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Low-level jets and their implications on air pollution: A review

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Low-level jets (LLJ) are a common phenomenon in the atmospheric boundary layer and have been reported worldwide. Additionally, they have considerable relevance in a series of fields. This review aimed to document their implications on air quality, specifically particulate matter, mineral dust, and ozone in recent literature focus on i) generalizing long-range advection of pollutants by the low-level jets; ii) analysing vertical transport due to low-level jets-enhanced turbulence mixing and the corresponding mechanisms for different pollutants; and iii) introducing the performance of state-of-the-art numerical models. Finally, we suggest that high-resolution spatiotemporal observations of the pollutants and turbulence must be conducted, and current parameterization schemes should be improved to better represent the low-level jets and nocturnal boundary layer structures for reproducing the complicated interactions between the low-level jets and pollutants.

KEYWORDS

low-level jets, regional transport, vertical dispersion, intermittent turbulence, PM2.5, ozone

1 Introduction

Low-level jets (LLJs) are a common phenomenon in the atmospheric boundary layer (ABL) and have been widely observed worldwide, including in North America (Smith et al., 2019), South America (Sánchez et al., 2022), East Asia (Wei et al., 2014; Miao et al., 2018), Europe (Tuononen et al., 2017), and Africa (King et al., 2021). However, there is no universal consensus on the definition of the LLJs (Fiedler et al., 2013). To summarize the definitions in previous literatures, the term LLJ used here refers to a stream of fast-moving flow with maximum wind speed and vertical wind shear in the lower part of the troposphere (Stull, 1988).

The occurrence and variation of the LLJs are modulated by a combination of mechanisms on different temporal and spatial scales. Blackadar's (1957) pioneering work proposed that inertial oscillations of ageostrophic components contribute to the diurnal cycle of the LLJs. The "Blocking Theory" (Wexler, 1961) attributed the speeding-up of flows to the blockage of terrains, such as the Rocky Mountains, an analogy to the

Gulf Stream in oceanography. The thermal—wind relationship leads to coastal jets because of the differential heating and cooling between the land and oceans (Lima et al., 2019). Sloping terrains and the associated horizontal temperature gradients are other ways for providing baroclinicity that the LLJs need to develop (Gebauer and Shapiro, 2019).

The LLJs are primarily a process in the ABL and are highly relevant in many fields, such as wind energy (Wimhurst and Greene, 2019), precipitation (Du et al., 2012), fog (Wu et al., 2020), urban heat islands (Hu et al., 2013a), wildfires (Čavlina Tomašević et al., 2022), aviation safety (Gultepe et al., 2019), and migration pathways of birds (Wainwright et al., 2016). This review aimed to examine how the LLJs impact pollutant transport locally and inter-regionally, considering mineral dust, fine particulate matter ($PM_{2.5}$), and ozone (O_3). Specifically, this paper focuses on the following:

Present the current state of knowledge of the LLJ—pollutant interaction mechanism.

Document the state-of-the-art methods to analyse the LLJs, including numerical models and signal analysis techniques.

Outline the remaining gaps between the current progress and future research.

2 Regional transport

The belt of high wind speed, one of the dominant features of the LLJs, is a crucial process in the long-range transport of the pollutants. The contribution of LLJ advection to a certain region depends on the season, wind direction, and location of pollutant sources. In the Sahara Desert, dust is primarily advected below 800 hPa to South America in winter and spring and to the Caribbean at 500 hPa in summer and autumn (Gläser et al., 2015). In the southwestern China, up to 80% of the summertime O_3 accumulation is because of horizontal transport (Yang et al., 2020). The LLJs are crucial to the redistribution of O_3 between source locations and downwind regions (Bao et al., 2008; Klein et al., 2019). Li et al. (2019) revealed that southerly LLJs could transport large amounts of $PM_{2.5}$ from upstream regions, leading to accumulation of the pollutants in the downstream zones. In contrast, the occurrence of the LLJs positively contributes to the dilution of pollutants in Beijing (Miao et al., 2019). In Tianjin, China, southwesterly LLJs transport polluted air masses from the southern industrial regions, deteriorating local air quality, whereas the northerly or southeasterly LLJs are helpful in improving visibility (Wu et al., 2020). In general, the existence of the LLJs favors the dilution of pollutants, whereas downwind regions suffer from pollutant advection by the LLJs.

In addition, the transport of precursors and moisture by the LLJs facilitates the formation of pollution periods. In the North China Plain, southwesterly LLJs establish a moisture channel from the South China Sea to the Bohai Rim Region, contributing to the frequent $PM_{2.5}$ events in winter (Ju et al., 2020).

