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Key Points:

- A strong vertical exchange between the boundary layer and free troposphere (FT) up to 3 km was observed over Shanghai
- Observation-constrained diagnostics show large air-mass exchange fluxes (-0.97 – $1.46 \text{ kg m}^{-2} \text{ s}^{-1}$), indicating strong ABL-FT coupling
- Downward transport from an aloft particle reservoir likely contributed to the near-surface enhancement of nucleation-mode particles

Supporting Information:

Supporting Information may be found in the online version of this article.

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Surface Nucleation-Mode Particles Increase During Intense Vertical Exchange Between the Atmospheric Boundary Layer and the Free Troposphere

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Abstract Vertical exchange between the atmospheric boundary layer (ABL) and the free troposphere (FT) is a key pathway for aerosol transport and can substantially influence surface air quality. In this study, an intense ABL-FT exchange event over Shanghai on 29 March 2024 was captured and analyzed using ground-based Doppler wind LiDAR, microwave radiometer, particle-size spectrometer measurements, and numerical diagnostics. Southwesterly warm-moist advection and daytime surface heating promoted the growth of a warm and moist boundary layer, while drier and more stably stratified air persisted above the ABL top. Under this thermodynamic background, the boundary-layer jet and associated dynamical disturbances favored vigorous ABL-FT exchange. During this period, vigorous vertical motions developed, with vertical velocities ranging from -1.5 to 2.0 m s^{-1} and extending to nearly 3 km. The estimated ABL-FT air-mass exchange flux ranged from -0.97 to $1.46 \text{ kg m}^{-2} \text{ s}^{-1}$, with vertical motion accounting for 58.5% of the total exchange. During the exchange event, ultrafine-particle concentrations increased markedly at the surface, while particles smaller than 10 nm did not show a corresponding increase. These observations are more consistent with downward transport of particles likely present aloft, followed by growth within the boundary layer, than with a purely local surface-formation mechanism. This study highlights a possible linkage among dust intrusion, particle processes aloft, and ABL-FT mixing in shaping near-surface aerosol number concentrations, and advances understanding of vertical aerosol transport in megacity environments.

Plain Language Summary How particles higher above the ground affect the air we breathe near the surface is still not fully understood. In this study, we observed a strong exchange of air between the atmospheric boundary layer and the free troposphere over Shanghai using Doppler wind LiDAR, a microwave radiometer, ground-based particle measurements, and numerical diagnostics. This event occurred when warm and moist air in the lower atmosphere lay beneath drier, more stable air aloft. A boundary-layer jet disturbed this transition zone, producing alternating upward and downward motions that enhanced exchange between the two layers. At the same time, the smallest particles did not show the clear increase typically expected from a purely local particle-formation event. Our results suggest that, even during dust intrusion, strong vertical exchange can influence near-surface ultrafine-particle concentrations. These findings improve our understanding of how high-altitude particle transport affects air quality near the ground.

1. Introduction

The troposphere can be partitioned into the atmospheric boundary layer (ABL) and the FT according to turbulence characteristics. The ABL is dominated by turbulent processes and is the primary region for exchanges of heat, water vapor, and aerosols between the surface and the atmosphere, whereas the FT is comparatively less affected by turbulence (Kakkanattu et al., 2023). Despite substantial improvements in air quality in China under continued emission-control efforts, vertical mixing remains a key process governing pollutant distributions, especially under conditions of high pollutant loading and unfavorable local meteorology (L. Chen et al., 2020). Long-range transported aerosols are an important driver of both regional (Hou et al., 2019) and local (K. Li et al., 2018; Tong et al., 2018) air quality deterioration. Vertical mixing can transport aerosols downward to near-surface levels in receptor regions (Sun et al., 2024) and can also redistribute pollutants to downwind areas through residual-layer transport, thereby influencing the spatiotemporal distribution of surface $\text{PM}_{2.5}$ (Kim et al., 2021; Lee et al., 2019). In addition, aerosol vertical distribution provides important a priori information for constraining

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transport pathways and climate-model simulations, which is critical for source attribution, understanding transport mechanisms, and evaluating climate feedbacks (Liu et al., 2017; Thomas et al., 2019). Nonetheless, observational studies of aerosol vertical structure and mixing state during long-range transport remain limited (Sun et al., 2024).

Vertical mixing is considered important for regulating the distribution and evolution of ultrafine aerosol particles, particularly newly formed particles (Kesti et al., 2022; Lai, Hai, et al., 2022). New particle formation (NPF) is a major source of ultrafine particles and is characterized by rapid increases in particle number concentrations at diameters below 100 nm. Particles that grow beyond 50 nm can act as cloud condensation nuclei, thereby affecting cloud and precipitation processes and, ultimately, climate (Dusek et al., 2006). The FT is an important source region for nucleation- and Aitken-mode particles (Bianchi et al., 2016; Venzac et al., 2008), and recent aircraft observations indicate that stratosphere–troposphere mixing provides an additional pathway for particle formation aloft beyond convective-cloud outflows (Zhang et al., 2024). Whether these particles influence near-surface particle populations depends on their subsequent downward transport and mixing into the ABL. Vertically resolved airborne and modeling studies further show that NPF and early particle growth can occur at different altitudes within the lower troposphere, including the upper mixed layer, residual layer, and residual-layer/free-troposphere interface (Lampilahti et al., 2020; Lampilahti, Leino et al., 2021; Lampilahti, Manninen et al., 2021; O'Donnell et al., 2023). In particular, particles formed aloft may later be entrained into the growing mixed layer and detected at the surface after partial growth. Wang (2023) reported that strong downdrafts associated with deep convective systems can transport nucleation-mode particles from the FT into the ABL. During this process, high-altitude particles are transported downward and can substantially enhance near-surface ultrafine particle concentrations (Lai, Hai, et al., 2022; Wu et al., 2024). However, in addition to episodic downdraft-driven transport, continuous material exchange also occurs across the ABL–FT interface. Previous studies have paid relatively limited attention to this process, particularly to potential role in surface particle enhancement, and the underlying mechanisms remain insufficiently understood.

The air-mass exchange flux across the ABL top is a useful metric for quantifying the intensity of vertical exchange, as it represents the rate of air-mass transfer per unit area across the top of the ABL (Serafin et al., 2018). This parameter influences pollutant transport pathways and residence times in the FT, because upward and downward fluxes determine where transported pollutants leave or enter the boundary layer during atmospheric transport. Jin et al. (2021), Jin et al. (2024) combined the WRF simulations with observations to evaluate wintertime ABL–FT exchange over the North China Plain and showed that this region can be an important source of long-range transported pollutants. In the Pearl River Delta, Qu et al. (2023) showed that vertical exchange at the ABL top was a primary process driving morning O₃ change. Nevertheless, quantitative studies of air-mass exchange fluxes across the ABL top in China remain limited (Qu et al., 2023), particularly observation-constrained analyses in core cities of the Yangtze River Delta.

