeostrophic to quasigeostrophic and finally supergeostrophic. Blackadar (1957) showed that inertial oscillation is an important factor for the formation of the LLJ. Later, Bonner and Paegle (1970) verified this viewpoint through a simple conceptual model.

Van De Wiel et al. (2010) extended Blackadar's concept of nocturnal inertial oscillation by including frictional effects within the nocturnal boundary layer. Figure 4 shows a schematic illustration of the wind velocity inertial oscillation profiles with different assumptions. Initially, the wind velocity gradually increases with height (Fig. 4a). Under the assumption of frictionless effects in the boundary layer, the wind velocity will maintain an inertial oscillation around the geostrophic wind vector based on the boundary layer equations for the mean average wind components, which is shown by the inertial circles (dashed lines in Fig. 4a). The envelope marked with an "×" shows the vertical profile of whole wind velocity with different oscillation radii at the moment of the strongest LLJ. The initial velocity profile in Fig. 4b is exactly the same as that in Fig. 4a; however, the nocturnal wind speed profile describes an oscillation around the nocturnal equilibrium wind vector rather than around the geostrophic wind vector, when including frictional effects. In comparison with Blackadar's concept model, the velocity profile in Van De Wiel et al. (2010) is more similar to observations, having a typical jet-profile and intense vertical shear. Inertial

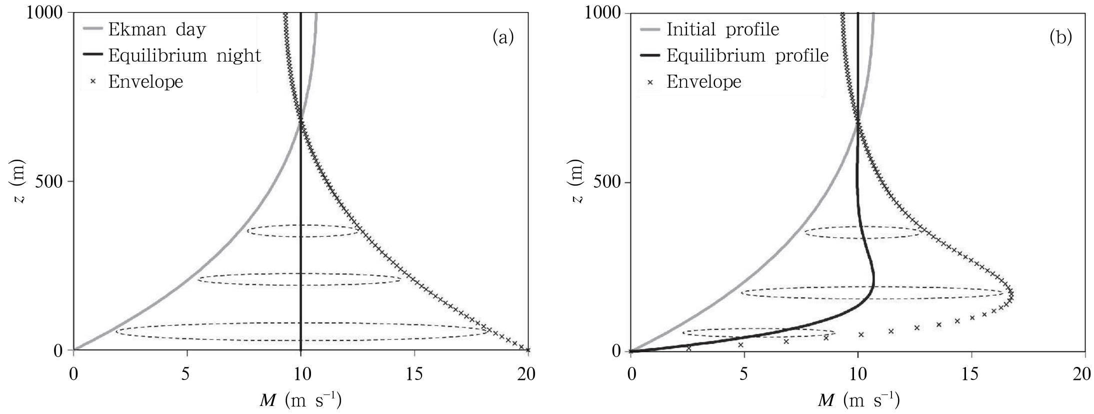

Fig. 4. Schematic illustration explaining (a) Blackadar's (1957) inertial oscillation around the geostrophic equilibrium; and (b) as in (a), but with the nocturnal wind oscillating around the nocturnal equilibrium profile. M represents the wind speed (m s^{-1}). This figure is taken from Van De Wiel et al. (2010).

oscillation is one of the most accepted mechanisms for the explanation of boundary layer LLJ formation with obvious diurnal variation.