3 Vertical transport of mineral dust

Although the long-range transport of chemical species by the LLJs between different regions has been studied previously, the vertical flux associated with them has not been intensely investigated (Figure 1). Recent studies have revealed that vertical dispersion induced by the LLJs may play a crucial role in the local air quality.

The downward momentum flux caused by the LLJs is recognized as one of the key mechanisms of dust emissions in the Sahara Desert, in addition to monsoon surges (Cuesta et al., 2010), cold pool outflows (Allen et al., 2013), and dry convective plumes (Ansmann et al., 2009). The LLJs develop in the ABL after sunset because of the inertial oscillations (Blackadar, 1957). The wind shear near the jet core creates turbulence in the upper layer and it is transported downward, generating peak winds near the surface. There is a time lag of several hours between the maximal wind speed of the LLJs and that at the surface layer, with the former occurring before sunrise and the latter occurring mid-morning. Dust is emitted once the surface wind exceeds the local dust emission threshold (Allen and Washington, 2014). Observations and model simulations (Todd et al., 2008) have confirmed that LLJ-induced downward momentum initiates mid-morning dust events. Approximately 60% of the total dust can be attributed to the peak wind caused by nocturnal LLJs (Fiedler et al., 2013). The LLJs are a common phenomenon in the Sahara Region and an average of 29% at night was observed (Fiedler et al., 2013). Frequently occurring LLJs are key drivers of the local dust emissions. According to satellite observations from 2006 to 2008 (Schepanski et al., 2009), the surface peak wind associated with the nocturnal LLJs accounted for 65% of dust source activations during the mid-morning across North Africa, which is larger than the values at midday. Once uplifted, the dust is horizontally transported by the LLJs to America, Europe, and beyond.

4 Vertical transport of $PM_{2.5}$

Due to the consumption of fossil fuels and the stable atmosphere, $PM_{2.5}$ pollution tends to occur frequently during winter, especially in densely populated metropolises. One feature of $PM_{2.5}$ pollutions in winter is persistent and it threatens public health (Dominici et al., 2014). Persistent heavy pollution events are divided into two stages (Zhong et al., 2017; Wei et al., 2018; Zhong et al., 2018; Ren et al., 2019a): the cumulative stage during which particles accumulate is due to the high emissions, adverse synoptic weather conditions, regional transport, and secondary pollutant production and the dissipation stage is characterized by an abrupt decline in $PM_{2.5}$ levels. Numerous studies (Wei et al., 2018; Ren et al., 2019a; Ren et al., 2019c; Li et al., 2020; Wei et al., 2020; Li et al., 2021) have revealed that the LLJs play a key role in the dissipation stage of $PM_{2.5}$.