In recent years, high-resolution ground-based remote sensing has attracted increasing attention for investigating vertical exchange processes. Compared with satellite remote sensing, which has lower sensitivity in the lower troposphere (Wang, Qiang, et al., 2021; Wang, Ma, et al., 2021; Zang et al., 2019), LiDAR provides higher spatiotemporal resolution and enables continuous monitoring of atmospheric vertical structure (Huang et al., 2024; Li, Sun, & Jiang, 2023; Li, Xia, et al., 2023; Sun et al., 2018; Wang et al., 2020; Wang, Wang, et al., 2023; Wang, Ma et al., 2023; Wang et al., 2024). In particular, Doppler wind LiDAR systems, including configurations from ultraviolet to near-infrared wavelengths, can provide high-resolution wind profiling for atmospheric dynamics studies (Shangguan et al., 2022). Because such systems can simultaneously provide wind and aerosol-related information, they have been widely used to investigate boundary-layer dynamics and the vertical mixing of air pollutants (Su, Lu, et al., 2024; Su, Xia, et al., 2024). Yang et al. (2019) used high-temporal-resolution Doppler LiDAR to analyze the vertical distribution of heavy particulate pollution in Hong Kong and its relationship with vertical wind profiles. Using a LiDAR network, Huang et al. (2021) investigated a trans-boundary air-pollution episode in Hong Kong and showed that nocturnal downward transport of aerosols depends on small-scale vortices under weak-wind conditions, whereas daytime transport was dominated by the upward movement of near-surface aerosols. Collectively, these high-resolution LiDAR observations provide a strong basis for investigating ABL–FT vertical exchange processes.

Shanghai, located at the estuary of the Yangtze River, has flat terrain and a coastal setting and serves as a core city in the Yangtze River Delta urban agglomeration. Influenced by monsoon circulation, sea-land breezes, and

regional pollutant transport, both atmospheric circulation and pollution sources in this region exhibit pronounced spatiotemporal variability. The Yangtze River Delta is also among the most active regions in the world for NPF events (Chu et al., 2019; Herrmann et al., 2014; Kulmala et al., 2017), providing favorable conditions for secondary aerosol formation. In particular, NPF frequency increases significantly in spring (Qi et al., 2015). Shanghai is therefore an ideal study site because it represents a typical urban atmosphere influenced by multiple overlapping pollution sources and offers favorable observational conditions for examining the effects of regional transport and vertical exchange on NPF.

In this study, we investigate a vigorous vertical exchange between the ABL and the FT observed over Shanghai and the thermal and dynamical mechanisms driving this process. Combined with WRF-based diagnostics of air-mass exchange fluxes across the ABL-FT interface, we quantitatively assess the intensity of the event and examine its possible influence on near-surface ultrafine-particle enhancement. As a process-oriented case study, this work focuses on the mechanisms of a well-observed event rather than on the climatological frequency of such events. These findings contribute to a better understanding of aerosol vertical transport and exchange processes in a megacity environment.

2. Observations and Methods

2.1. Field Observation

From December 2023 to April 2024, comprehensive field measurements were conducted on the campus of Fudan University (121.51°E, 31.34°N) in Shanghai, using an integrated suite of instruments, including a coherent Doppler wind LiDAR (CDWL), a microwave radiometer, and two scanning mobility particle sizers (SMPSs), to characterize the ABL structure, wind-field dynamics, and aerosol number size distributions.

The CDWL operated at a wavelength of 1.5 μm and performed Velocity Azimuth Display scans at an elevation angle of 60° with a temporal resolution of 3 min, providing vertical profiles of aerosol attenuated backscatter, wind fields, and turbulence intensity. The performance and retrieval accuracy of this CDWL system have been evaluated in previous validation studies. In particular, the LiDAR wind retrievals have been compared with GTS1 radiosonde observations during a field experiment at the National Meteorological Observing Station of Anqing (T. Wei et al., 2019), and the LiDAR measurements have also been evaluated against collocated ultrasonic anemometers (Xia et al., 2024). Further technical details of the CDWL system are available in previous studies (T. Wei et al., 2020; Xia et al., 2024). The microwave radiometer (Radiometer Physics, Germany) was equipped with multi-channel sensors capable of retrieving key atmospheric parameters, including temperature and humidity profiles, brightness temperature, and liquid water path, with a maximum retrieval height of 10 km (Han et al., 2024). Aerosol number size distributions were measured using two SMPSs, including a TSI Nano-SMPS system (DMA 3086 + CPC 3756; TSI Incorporated, Shoreview, MN, USA) covering 2.1–63.8 nm and a conventional TSI SMPS 3934 system covering 14.1–736.5 nm. The combined measurements provided high-resolution aerosol number concentration distributions over the 2.1–736.5 nm size range (Wang, Wang, et al., 2023; Wang, Shi, et al., 2023). Standard instrument maintenance and routine data screening were applied, and abnormal scans were excluded prior to analysis. Quality control of the SMPS data included the removal of abnormal scans, as well as multiple-charge and diffusion-loss corrections during data processing. In addition, the CPC and DMA flow rates were routinely checked to remain within the prescribed ranges, and the particle sizing accuracy and flow rate were regularly calibrated using polystyrene latex (PSL) particles (Singh & Kuang, 2024). All data and results are presented in Beijing Time (BJT). Surface PM concentration data were obtained from the National Urban Air Quality Real-Time Release Platform (<https://air.cnemc.cn:18007>) for the period from 29–30 March 2024, with an hourly temporal resolution. Data from two nearby national air quality monitoring stations, Hongkou station (121.47°E, 31.30°N) and Yangpu-Sipiao station (121.54°E, 31.27°N), were used to supplement the characterization of surface PM variability in the study area. In addition, routine radiosonde observations from the Baoshan station (58362; 121.45°E, 31.42°N), located in the Shanghai metropolitan area, were used as Supporting Information S1 to characterize the thermodynamic and wind structure of the lower troposphere during the event.

Based on these observations, this study analyzed a 48-hr atmospheric evolution from 29–30 March 2024, with a particular focus on an intense vertical-exchange event observed on 29 March 2024.

2.2. Reanalysis and Satellite Data

ERA5 reanalysis data and Himawari-9 satellite observations were used to characterize the large-scale meteorological background and cloud conditions during the event. ERA5, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), is a global meteorological reanalysis product with a spatial resolution of $0.25^\circ \times 0.25^\circ$ and an hourly temporal resolution, covering multiple atmospheric layers from the surface to the upper troposphere (Hersbach et al., 2023; <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels>).

Himawari-9, a geostationary meteorological satellite operated by the Japan Meteorological Agency, provides full-disk observations over 60°S – 60°N and 80°E – 20°W with a temporal resolution of 10 min. The observations used here include visible, near-infrared, and thermal-infrared information, with a spatial resolution of approximately 2 km for the relevant bands.

2.3. WRF Simulation and Diagnosis of ABL-FT Air-Mass Exchange Flux

The WRF model, version 4.7 (Weather Research and Forecasting model), was employed to provide three-dimensional meteorological fields for diagnosing the air-mass exchange flux across the ABL-FT interface. The simulation period covered the analysis period of the target event. Two nested domains were configured with horizontal resolutions of 3 and 1 km, respectively. The domain centers were located over Shanghai (31.38°N , 121.38°E), and a Lambert conformal conic projection was used (Figure S1 in Supporting Information S1). A total of 38 vertical levels were set, with 25 levels located within the lowest 3 km to better resolve the ABL structure and its transition to the FT.