3.2 Topographic thermal and dynamic forcing

The diurnal oscillation of horizontal temperature gradients over sloping terrain and the subsequent geopotential height variation induced upslope and downslope motions can also account for the LLJ formation. Solar radiation is strong after noon, and therefore the negative temperature gradient from mountains to valleys leads to the reverse in terms of the pressure gradient. This induces upslope winds on the eastern side of sloping terrain. The air stream gradually veers with the influence of Coriolis force and inertial oscillation, and finally shows an obvious southerly component after several hours (in nighttime). This strengthens the previously existing southwesterly wind and leads to the formation of the LLJ. The above activities are reversed at nighttime. The downslope wind resulting from the opposite temperature gradient veers and northerly wind forms during daytime, which heavily counteracts the prevailing southwesterly wind and finally makes the LLJ disappear (Holton, 1967; Jiang et al., 2007). Meanwhile, the rotation of thermal wind due to the thermal contrast over the sloping terrain also promotes the formation and disappearance of the LLJ (Bonner and Paegle, 1970). Under the background of thermal differences due to terrain, most LLJs over the east of the Tibetan Plateau and Rocky Mountains form as the gradient wind and thermal wind adjust with the change of surface temperature (Stensrud, 1996; Sai and Miao, 2012) (Note that the mechanisms of land-sea thermal contrasts are similar to those over sloping terrain, and therefore we do not explain them in this paper). In addition, the positive feedback between the inversion layer and intense vertical shear is another important factor for LLJ formation and development. During nighttime, radiative cooling is significant over the surface layer of the terrain, and the inversion forms when the air over the terrain is advected over the valley (Hao et al., 2001). This stable layer structure inhibits the development of turbulence within the boundary layer and favors the retention of momentum. When the top of the inversion layer coincides with the maximum wind peak, turbulence can exist beneath and help the inversion layer to sustain and develop upward. Hence, the existence of the inversion layer provides favorable conditions for an increase of wind speed within the boundary layer. Conversely, the strong vertical shear helps to sustain and develop the inversion layer. The positive feedback between them promotes LLJ formation and enhancement (Blackadar, 1957; He and Wu, 1989).

Topographic dynamic blocking effects cannot be neglected either. During the warm season in North America, the easterly wind of the Atlantic subtropical high can reach the eastern side of the Rocky Mountains, and then the air current veers northward when it climbs up the mountain. Under the control of potential vorticity conservation, the air mass gradually speeds up as it travels northward, and then the LLJ forms (Wexler, 1961). This kind of LLJ is regarded as a "barrier jet", which is closely associated with large-scale background circulations. Chen et al. (2005) revealed several characteristics of the barrier jet, such as its appearance at relatively lower levels; being without or with weak vertical shear, and less movable; and possessing no obvious diurnal variation. Therefore, the barrier jet can be ascribed into "low-level high-speed air streams". In addition, sloping terrain can significantly reduce air mass transport when the air current moves across isobars, which ensures the persistence of LLJ events (Holton, 1967). In fact, the high and low pressure system configurations due to heating differences along sloping terrain and the "narrow pipe effect" both help the formation and development of LLJs (Pamperin and Stilke, 1985; Chen et al., 2006).

3.3 Coupling between upper- and lower-level jets

LLJs provide favorable conditions for the development of convective systems through transfer of momentum, heat, and water vapor, whereas upper-level jets provide favorable convergent or divergent situations through circulation configuration. At the same time, the direct and indirect forced circulations induced by the upper-level jet can also promote three-dimensional mass and momentum transport, and thus is coupled with the LLJ. The interaction between upper- and lower-level jets is one of the most important factors making the organized rainstorms form at the exit region of the upper-level jet; and the upper-level jet also promotes the formation, development, and enhancement of the LLJ (Uccellini, 1980; Ding, 2005). Using a straight upper-level westerly jet as an example, directly and indirectly forced circulations respectively form at the entrance and the exit region while moving under the effect of inertial rotation (Ding, 2005). The low-level backflow branch of the indirect circulation leads to an increase of horizontal pressure gradient force and thus enhances northward isallobaric wind. The enhancement of the isallobaric wind and westerly wind component results in the LLJ formation, which is embedded in the low-level backflow. At this time, the upper-level jet continuously transports cold and dry air masses eastward and the LLJ transports warm and moist air masses northward; the coupling between the upper- and lower-level jets produces favorable conditions for deep convection systems and rainstorms (Uccellini and Johnson, 1979). According to the convergence and divergence characteristics of upper-level jets, LLJs can also develop on the right side of the exit region of upper-level jets (Si et al., 1982; Xiao and Chen, 1984). Brill et al. (1985) proved the existence of this transverse indirect circulation at the exit region of upper-level jets, and the strengthening effects from the upper-level jet and the diabatic heating on the LLJ. From the viewpoint of inertial gravity wave instability, Chen (1982) discussed the coupling process between upper- and lower-level jets. Given enough water vapor supply and a conditionally unstable atmosphere to the south of the upper-level jet, the nongeostrophic wind caused by advection will induce the development of the LLJ during its adaptation process to the south of the upper-level jet entrance region. With the help of numerical sensitivity experiments, Saulo et al. (2007) demonstrated the interactions among the LLJ, mesoscale convection systems, and the upper-level jet, and exhibited a positive feedback process among them through a conceptual model. Generally, the upper-level jet related to an LLJ appears at a much higher level and does not possess obvious diurnal variation (Uccellini et al., 1987).