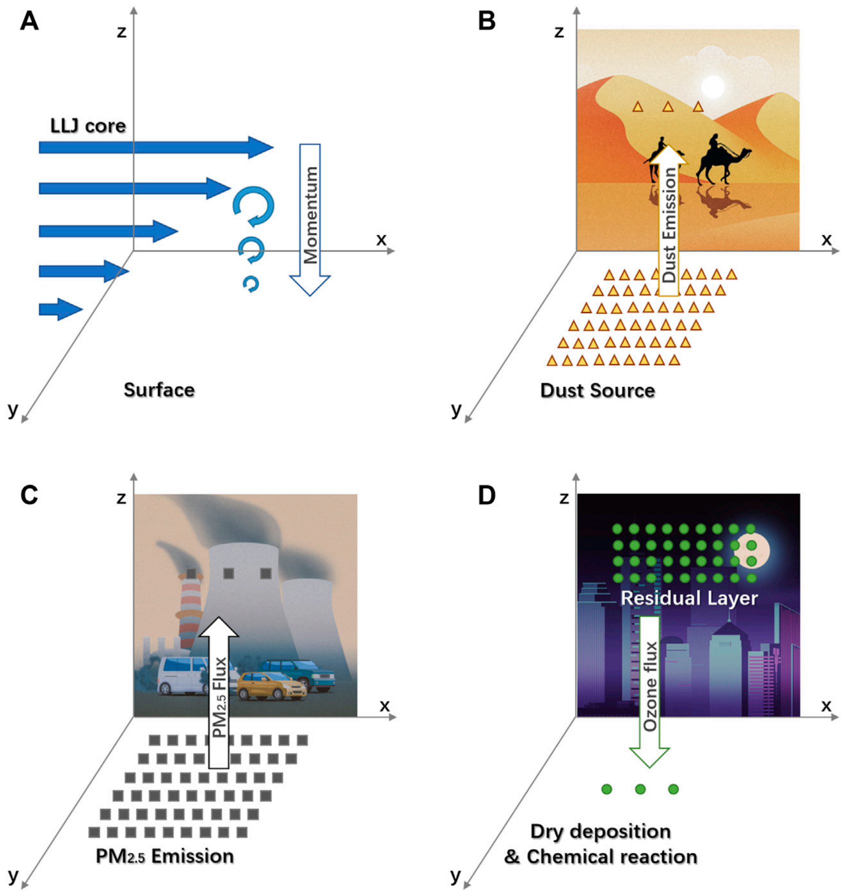

FIGURE 1
Schematic of vertical interaction between LLJs and pollutants with transport of **(A)** momentum, **(B)** dust, **(C)** fine particulate matter, and **(D)** ozone.

Inversion layer frequently develops in winter and traps $PM_{2.5}$ emitted from the ground within a shallow layer. According to the "barrier effect" theory (Ren et al., 2021), turbulence disappears at some heights and laminar flow develops during heavily polluted periods, which serves as a barrier layer impeding vertical turbulence transport. In the presence of the LLJs, turbulence bursts produced by aloft wind shear enhance vertical mixing, break the decoupled ABL structure, and rebuild the heat/momentum/material exchange between different heights. Field observations (Li et al., 2020) confirmed that the LLJs frequently occurred during the transition between the two stages. Miao et al. (2018) investigated the climatology of the LLJs in the Beijing Region and discovered that they frequently occurred in spring and winter and were mostly concentrated during nighttime. The consistency between the LLJs and severe $PM_{2.5}$ events implies that they play a crucial role in $PM_{2.5}$ pollution, which has been confirmed in a wide range of areas in China.

The LLJs can affect the diffusion of $PM_{2.5}$ indirectly *via* propagating internal gravity waves (IGWs), in addition to their direct impact on pollutant transport. The IGWs are a type of wavelike motion in the stable boundary layer (SBL) triggered by the LLJs (Jia et al., 2019). One puzzling phenomenon of heavy pollution is that $PM_{2.5}$ concentrations at different levels experience non-simultaneous drops or inverse variations (Ren et al., 2020). In the presence of the LLJs, the IGWs are generated and propagated downward, intermittently triggering turbulence layer by layer (Wei et al., 2022). The vertical spreading of the IGWs is responsible for short-term $PM_{2.5}$ removals during the cumulative stage and asynchronous variation at different heights.

5 Vertical transport of tropospheric O_3

As a volatile secondary photochemical pollutant, O_3 concentration at the surface undergoes a marked diurnal variation: i) High emission of precursors and photodissociation leads to high O_3 concentration during the daytime. ii) After sunset, the photochemical production shuts down and O_3 is removed *via* dry deposition and chemical reactions within the surface layer. Meanwhile the aloft residual layer traps O_3. iii) The following morning, strong turbulence develops and fully mixes the aloft O_3. In this scenario, nocturnal O_3 concentration at the surface should be near zero owing to the absence of production, removal processes, and a decoupled SBL. However, nighttime O_3 spikes have been frequently reported in different regions since the 1970s (Samson, 1978; Reitebuch et al., 2000).

At night, the surface layer decouples with the aloft residual layer, thus making the residual layer a "reservoir" of daytime pollutants. In the presence of the LLJs, the strong wind shear near the jet core generates turbulence bursts, enhancing the vertical mixing between the two layers. Thus, the O_3 restored in the residual layer leaks into the surface layer. Studies (Reitebuch et al., 2000; Hu et al., 2012; Hu et al., 2013b) have verified that the concentration of O_3 in the residual layer, accompanied by O_3 spikes near the surface, is highly variable, implying active vertical exchanges. This aloft turbulence source associated with the LLJs depicts a reversed vertical structure from the traditional SBL, where most of the turbulence is produced by surface friction and transported upward. The turbulence induced by the LLJs is highly sporadic and is marked by intermittent bursts which remains an intriguing problem. Apart from the LLJs, other mechanisms causing intermittent turbulence include Kelvin–Helmholtz instabilities, gravity waves, wake vortices, and density currents (Wei et al., 2017). Considering that favorable synoptical patterns for the LLJs are also beneficial to heavy O_3 periods in some regions (Ryan, 2004), the importance of the LLJs in O_3 pollution cannot be ignored.