This study employed the widely used Yonsei University (YSU) planetary boundary layer scheme. The YSU scheme is a nonlocal closure approach that explicitly accounts for counter-gradient transport and entrainment processes (Hong et al., 2006), thereby allowing a more realistic representation of the ABL structure and evolution. The ABL height was diagnosed using the bulk Richardson number method. The Lin microphysics scheme (Lin et al., 1983), the Rapid Radiative Transfer Model for longwave radiation (Mlawer et al., 1997), the Dudhia shortwave radiation scheme (Dudhia, 1989), and the unified Noah land surface model (F. Chen & Dudhia, 2001; Tewari et al., 2004) were selected. Given the convection-permitting resolution used in this study, cumulus parameterization was disabled (Tao et al., 2020). Initial and boundary conditions were provided by the ERA5 reanalysis data set from ECMWF with a resolution of $0.25^\circ \times 0.25^\circ$.

The ABL-FT air-mass exchange flux was calculated following Jin et al. (2024):

$$F = \rho_h \frac{\partial h}{\partial t} + \rho_h \left(u_h \frac{\partial h}{\partial x} + v_h \frac{\partial h}{\partial y} \right) - \rho_h w_h \quad (1)$$

where F denotes the air-mass exchange flux across the ABL top; positive values indicate flux into the ABL, whereas negative values indicate flux out of the ABL. Here, h is the ABL height, u_h , v_h , and w_h are the wind components, and ρ_h is the air density. The subscript h denotes quantities evaluated at the top of the ABL. The three terms on the right-hand side of Equation 1 represent the local temporal variation of the ABL height, denoted as $F_{h(t)}$; horizontal advection across the sloping ABL top, denoted as F_{hadv} ; and vertical motion across the ABL-FT interface, denoted as F_{vmot} . It should be noted that the estimated flux is an air-mass exchange flux rather than a direct aerosol mass or number flux. In this study, it is used as a dynamical indicator of the intensity and direction of ABL-FT exchange.

3. Results

On 29 March 2024, LiDAR observations identified a vigorous ABL-FT exchange event. As shown in Figure 1a, a distinct elevated aerosol layer was detected at approximately 3.2 km within the FT around 12:50 BJT, with an aerosol attenuated backscatter coefficient reaching $10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$ (T. Wei et al., 2025). This layer persisted until 17:45 BJT. The mixed-layer height (MLH) was determined using a turbulent kinetic energy dissipation rate threshold of $10^{-4} \text{ m}^2 \text{ s}^{-3}$, following previous studies (Banakh et al., 2021; Su, Lu, et al., 2024; Su, Xia, et al., 2024; L. Wang et al., 2021). For comparison, the MLH was also retrieved using the attenuated-backscatter-gradient method (H. Li et al., 2017; Schween et al., 2014). The two methods showed

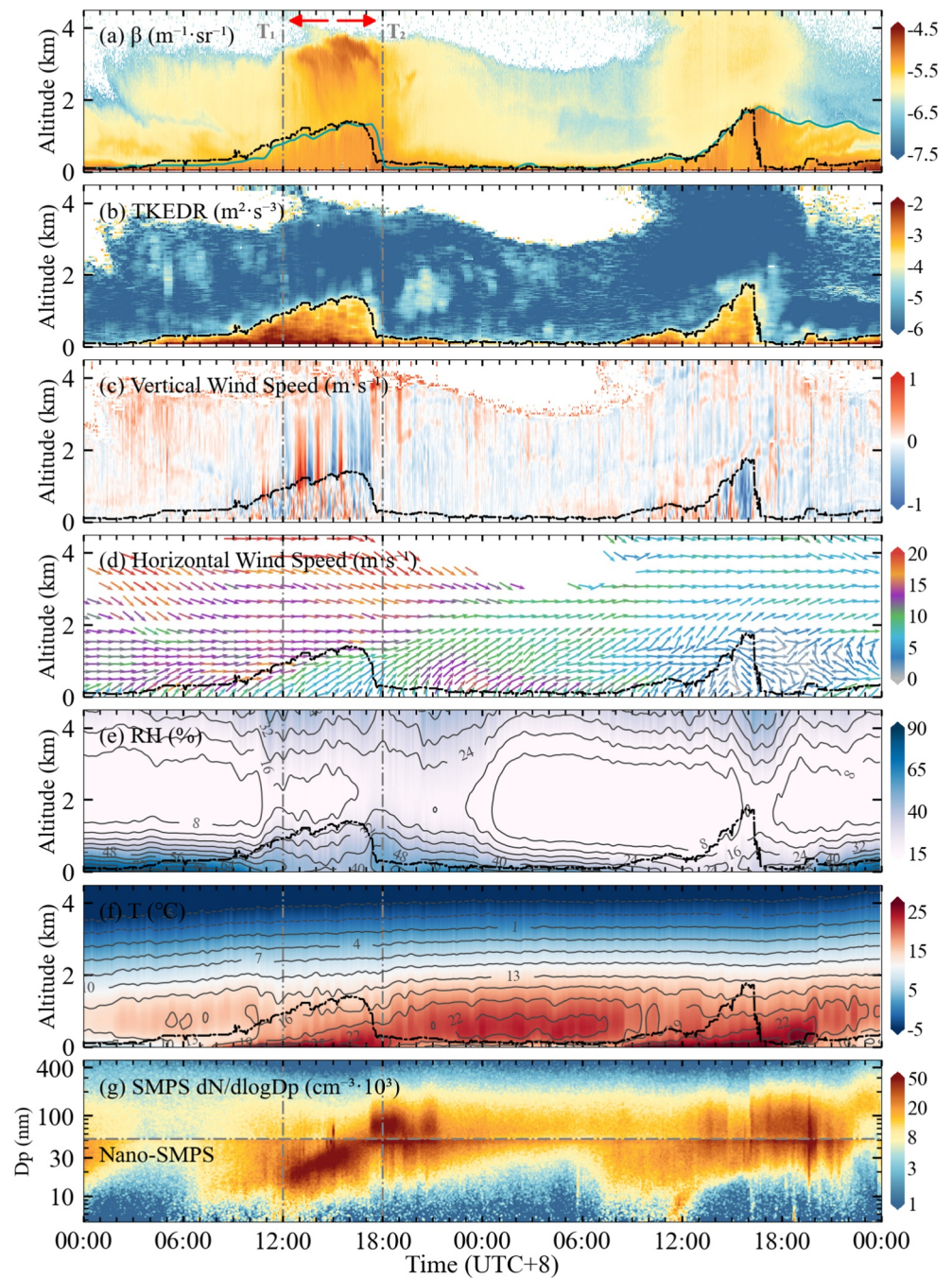


Figure 1. Observations from the LiDAR, microwave radiometer, and particle size spectrometers at Fudan University on 29–30 March 2024: (a) attenuated backscatter coefficient ($\text{m}^{-1} \cdot \text{sr}^{-1}$); (b) turbulent kinetic energy dissipation rate; (c) vertical wind speed ($\text{m} \cdot \text{s}^{-1}$), with positive values indicating downward motion and negative values indicating upward motion; (d) horizontal wind speed ($\text{m} \cdot \text{s}^{-1}$) and wind direction ($^{\circ}$); (e) relative humidity (%); (f) temperature ($^{\circ}\text{C}$); (g) particle number concentrations from the Nano-SMPS and scanning mobility particle sizer, showing the evolution of ultrafine particle size distributions during the event. T_1 and T_2 denote the start and end times of the vertical exchange event, respectively. The cyan solid line in panel (a) denotes the mixed-layer height (MLH) retrieved using the attenuated-backscatter-gradient method, whereas the black dash-dotted lines in panels (a)–(f) denote the MLH retrieved using the TKEDR-threshold method.