3.4 Synoptic system forcing

LLJs do not appear every day, despite topographic forcing and inertial oscillation always being in existence. Whether or not the wind speed can reach the necessary level of the criteria that define an LLJ may also depend to a certain degree on midlatitude synoptic system forcing. By conducting a numerical simulation of coastal secondary circulation, Uccellini et al. (1987) found that the low-level wind speed significantly increased and reached a peak intensity of 30 m s^{-1} in response to the parcels' vertical acceleration under a baroclinic environment. When the parcel moved toward the low-pressure system from the northeast direction, it experienced external forcing caused by the pressure gradient changes. Although this forcing was mild in the horizontal direction, the rapid upward acceleration became prominent in a baroclinic environment and with the effect of the coastal front. The significant enhancement of ageostrophic wind resulted in the formation of an LLJ during the parcel's upward acceleration.

When the LLJ accompanying rainstorms over the Yangtze River basin or South China occurs, the western Pacific subtropical high and a low-pressure system (e.g., southwest vortex) always exist to the east and west side of the LLJ. A large horizontal pressure gradient forms within the transition zone between the high- and low-pressure systems, and thus it increases the wind speed, which is favorable for the development of the LLJ (Xu et al., 2004). Through the transformation and decomposition of ageostrophic wind in the natural coordinate systems, Wang and Zhang (2012) gave four factors influencing the ageostrophic characteristics of the LLJ; namely, the non-constant wind field; inhomogeneous wind speed in the flow direction; curved streamline; and the atmospheric baroclinicity. The changes in the intensity and location of the western Pacific subtropical high and the lee systems from the Tibetan Plateau both have important influences on the above four factors, especially the geostrophic deviation caused by the curved streamline. The occurrence of LLJs in April over Southeast China mainly results from the northward shifting of the western Pacific subtropical high, and the occurrence of LLJs in

July results from the intensification of detouring flow around the Tibetan Plateau (Wang et al., 2013). In addition, the LLJ is closely related to the formation of fronts, leeside cyclones, and leeside troughs (Ding, 2005).

3.5 Positive feedback from diabatic heating

Diagnostic studies and numerical simulations both indicate that diabatic heating plays an important role in the development and strengthening of mesoscale LLJ events (Huang, 1981; Uccellini et al., 1987; Nicolini et al., 1993). Chen and Yu (1988) and Si (1994) showed that the secondary circulation associated with rainstorms is one important factor involved in the intensification of the LLJ. When a rainstorm happens, upward motion and latent heat release enhance the upper-level divergence, and the surface pressure decreases. Meanwhile, two secondary circulations form on both the north and south sides of the rainfall area. The southern indirect circulation features southerly winds, which gradually intensify and finally become the LLJ following the impacts of the pressure gradient and Coriolis forces. Qian et al. (2004) carried out a case study of torrential precipitation during 11–17 June 1998 using the Pennsylvania State University-NCAR Mesoscale Model (MM5). Their results demonstrated that the main source of water vapor for this heavy precipitation event over the Yangtze River basin was from the Bay of Bengal, and the moisture was transported by a southwesterly LLJ southeast of the Tibetan Plateau. Although the LLJ was largely manipulated by large-scale forcing, the mesoscale circulation that resulted from Meiyu condensational heating acted to increase the maximum wind speed of the LLJ. The intensified LLJ further promoted moisture transport and thus formed a positive feedback and sustained the Meiyu precipitation system. Similarly, Zhao (2012) performed a case study of a localized extreme heavy rainfall event during mid-summer in central China with the Weather Research and Forecasting (WRF) model. He found that both the LLJ and simulated rainfall intensity were significantly decreased when the latent heat release was shut down in the simulation, which proved that diabatic heating was one of the most important factors enhancing the LLJ.