The maxima O_3 concentrations at nighttime may not be comparable to those in the afternoon. However, relevant research still has implications: i) The LLJs are important contributors to the horizontal transport. Considering that the vertical O_3 flux leads to a leaky residual-layer reservoir, the impact of pollutants carried by the LLJs downwind may be relieved. ii) O_3 dispersed to the surface is permanently removed *via* dry deposition at night. As photochemical production does not occur, the net effect is that the total amount of O_3 is reduced, further easing the next-morning O_3 levels. iii) In persistent O_3 periods, the amount of O_3 removed by nighttime vertical mixing is crucial for the total O_3 budget over several days (Banta et al., 2007). iv) Nighttime spikes have been reported in different chemical species, including hydrogen peroxide (Das and Aneja, 1994), isoprene (Starn et al., 1998), volatile organic compounds (VOCs) (Ganzeveld et al., 2008), carbon dioxide (CO_2) (Hicks et al., 2015), and $PM_{2.5}$ (Wei et al., 2018). Therefore, the studies on the LLJ–O_3 mechanism also have implications for other pollutants.

6 Models and analyses methods

Model simulation has become a useful tool for investigating the LLJs and their interactions with air pollutions. Based on the inertial oscillation theory, numerical models can reproduce the diurnal variation in the LLJs (van de Wiel et al., 2010). However, the underestimation of the maximal wind speed and deviations of profiles by the numerical models have been widely reported (Smith et al., 2018; Haikin and Castelli, 2022). The simulation bias of the maximal wind strength and profiles could further affect the wind shear and turbulence mixing. The simulation of the nocturnal LLJ is highly sensitive to the vertical resolution, planetary boundary layer (PBL) schemes and surface-layer parameterizations. Refining vertical spacing is helpful to improve the LLJs while the computational cost and model stability should be considered.

The simulation bias in the diurnal variation of $PM_{2.5}$ levels is largely due to turbulence mixing during nighttime. Considering that the LLJs and serious $PM_{2.5}$ pollution tend to occur in stabilized atmosphere, local closure PBL schemes are suitable for the simulation of the LLJs and $PM_{2.5}$ events (Jia and Zhang, 2020). Some literatures (Udina et al., 2020; Yang et al., 2021) have confirmed that the Mellor—Yamada—Janjic scheme (Janjic, 2002) shows better performance compared with other schemes, while it still cannot reproduce the different stages of haze events. The turbulence mixing coefficient is one of the key parameters to control the PBL mixing. Du et al. (2020) revealed that increasing the threshold of turbulence mixing coefficient was helpful to the simulation of diurnal variation of $PM_{2.5}$. Jia et al. (2021) developed a turbulence diffusion term for aerosols and embedded it into a mesoscale model for the first time.

The high wind speed of the LLJs is crucial to achieving long-range transport of dust. The underestimation of the jet core speed implies a weakened region-to-region transport simulation. In addition, parameterization of the mineral dust budget depends on the simulation of the downward momentum flux (Pérez et al., 2011; Knippertz and Todd, 2012). However, a weakened LLJ strength can lead to an underestimation of the dust emissions, as the surface wind speed is not strong enough to reach the dust emission threshold. Besides, the overestimation of LLJ strength and vertical mixing at night alters the diurnal variation of the wind field in the ABL (Sandu et al., 2013).

The tropospheric O_3 concentration during the daytime can be simulated in accordance with the field observations, although distinct differences exist at night. The primary reason for this is the representation of the nighttime turbulence transport by the LLJs. Although the horizontal structure of the LLJs can be reasonably simulated, the results of the simulated LLJ vertical profiles are far from satisfactory. Sensitivity simulations (Hu et al., 2012) elucidated that longer turbulence lengths and long-tail stability functions are more suitable for O_3 and LLJs modelling, implying that turbulence mixing during nighttime requires careful treatment.

TABLE 1 Summary of main studies (mostly after 2012) on the LLJs and chemical species transport in different regions.