similar mixed-layer evolution on 29 March, particularly during the main exchange period (Figure 1a). After approximately 16:00 BJT on 30 March, however, the gradient method continued to track a persistent aerosol layer aloft, while the TKEDR-based MLH decreased with weakening turbulence. This divergence indicates that the

gradient method may identify residual or elevated aerosol layers as the mixed-layer top. Therefore, the TKEDR-derived MLH was used to represent the actively turbulent mixing depth in the subsequent ABL-FT exchange analysis. During mixed-layer development, strong turbulence lifted local aerosols up to approximately 1.4 km, where they interacted and mixed with the elevated aerosol layer transported from aloft. The vertical wind field (Figure 1c) shows that pronounced vertical air motions penetrated the ABL top and extended into the FT up to approximately 3 km, establishing dynamic coupling between the two layers and facilitating enhanced vertical aerosol exchange. To further investigate aerosol transport pathways at different altitudes, 48-hr backward trajectories were calculated using the NOAA HYSPLIT model for air parcels arriving at 100 m and 3 km, representing the ABL and the FT, respectively. The results show that air masses arriving at 3 km originated from northwestern China and exhibited clear long-range transport characteristics, whereas air masses arriving at 100 m also originated from the northwest but gradually shifted to southwesterly flow after passing through Jiangxi and Anhui provinces (Figure S2 in Supporting Information S1).

Figure 1d illustrates the horizontal wind field during the vertical exchange event. At 07:00 BJT on 29 March 2024, a boundary-layer jet was detected at an altitude of 750 m, with wind speeds exceeding 15 m s^{-1} , and it gradually ascended through turbulent mixing. In the FT, persistent high-speed airflow with velocities above 20 m s^{-1} was observed, while wind speeds in the ABL exceeded 7 m s^{-1} , substantially enhancing horizontal aerosol transport and mixing. Microwave radiometer observations show a pronounced humidity stratification during the exchange event (Figure 1e), with relatively moist air confined mainly to the lower boundary layer and much drier air in the lower FT. This dry-moist contrast indicates a clear thermodynamic and moisture discontinuity across the boundary-layer top. The low humidity in the upper layers suggests that the elevated aerosols observed by the LiDAR were unlikely to be cloud particles. Figure 1f further shows that a warm lower-tropospheric layer was present during the exchange period and persisted into the evening and the following day. During the exchange event, the near-surface aerosol size distribution exhibited pronounced variations. Nano-SMPS observations showed a substantial increase in particle concentrations at approximately 12 nm on 29 March, forming a time-evolving growth pattern in the ultrafine particle size distribution in which the concentration maximum shifted from smaller to larger particle diameters with time (i.e., a banana-shaped feature; Figure 1g). This growth-like feature coincided temporally with the onset of vigorous vertical exchange. However, because such a size-distribution pattern is not unique to FT-to-ABL transport, its possible relationship with downward entrainment is evaluated below together with the vertical-wind, exchange-flux, and size-resolved particle evidence.

3.1. Long-Range Transport of Elevated Dust Driven by a Cold Vortex Over Northeastern China

From 27–29 March 2024, a widespread dust storm developed over northern China under the combined influence of a Mongolian cyclone and a surface cold front, with severe dust impacts reported over central-eastern Inner Mongolia and adjacent regions (Zhao & Zhang, 2024). To better constrain the likely source region of the dust affecting Shanghai, we examined the distribution of surface PM_{10} concentrations prior to dust arrival in Shanghai. Stations with elevated PM_{10} concentrations exceeding $1,100 \mu\text{g m}^{-3}$ at 23:00 BJT on 27 March 2024 were first identified, and the largest spatial cluster of these high- PM_{10} stations was then retained as a possible dust source-related region. This clustered region was located over Inner Mongolia and northern Shanxi, broadly consistent with the dust-affected area reported by Zhao and Zhang (2024). Geographically, this region is close to the Kubuqi Desert and the Mu Us Sandy Land, supporting its interpretation as a plausible near-source region for the subsequent downstream dust transport.

As shown in Figure 2a, the identified source-related region was situated upstream of Shanghai under prevailing northwesterly flow at 500 hPa. At 02:00 BJT on 29 March, Shanghai was located near the trough axis and was affected by strong northwesterly flow in the middle troposphere. By 13:00 BJT (Figure 2b), although the trough axis had shifted eastward, strong northwesterly winds aloft persisted. This synoptic pattern was favorable for southward transport of elevated dust from Inner Mongolia and northern Shanxi toward eastern China. The inferred transport pathway is also consistent with the free-tropospheric winds observed by the LiDAR in Figure 1d, indicating that the elevated aerosol layer observed over Shanghai was associated with long-range transported dust rather than local emissions.

Using Himawari-9 satellite observations, elevated dust aerosols were identified based on the Fractional Dust Coverage Index (FDCI), which is derived from a dynamic background field (B. Li et al., 2023). Compared with conventional fixed-threshold or single dynamic-threshold methods, this approach provides greater stability and

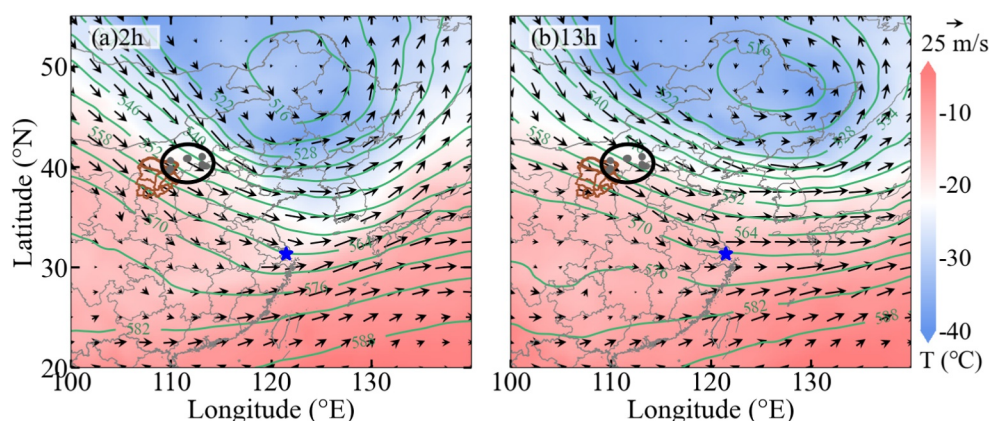


Figure 2. ERA5 reanalysis fields of temperature (shaded), geopotential height (green contours), with horizontal wind vectors (black arrows) at 500 hPa on 29 March 2024. (a) 02:00 BJT; (b) 13:00 BJT. The blue pentagram indicates the observation site in Shanghai. The black ellipse marks a possible dust source-related region over Inner Mongolia and northern Shanxi, identified from the largest spatial cluster of stations with PM_{10} concentrations exceeding $1,100 \mu\text{g m}^{-3}$ at 23:00 BJT on 27 March 2024. The areas outlined by yellowish-brown solid lines indicate the Kubuqi Desert and the Mu Us Sandy Land.

higher detection accuracy. The FDCI over Shanghai exceeded 0.4 at 14:00 BJT, indicating the occurrence of a dust event. Based on the FDCI-derived Enhanced Dust Intensity Index (EDII), the EDII value over Shanghai was approximately 0.47 (Figure 3b), corresponding to a normalized visibility-based dust intensity category of floating dust. Satellite observations indicate that, under the influence of strong northwestern cold-air, long-range transported dust had reached the Shanghai region, confirming that the elevated aerosol layer observed by the LiDAR in Figure 1a originated from distant sources. Together with the LiDAR-observed elevated aerosol layer and the 3-km backward trajectories, these observations further support the conclusion that Shanghai was affected by long-range transported dust aerosols.