In addition, Tao et al. (1980) found that the downward transport of upper-level momentum can also increase lower-level wind speed and lead to LLJ events, according to their diagnostic analysis. Convective mixing tends to make wind speed uniform in the troposphere, and therefore promotes the downward transport of upper-level momentum, and forms a strong wind field over the convection area. It is important to note that this kind of low-level wind speed enhancement can only be mesoscale, and is not suitable for synoptic-scale jets. However, they also pointed out a shortcoming of this theory in so far as that it is hard to explain how the momentum concentrates at certain levels. At the time of writing, we could find no research results that provide a reasonable explanation for this possible mechanism of mesoscale LLJ formation.

In fact, it is clear that no one factor explains all the phenomena and characteristics of LLJs from the above listed mechanisms. It is the synergistic effect of each element that promotes the formation and development of the LLJ.

4. Relationships between LLJ and rainfall as well as other interdisciplinary fields

4.1 Rainfall

Among all the weather systems, LLJs show the closest relationship with rainfall, which therefore attracts the most attention from meteorological researchers. Due to the influence of the East Asian summer monsoon and the existence of complex topography, China consistently suffers from torrential rainfall events. Statistical results show that the correlation coefficient between LLJ and rainstorm can be up to 80% in China (Tao et al., 1979). In the 1950s, Tao (1965) used the position of the LLJ to make rainfall forecast, and then a large number of studies appeared in the 1980s, focusing on the relationship between LLJ and torrential rainfall events (e.g., Sun and Zhai, 1980; Huang, 1981; Yu, 1986). At present, the LLJ is still a key indicator in rainfall prediction over East China. Because of the sharp vertical shear below the jet core, this region is always accompanied by potential instability. Therefore, the LLJ not only transports heat and moisture during precipitation, but also frequently stimulates the mesoscale fluctuation propagating along the jet core due to its strong instability. This kind of sharp increase of wind speed can trigger mesoscale convective systems and thus lead to torrential rainfall events (Sun and Zhai, 1980).

Many studies have been carried out to investigate the unstable conditions caused by the LLJ. According to the numerical solutions of the linear and inviscid Boussinesq approximation equations, Mastrantonio et al. (1976) derived the LLJ-generated gravity waves. Tao et al. (1979) indicated that the minor-cycle wind pulsation over the jet core may reflect the effects of gravity waves triggered by ageostrophic movements. The adaptation theory of atmospheric motion shows that the geostrophic deviation can excite inertial gravity waves, and the intensity of waves is proportional to the magnitude of geostrophic deviation. Along with the dispersion of unstable energy caused by inertial gravity waves, super-geostrophic wind gradually weakens and the severe rainstorm disappears (Yu, 1986). In addition, Kuo and Seitter (1985) pointed out that the geostrophic LLJ can produce unstable mesoscale disturbances that resemble frontal cloud bands and squall lines. Limaitre and Brovelli (1990) also indicated that the basic flow of the LLJ can generate baroclinic symmetric instability, which may generate a narrow mesoscale unstable line during the tilting motions. Both theoretical analysis and a case study were carried out by Zhang and Zhou (2003) concerning the inertial and symmetric stabilities for the front-left region of a southwesterly LLJ and the back-right region of an upper-level strong northerly flow. Their results showed that the existence of the maximum inertial stability in the front-left region of the LLJ is favorable for the accumulation of moist thermal energy, and conditional symmetric instability or convective instability can be expected for the development of slanted convective instability in this region.

The LLJ is the major water vapor transport channel for rainfall events (Findlater, 1969; Saulo et al., 2007). Roads et al. (1994) found that in most areas of the United States, moisture flux convergence from model outputs exhibits a good correlation with rainfall observations, which is likely due to the moisture transport by the LLJ. Higgins et al. (1997) further examined the summer rainfall and moisture transport over the central United States with observations and high temporal and spatial resolution assimilated datasets. Their results demonstrated that the Great Plains LLJ is extremely important for the moisture budget throughout the summer season. The impact of the LLJ on the overall moisture budget during summer is considerable, with low-level inflow from the Gulf of Mexico increasing on average by more than 45% over nocturnal mean values. Similarly, the peak precipitation episode of the 1993 summer flood over the Great Plains was associated with a sustained period of high incidence of strong LLJs (over 20 m s^{-1}) (Arritt et al., 1997).