Research focus	Regions and references
Dust	Africa: Knippertz and Todd, (2012); Fiedler et al. (2013); Allen and Washington, (2014); Gläser et al. (2015); Schepanski et al. (2015); Kalenderski and Stenchikov, (2016); Wiggs et al. (2022)
	East Asia: Ge et al. (2016); Zhou et al. (2019); Han et al. (2022)
	West Asia: Gandham et al. (2022) the dust belt: Shi et al. (2021); Tindan et al. (2022)
$PM_{2.5}$	Asia: Chen et al. (2018); Wei et al. (2018); Wei et al. (2020); Ren et al. (2019a); Ren et al. (2019b); Ren et al. (2019c); Li et al. (2019); Miao et al. (2019); Jin et al. (2020); Li et al. (2020); Li et al. (2021); Wei et al. (2022); Mei et al. (2022)
	South America: Martin et al. (2018); Rodriguez-Gomezetal et al. (2022)
	North America: Dreessen et al. (2016); Wang et al. (2018)
O_3	Europe: Kulkarni et al. (2016); Klein et al. (2019)
	North America: Hu et al. (2012); Hu et al. (2013b); Ryan, (2004); Caputi et al. (2019)
	South America: Martins et al. (2018); Melo et al. (2019)
	Asia: Zhu et al. (2020); Zhao et al. (2022)
CO_2	Africa: Han et al. (2015)
Black Carbon	South America: Martins et al. (2018)
Sulphur and NO	Europe: Arkadievi Obolkin et al. (2014)

Turbulence intermittency has still not been effectively considered in the numerical models, although field observations have confirmed its importance in the transport of O_3 (Salmond and McKendry, 2002; Salmond and McKendry, 2005), $PM_{2.5}$ (Wei et al., 2018; Ren et al., 2019b), and CO_2 (ElMadany et al., 2014; Hicks et al., 2015). The classical Monin—Obukhov similarity theory (MOST, Monin and Obukhov, 1954), which has been widely adopted in atmospheric and environmental models, is only suitable for unstable ABL or traditional surface-forced SBL. Large uncertainties may exist when applying the MOST-based models to intermittent turbulence. Furthermore, no overarching agreement has yet been reached an appropriate method to describe the turbulence intermittency in the ABL. The traditional Fourier transform cannot be applied to the analysis of non-linear and non-stationary turbulence bursts. The wavelet analysis was used to separate the LLJ-induced intermittent turbulence during O_3 periods (Salmond, 2004). Based on the self-adaptive Hilbert—Huang transform (Huang et al., 1998), several indexes have been proposed to quantify the strength of the turbulence intermittency (Wei et al., 2018; Ren et al., 2019b; Ren et al., 2019c).

7 Summary and discussion

This review summarized the current state of interactions between the LLJs and pollutants from the perspective of observations, models, and mechanisms. With the literature of the three most-studied species (i.e., mineral dust, $PM_{2.5}$, and O_3), the effects of the LLJs can be divided into long-range horizontal transport and local vertical dispersion. Recent works have been listed in Table 1. The fast-moving stream of the LLJs is an important pathway for the region-to-region transport of moisture, precursors, and pollutants. Whether the LLJ is a boon or bane for the local air quality depends on the season, wind direction, and location of the pollutant sources. Recently, vertical mixing induced by the LLJs has been under the spotlight for explaining the local variation of pollutant levels. The downward transport of intermittent turbulence resulting from the LLJs is crucial for re-coupling nocturnal SBLs, enhancing vertical mixing, transporting pollutants downward/upward, and worsening/improving the air quality. What the three species have in common is that the downward momentum due to LLJs strengthens the turbulence mixing and pollutants transport. Specifically, O_3 dissipates downward from the aloft "reservoir", leading to O_3 peaks at night. The mineral dust was uplifted from the underground the next morning. The $PM_{2.5}$ is mostly transported upward and diluted over a deeper layer. The intermittency of LLJ-induced turbulence perplexes the mechanism of the vertical dissipation of pollutants.

In the future, high-resolution turbulence and pollutant observational data is needed to investigate the complicated vertical LLJ—pollutant interaction and establish the turbulence diffusion relationship of pollutants. Most current work is based on surface observations of pollutants and turbulence. However, to study the fine structure of the SBL, continuous profiles are required. A meteorological tower can provide multilevel observations, however, its spatial resolution is far from satisfactory. Radiosonde data suffers from a low time resolution. Carrying out intensive observation period experiments can be a good way for addressing these problems. Remote sensing technologies, such as Lidar are helpful methods to obtain continuous observation. Furthermore, the current findings were mostly obtained from one site. There is a large scope for further research on the spatial distribution of intermittent turbulence and pollutants based on multi-site observation.

The numerical models perform well in the simulation of the horizontal structure of the LLJs, while the vertical distribution remains unsatisfactory. PBL schemes need to be further improved for better representing nighttime processes. Accurate simulation of the LLJ profiles and development is crucial for nocturnal turbulence mixing. In addition, present models do not consider the turbulence intermittency, and most studies on the LLJ-burst interplay focus on O_3 and $PM_{2.5}$. How this mechanism impacts the variation of other chemical species, such as nitrogen oxides (NO), VOCs, and carbon monoxide, remains to be assessed.

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All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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