3.2. Strong Vertical Exchange Associated With Boundary-Layer Growth, Wind Shear, and Thermodynamic Interface Disturbances

Figure 4a shows a pronounced high-value region in the FT on March 29, indicating the presence of dust aerosols aloft. Within the ABL, vigorous turbulence promoted vertical mixing, resulting in a relatively uniform attenuated-backscatter structure with height. In contrast, on 30 March, weaker turbulent mixing within the ABL was associated with a more rapid decrease in attenuated backscatter with altitude. Meanwhile, horizontal wind speed

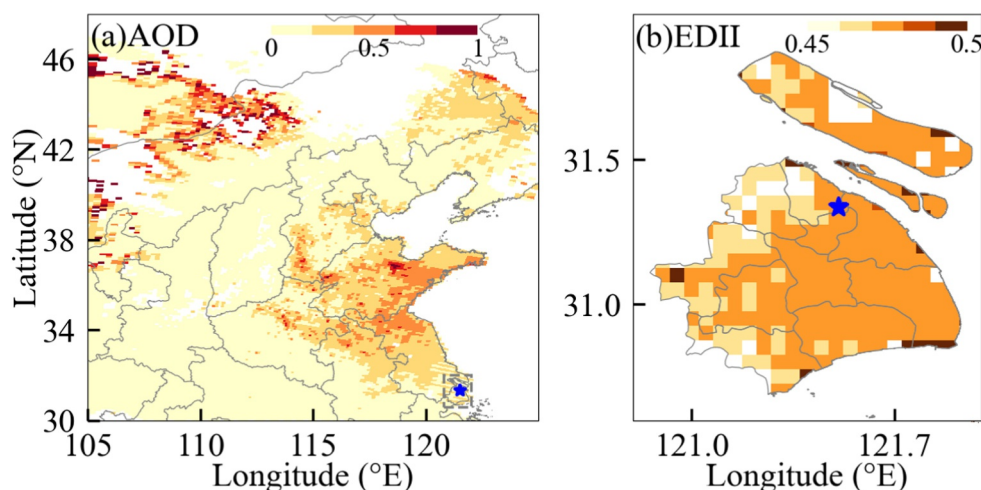


Figure 3. Identification of dust aerosols over the Shanghai region on 29 March 2024. (a) AOD at 10:40 BJT; (b) Enhanced dust intensity index at 14:00 BJT. The blue pentagram indicates the location of the Shanghai observation site.

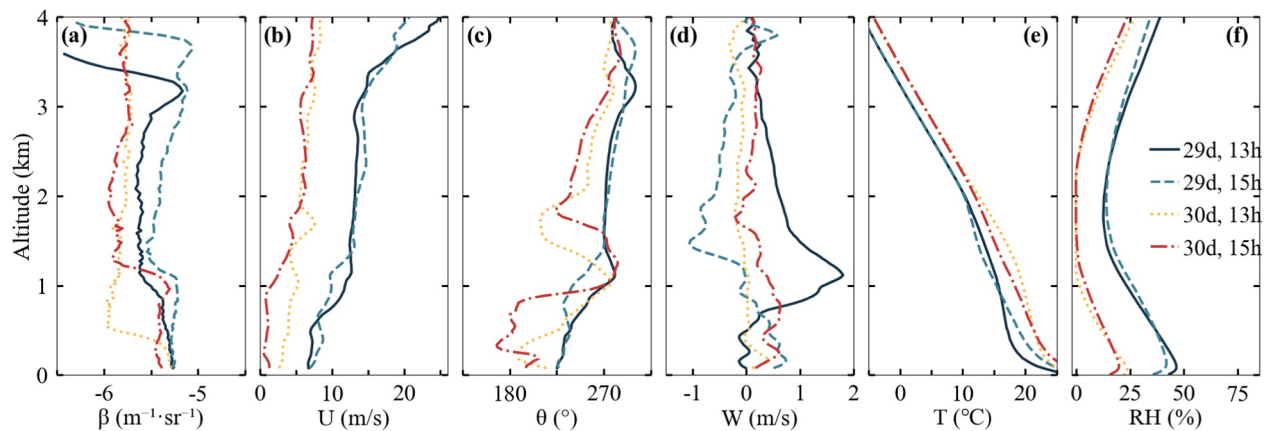


Figure 4. Vertical profiles observed by the LiDAR and microwave radiometer at 13:00 and 15:00 BJT on 29–30 March 2024: (a) attenuated backscatter coefficient (β , $\text{m}^{-1} \text{sr}^{-1}$); (b) horizontal wind speed (U , m s^{-1}); (c) wind direction (θ , $^{\circ}$); (d) vertical velocity (w , m s^{-1}); (e) temperature (T , $^{\circ}\text{C}$); (f) relative humidity (RH , %).

increased markedly with height and exhibited a strong vertical gradient within the ABL, while wind direction veered clockwise with height (Figures 4b and 4c), indicating pronounced vertical wind shear and differing flow regimes between the lower and upper troposphere. These wind-structure characteristics were much weaker on March 30, indicating that the lower troposphere on 29 March was more dynamically favorable for deep ABL-FT coupling.

During the exchange event, vertical velocities reached approximately 2 m s^{-1} , substantially exceeding typical turbulent vertical motions in the ABL, which are generally less than 1 m s^{-1} (Yang et al., 2019). The coexistence of pronounced upward and downward motions (Figure 4d) indicates vigorous exchange across the ABL top and is consistent with enhanced transport and mixing of aerosols from aloft. Figure 4e shows that the lower troposphere was warm during the episode, but comparable or even higher temperatures were also observed on 30 March. Figure S3 in Supporting Information S1 places this thermal structure in a broader temporal context: both the MWR- and ERA5-based analyses show pronounced positive temperature anomalies in the lower troposphere during the episode, while comparable anomalies persisted on 30 March. These results indicate that the lower-tropospheric warmth represented an anomalous background condition but was not sufficient to explain the vigorous exchange specifically observed on 29 March. In contrast, the 29 March event was distinguished by the simultaneous occurrence of strong wind shear, pronounced vertical motions, and an elevated aerosol layer aloft. Figure 4f further shows that the lower boundary layer on 29 March was relatively moist, whereas the lower FT remained dry. This dry–moist contrast indicates a distinct thermodynamic interface near the ABL top, which provided a stratified background for shear-related disturbances and entrainment during the exchange period.