4.2 Air pollution

LLJs, especially those occurring below 200 m, significantly affect the vertical wind shear within the layer from the ground surface to the jet core. As a consequence, LLJs control the exchange process of pollutants between the surface and the atmosphere and determine the air quality over the region. Studies on the relationship between the LLJ and air pollution have gradually increased in recent years because of rapid urbanization and increasing attention on environment issues. For example, Banta et al. (1998) indicated that the transmission effect by nocturnal LLJs shows significant influences on sustained pollution events in urban areas. Ryan (2004) pointed out that O_3 concentrations are enhanced when southwest LLJs occur, with an average peak of 82.5 ppbv over the mid-Atlantic states, with 44% of these days exceeding the 8-h Code Orange threshold (85 ppbv) and 22% exceeding the Code Red threshold (105 ppbv). When southwest LLJs are not associated with high O_3, it is typically due to thunderstorm formation or cloud cover in advance of frontal boundaries. Airborne observations of trace gases, particle size distributions, and particle optical properties were made by Taubman et al. (2004) at a constant altitude along a transect from New Hampshire to Maryland on 14 August 2002, the final day of a multi-day haze and ozone (O_3) episode over the mid-Atlantic and northeastern United States. These observations, together with chemical, meteorological, and dynamical analyses, suggested that the influence of the Appalachian lee trough and LLJ during this episode redirected the westerly synoptic flow in a more southerly direction during the day and evening, respectively. As a result, the polluted air masses transported from the industrialized Midwest mixed with the urban plumes of the eastern seaboard, which reinforced the air pollution over this region.

4.3 Wind energy utilization

Because of the strong wind speed and sharp vertical and horizontal wind shear, LLJs have an important role in harnessing wind energy as well as wind turbine protection. Considering the huge potential demand for renewable energy, especially wind energy, in the coming years, a project named the Lamar Low-Level Jet Program (LLLJP) was established in 2003 as a joint effort among the U.S. Department of Energy and other research centers and companies. The purpose of the project is to develop an understanding of the influence of nocturnal LLJs on the inflow turbulence environment and to document any potential operational impacts on current large wind turbines and the Low Wind Speed Turbine (LWST) designs of the future (Kelley et al., 2004). Baidya Roy et al. (2004) explored the possible impacts of a large wind farm in the Great Plains on local meteorology with the regional atmospheric modeling system (RAMS) model. Their results showed that the wind farm significantly decreases the wind speed at the turbine hub-height level. Meanwhile, turbulence generated by rotors creates eddies that can enhance vertical mixing of momentum, heat, and moisture, usually leading to warming and drying of the surface air and reduced surface sensible heat flux. As a result, this process changes the impact of the LLJ on regional climate. This effect is most intense in the early morning hours when the boundary layer is stably stratified and the hub-height level wind speed is the strongest due to the nocturnal LLJ. The frequent nocturnal LLJ events over the Great Plains make this region quite favorable for wind energy collection and utilization (Storm et al., 2008). However, the presence of LLJs can significantly modify vertical shear and nocturnal turbulence in the vicinities of wind turbine hub heights, and therefore the LLJ poses a potential threat to turbine rotors. Hence, our knowledge on LLJs will to some extent determine the precise assessment of wind energy resources, as well as the reliable prediction of power generation and robust designs of wind turbines (Storm et al., 2008).