To further diagnose the stability and moisture structure near the ABL top, the potential temperature gradient and specific humidity were examined in Figure 5. The temperature and humidity profiles were obtained from microwave-radiometer retrievals, while the vertical pressure profile used in the calculations was taken from the model simulation. Figure 5a shows a positive potential-temperature gradient near and above the ABL top, indicating a stably stratified interface between the mixed layer and the lower FT. During the exchange period on 29 March, the $d\theta/dz$ contours near the upper part of the boundary layer became distorted and locally weakened, suggesting that this stable interface was disturbed. Figure 5b further shows that specific humidity was relatively high within the lower boundary layer on 29 March, likely reflecting southwesterly warm-moist advection, whereas a much drier layer existed above in the FT. The vertical displacement and deformation of q contours during the exchange period indicate active perturbation of the moisture interface, consistent with enhanced entrainment and vertical redistribution of water vapor.

This stratified thermodynamic background is also supported by the 08:00 BJT radiosonde sounding from the Baoshan station (Figure S4 in Supporting Information S1). The sounding shows a shallow moist layer near the surface, overlain by a markedly warmer and much drier layer between about 925 and 850 hPa. Surface-based CAPE was negligible (1.4 J kg^{-1}), while CIN was strongly negative (-441.2 J kg^{-1}), indicating that the lower troposphere was not favorable for deep moist convection. At the same time, winds in the lower troposphere

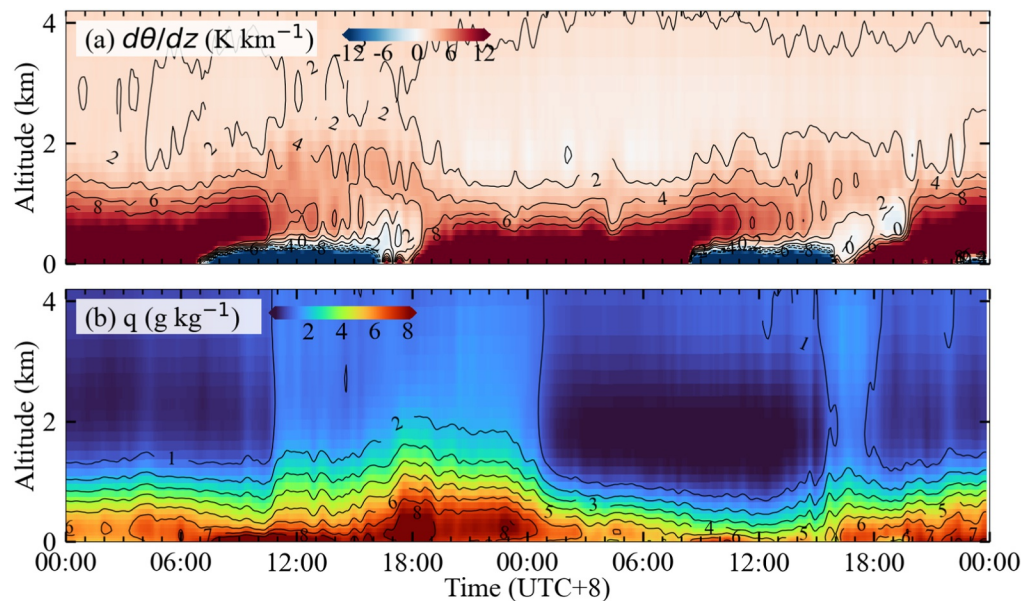


Figure 5. Vertical distributions of (a) potential-temperature gradient and (b) specific humidity from 29–30 March 2024, derived from microwave-radiometer temperature and humidity retrievals combined with the model-simulated vertical pressure profile.

remained strong, and pronounced shear extended from the boundary layer into the lower FT, consistent with a dynamically driven exchange regime dominated by wind shear, boundary-layer growth, and entrainment rather than buoyant moist convection.

Under these conditions, the boundary-layer jet near the ABL top interacted with the warm-moist warm boundary layer and the stably stratified air above, creating a thermodynamic-dynamical configuration favorable for the development of interface disturbances. These disturbances appeared in the vertical-velocity field as quasi-periodic banded structures with alternating upward and downward motions (Figure S8 in Supporting Information S1), exhibiting characteristics consistent with nonorographic gravity-wave-like features. The resulting interface perturbations likely enhanced exchange and mixing across the ABL-FT boundary, thereby facilitating the downward transport of aerosols, including possible downward mixing from aloft. Previous work has shown that strong vertical wind shear near a jet can lead to shear instability and provide energy for wave growth (Shou et al., 2016). Although the stable stratification on 30 March was deeper, the absence of a comparable jet-related disturbance near the ABL top likely limited the occurrence of exchange as intense as that observed on 29 March.

Strong horizontal advection likely contributed to the warm and moist lower-tropospheric background during the event. As shown in Figure 6a, at 850 hPa on 29 March, the flow transported relatively warm air eastward from southwestern China toward the lower reaches of the Yangtze River Plain. Figure 6b further shows that the lower troposphere over and south of Shanghai was influenced by southwesterly flow, whereas stronger northwesterly flow persisted aloft. This synoptic structure is consistent with the vertically veering wind profile observed over Shanghai in Figure 4 and suggests differing air-mass influences between the lower and upper troposphere during the event. Under these conditions, clear-sky conditions (Figure S5 in Supporting Information S1) allowed daytime shortwave heating, which likely supported boundary-layer growth. Together, large-scale warm advection and daytime surface heating helped establish the thermodynamic background for the event. However, this background alone did not determine the occurrence of vigorous exchange; the strong wind shear, boundary-layer-jet-related disturbances, and elevated aerosol layer aloft were essential for the intense ABL-FT exchange observed on 29 March.

3.3. Estimation of ABL–FT Air-Mass Exchange Fluxes During the Vertical Exchange Event

Boundary-layer height and the three-dimensional wind components near the ABL top are critical meteorological variables for estimating ABL-FT exchange fluxes. Accurate determination of the exchange flux depends strongly

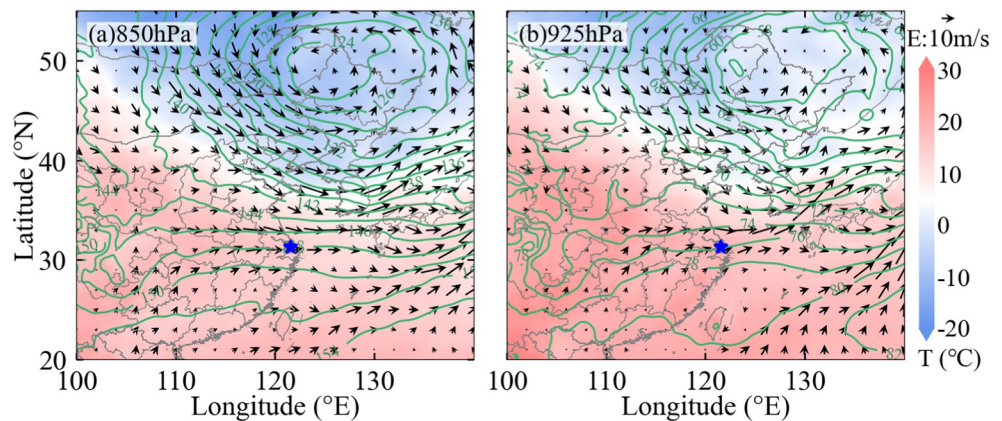


Figure 6. ERA5 reanalysis fields of temperature (shaded), geopotential height (green contours), and horizontal wind vectors (black arrows) at 13:00 BJT on 29 March 2024: (a) 850 hPa; (b) 925 hPa. The blue pentagram indicates the observation site.