4.4 Aviation safety and other interdisciplinary fields

LLJs aligned in the direction of an airport runway can cause wind shear during aircraft take-off and landing. Wind shear (a sudden change in the wind direction and/or wind speed) results in a change in the lift of the aircraft. The risk is particularly high for departing aircraft entering the jet at a steep angle in the initial climbing phase. The sudden gain in headwind in an LLJ, immediately followed by an abrupt loss, may be likened to the experience of passing through a microburst, although in this instance there is clearly no convective activity to cause any microburst (Lau and Chan, 2003). The change in vertical buoyancy caused by the vertical wind shear greatly affects the smoothness of the aircraft's flight, and especially impacts upon safety during take-off and landing (Li, 2006). Weather information and warnings on wind shear are thus very important to aircraft operation and safety. Many air crash events have been caused by sudden dramatic wind shear during flight.

Furthermore, Fromm and Servranckx (2003), Tang et al. (2004), and Liechti (2006) have carried out extensive research on the relationships between LLJs and sandstorms, forest fires, and bird migration, and obtained meaningful results. For example, Tang et al. (2004) demonstrated that the position and intensity of the LLJ can be an important prediction index for the intensity and affected area of a sandstorm. The results from Fromm and Servranckx (2003) and Liechti (2006) respectively indicated that LLJs can accelerate the spread of forest fire, and also act as an orientation reference for the seasonal migration of birds, helping to reduce their energy consumption. In addition, the LLJ can change the regional climate in Antarctica through its influence on sea-ice distribution (Schwerdtfeger, 1975), and LLJs also appear to be essential in prescribing the larger-scale circulations near the South Pole when associated with drainage flows

(Parish and Bromwich, 1991). Overall, LLJ-related research provides valuable points of reference that can be applied to improving people's quality of life, environmental protection, and resource development and utilization. Further studies on LLJ events will enrich our understanding of meteorological phenomena and thus help us to more successfully forecast and prevent associated meteorological disasters.

5. Future challenges and prospects for LLJ research

Currently, a majority of LLJ research focuses on the Great Plains of North America, the Andes Mountains in South America, and the Somali region of East Africa. Comparatively inadequate studies have been carried out to explore LLJ characteristics and their mechanisms of evolution in East Asia, especially for LLJs over complex terrain to the east of the Tibetan Plateau.

5.1 Coarse LLJ definition

The definitions for East Asian LLJs, especially the LLJs over mainland China are relatively coarse. Most studies do not consider vertical shear, but only use the maximum wind speed at a single pressure level (usually below 600 hPa) as the LLJ selection criterion. For example, the LLJs in Wang et al. (2003) satisfy the following criteria: the wind speed at a single station should be $\geqslant 12$ m s^{-1} at 700 or 850 or 925 hPa; the wind direction should be $\geqslant 180°$ and $\leqslant 265°$. In a study on the characteristics and formation mechanisms of the Beijing summer boundary layer LLJ, Sun (2005) defined the LLJ as: the wind should be easterly or southerly and the speed should be $\geqslant 12$ m s^{-1} below 1500 m at 2000, 0200 or 0800 LST; meanwhile, the synoptic-scale LLJ was excluded. Similar definitions were widely adopted in early studies of LLJs and rainstorms in China (Yuan, 1981; Yu et al., 1983). The LLJs with such criteria may belong to the low-level jet stream, and research using these coarse definitions may mislead our understanding to a certain extent on LLJ characteristics, the relationship between LLJ and rainfall, as well as other weather and climate phenomena. Therefore, we need clear LLJ selection criteria in future studies so as to correctly understand LLJs in China.

5.2 Lack of observations and inadequate quality control

Sounding stations are sparsely distributed in China, and regular soundings are released only twice daily at 0000 UTC and 1200 UTC, which do not tally with the strongest and weakest times of LLJ occurrence. Hence, we cannot use these sounding data to capture detailed LLJ characteristics. In fact, the amounts of other types of sounding data over China have increased in recent years. However, they are not in standardized data formats, and data post-processing problems and barriers to data sharing make these data less well used. Because the cost of field experiments is relatively high and it is hard to ensure quality control of the observational data they yield, they are seldom launched. Furthermore, China still does not have high spatial and temporal resolution regional reanalysis data for scientific research due to limitations in data observation and data assimilation techniques. The above-mentioned factors greatly limit LLJ research in China, and our knowledge on LLJ-related issues remains inadequate as a result. However, on the positive side, recent increases in regular observations and wind profiler radar data provide good opportunities for LLJ studies. For example, with half-hourly data from a wind profiler radar at the Qingpu site during the warm season of 2008–2009, Du et al. (2012) developed a climatology of the LLJs over Shanghai and exhibited the LLJ types, temporal evolution, and statistical relationship with rainfall events.

5.3 Few thorough explorations of LLJ characteristics and formation mechanisms

Most LLJ studies in China focus on the relationships between LLJ and rainstorms or the East Asian monsoonal system (Tao et al., 1979; Si, 1994; Zhang et al., 2002), and very little attention has been given to LLJ structural and evolutionary mechanisms. Although some early studies were carried out on the status of LLJ distributions, horizontal and vertical structures, as well as diurnal variations, they did not capture enough detailed information due to the too-coarse temporal and spatial resolutions at that time (Li et al., 1981; Sun, 1986). Besides, as mentioned, research on the mechanisms of LLJ evolution and other key factors over China is inadequate. For example, the terrain of East Asia is complex, characterized by obvious three-step topography: (1) the Tibetan Plateau; (2) the Hengduan Mountains, Yunnan-Guizhou Plateau, Loess Plateau, and Inner Mongolian Plateau; and (3) the Southeast Hills, North China Plains, and Northeast Plain. Unfortunately, most studies do not consider this three-step structure and instead focus only on the Tibetan Plateau to test the effect of topography on the LLJ over China (Chen and Qian, 1993; Liu and Jiao, 2000). Obviously, this approach means that it is hard to explain the relative contributions from each terrain type. That said, on the positive side, higher resolution numerical models provide a good platform upon which LLJ research can build. Scientists can adopt numerical experiments to further investigate the individual and collective contributions of each factor influencing LLJs over East Asia.

5.4 Limited studies in interdisciplinary fields

Compared to the large amount of research on the relationship between LLJ and precipitation processes, limited studies have been carried out in other interdisciplinary fields. With the rapid economic and social development in recent decades, the issues of environmental pollution and new energy exploration become especially urgent. The frequent appearance of haze and sandstorms can impose serious harm on people's health and quality of life. Besides, the dependence on foreign energy inhibits China's comprehensive and sustainable development potential in economic terms. The excessive use of fossil fuels accelerates global warming and leads to the frequent occurrence of extreme weather and climate events. Therefore, we need to understand the interactions between LLJs and air pollution, wind energy utilization, as well as other interdisciplinary fields, in order to deal with the problems encountered during the process of economic development. Such studies are of great realistic significance.

6. Summary

In this article, we have summarized and assessed the current knowledge of LLJ-related subjects over the past five decades from both home (China) and abroad. We focused especially on three aspects: LLJ classification, definition, distribution, and structure; LLJ formation and evolution mechanisms; and the relationship between LLJ and rainfall, as well as other interdisciplinary fields. The shortcomings of LLJ studies in China are discussed, and the future prospects for several LLJ research avenues are speculated upon.

LLJ research in China currently has the problems such as coarse LLJ definitions, lack of observations and inadequate quality control of data, too few thorough explorations of LLJ characteristics and formation mechanisms, and limited studies in interdisciplinary fields. Therefore, we need to pay attention to the following aspects in future studies. (1) Making clear regulations regarding LLJ criteria. We should not only consider the horizontal maximum wind speed, but also give strict requirements on vertical and horizontal shears. (2) Strengthening observational data collection and organization, increasing observation in specific layers, and carrying different types of field experiments. Critical quality control of observations should also be carried out, such as on wind profiler data. (3) Based on previous studies, investigating LLJ structure and evolutionary mechanisms, especially by exploring the impact of complex terrain in East Asia on LLJ development. (4) Performing work in interdisciplinary fields so as to understand related issues, and provide a basis for weather forecasting and disaster prevention and mitigation. As observations increase, study methods develop, and more scientists invest their time in LLJ research, we will undoubtedly gain a deeper understanding of LLJs in the future. Such knowledge can then be applied to providing better guidance in social and economic contexts, as well as reducing the amount of serious losses caused by related disastrous events.

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