on reliable identification of the boundary-layer height, because the wind field, thermodynamic variables, and turbulence-related parameters used in the calculations are extracted or interpolated relative to this height. The boundary-layer height simulated using the bulk Richardson number method was evaluated against LiDAR-based retrievals and showed good agreement during the vertical exchange on 29 March (Figure 7a). The simulated horizontal wind and thermodynamic fields were also generally consistent with observations (Figure S6 in Supporting Information S1), enabling a reasonable reproduction of daytime boundary-layer growth. Although the nighttime boundary-layer height was slightly underestimated in the simulation, this bias did not substantially affect the representation of the main processes during the target event.

Although the model reproduced the horizontal wind structure reasonably well, significant biases remained in the simulated vertical wind field, indicating a persistent limitation in the model representation of vertical motions (Figure S7 in Supporting Information S1). Under these conditions, high-resolution vertical-wind measurements from Doppler LiDAR are particularly valuable for improving the accuracy of flux estimates, because the calculation of exchange across the ABL-FT interface is highly sensitive to the vertical velocity field. Because the

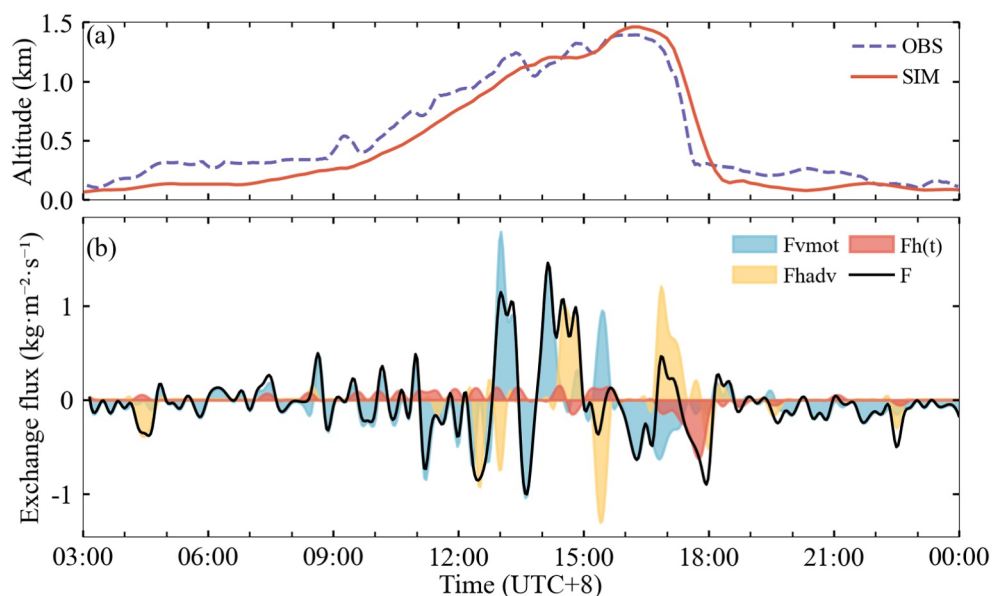


Figure 7. Simulated and observation-constrained ABL-FT exchange fluxes over Shanghai on 29 March. (a) Lidar-derived observed atmospheric boundary layer (ABL) height (purple dashed line) and simulated ABL height (red solid line). (b) Temporal evolution of the estimated ABL-FT air-mass exchange flux and its three components at 10-min resolution.

exchange-flux formulation requires the evolving ABL height together with multiple thermodynamic and dynamical variables at the interface, a hybrid approach was adopted in this study. The model was used to provide the time-varying ABL geometry and related state variables, while the LiDAR observations were used to better constrain the wind field near the interface, particularly the vertical velocity.

Accordingly, the interface wind components (u_h , v_h and w_h) were obtained from LiDAR observations and interpolated to the modeled boundary-layer height, while the remaining variables required by the flux formulation were derived from the model output. It should be noted that before 03:00 BJT on 29 March, the boundary-layer height was below the minimum altitude detectable by the LiDAR, resulting in temporal gaps in the interpolation.

Figure 7b shows the temporal evolution of the estimated ABL-FT air-mass exchange flux across the ABL top, decomposed into three components: $F_{h(t)}$ associated with temporal changes in ABL height, F_{adv} associated with horizontal advection across the sloping ABL top, and F_{vmot} associated with vertical motions at the interface. Positive values indicate flux into the ABL, whereas negative values indicate flux out of the ABL. The flux was evaluated at the instantaneous modeled ABL top, which was treated as the ABL-FT interface. Thus, the calculation follows the evolving boundary-layer height rather than a fixed pressure level or geometric altitude. This choice is physically consistent with the framework of Jin et al. (2024), in which cross-boundary exchange is defined across the ABL top. Results show that, under the combined influence of these three mechanisms, the total exchange flux fluctuated between -0.97 and $1.46 \text{ kg m}^{-2} \text{ s}^{-1}$, with contribution ratios of 12.5%, 29%, and 58.5%, respectively. In this observation-constrained calculation, F_{vmot} made the largest contribution, indicating that vertical motions at the evolving ABL top were a major pathway for exchange during the event. The pronounced temporal variability of the flux indicates active and highly intermittent air-mass exchange across the ABL-FT interface during the event. Notably, under the influence of the northeastern cold vortex, the morning of 29 March was characterized mainly by downward transport from the FT into the ABL. In the afternoon, strong exchange, primarily driven by vertical motions, became more pronounced. Around 15:00 BJT, the horizontal-advection term also became pronounced, reflecting the role of strong winds across the sloping ABL interface, and the rapid decrease in ABL height contributed to fluxes associated with boundary-layer-height tendency.

3.4. Potential Impacts on Surface Ultrafine Particles and Particulate Matter

Figure 8 shows the evolution of meteorological conditions and particle characteristics during the ultrafine-particle enhancement event. On the morning of 29 March, physically inconsistent PM_{10} values lower than $\text{PM}_{2.5}$ were reported at both the Hongkou and Yangpu-Sipiao stations, and the corresponding PM_{10} data were therefore excluded from the analysis. During the subsequent vertical exchange period, however, data from both stations were retained, and the PM concentrations at the two sites exhibited broadly consistent variations (Figure 8a). During this period, both stations recorded a continuous increase in the $\text{PM}_{10}/\text{PM}_{2.5}$ ratio (Figure 8b), indicating a growing contribution of coarse particles, which is a typical signature of dust transport (Yang et al., 2019). Figure 8c presents LiDAR-derived horizontal wind observations at 78 m, the lowest valid range gate, indicated by arrows. Although wind speeds decreased during the daytime, they still contributed to ventilation and horizontal dispersion near the surface, helping to maintain relatively low PM concentrations. In addition, the combined effects of strong turbulent mixing within the boundary layer and strong winds aloft further limited the accumulation of near-surface particles. Previous studies have shown that ventilation under high-wind conditions is a key factor preventing near-surface accumulation of long-range transported aerosols (Koo et al., 2024). By contrast, on 30 March, weaker near-surface winds and less vigorous turbulent exchange favored the accumulation of PM near the surface. Therefore, the PM increase on 30 March is more likely associated with reduced dispersion and local or regional accumulation rather than with a deep ABL-FT exchange event comparable to that on 29 March.

To further examine the potential influence of vertical exchange on surface ultrafine-particle concentrations, vertical wind observations from the Doppler LiDAR in the ABL (0.52 and 1.22 km) and FT (2.83 km) were analyzed (Figure 8c), together with the temporal evolution of particle number concentrations at different sizes (Figure 8d). In this study, particles with diameters smaller than 25 nm are classified as nucleation-mode particles, whereas those in the 25–100 nm size range are classified as Aitken-mode particles. The 5–10 nm size range is treated separately to represent the smallest ultrafine particles and a possible incipient NPF signal. This treatment is consistent with vertically resolved NPF studies that use the appearance of sub-10 nm or 3–10 nm particles as an indicator of very recent particle formation, while also recognizing that such particles may be rapidly scavenged or

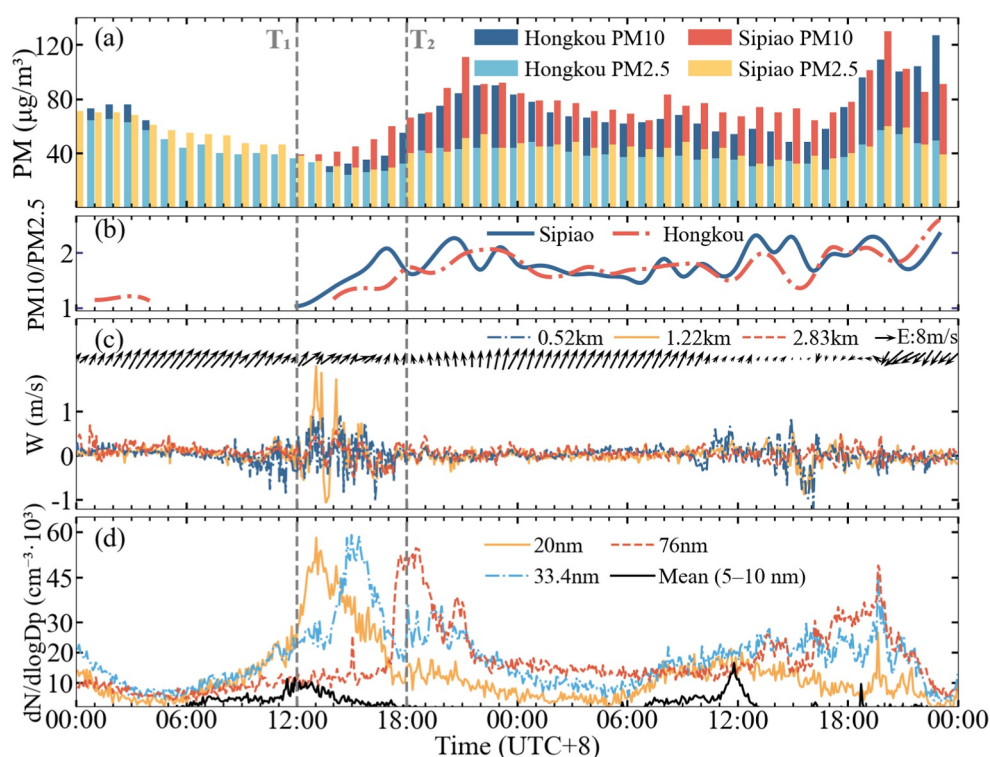


Figure 8. Evolution of meteorological conditions and particle characteristics during the ultrafine-particle enhancement event. (a) PM concentrations at the two sites. (b) $\text{PM}_{10}/\text{PM}_{2.5}$ ratio at the two sites. (c) Horizontal wind at 78 m and vertical velocity at multiple heights; (d) Temporal evolution of the mean particle concentrations in the 5–10 nm range and number concentrations of particles with diameters of 20 nm, 33.4 nm, and 76 nm. T_1 and T_2 denote the start and end time of the vertical exchange event, respectively.

spatially heterogeneous (Lampilahti, Manninen, et al., 2021; O'Donnell et al., 2023). In the following analysis, 20 nm particles represent nucleation-mode particles, whereas 33.4 and 76 nm particles represent Aitken-mode particles. During the exchange event, a jet was present near the ABL top, and turbulence was active, with pronounced vertical-wind fluctuations observed in both the ABL and the FT, indicating vigorous vertical exchange. Between 12:00 and 13:00 BJT, enhanced positive vertical velocities were recorded, suggesting intensified downward transport. Concurrently, ground-based observations showed a marked increase in particle concentrations: 20 nm particles increased to $5.8 \times 10^4 \text{ cm}^{-3}$, and 12 nm particles reached a peak of $2.8 \times 10^4 \text{ cm}^{-3}$. By contrast, particles smaller than 10 nm, represented by the mean concentration of 5–10 nm range, did not show a comparable increase, and their concentrations did not exceed those observed at the corresponding times on 30 March. These results suggest that the observed enhancement of nucleation-mode particles was unlikely to be driven primarily by local NPF and was more consistent with downward transport from aloft.

On 29 March, the lower FT was cloud-free and exposed to strong solar radiation (Figure S5 in Supporting Information S1), indicating a photochemically active environment in which oxidants and low-volatility vapors, such as sulfuric acid and oxidized organic vapors, could be produced more efficiently. Such conditions may have favored the formation or survival of nucleation-mode particles aloft, although direct precursor-gas measurements were not available (Boulon et al., 2011; Lee et al., 2003; Rose et al., 2015). Previous airborne and modeling studies have shown that NPF or enhanced nucleation-mode particle concentrations can occur above the surface, particularly near the upper mixed layer, residual layer, or RL–FT interface, where lower temperature, reduced particle sinks, and vertical gradients in precursor gases may favor particle formation and survival (Lampilahti, Leino, et al., 2021; O'Donnell et al., 2023). Mineral-dust photochemistry may provide one potential pathway for such aloft particle production, as laboratory experiments have shown that irradiated mineral dust can induce nucleation events in the presence of SO_2 under appropriate conditions (Dupart et al., 2012). During vigorous vertical exchange, particles likely present in the FT may have been transported downward into the ABL and subsequently detected at the surface (Wang, Wang, et al., 2023; Wang, Shi, et al., 2023). As exchange continued,

the initial enhanced nucleation-mode particles may have gradually grown into Aitken-mode particles, producing the observed growth-like pattern. However, because vertical observations of precursor gases were not available during the present campaign, particle formation in the FT cannot be directly confirmed. During the evening, reduced solar radiation, increased boundary-layer stability, and weakened vertical transport allowed particles to accumulate near the surface. In contrast, on 30 March, the absence of a comparable dynamically organized exchange event was accompanied by the absence of a similar surface ultrafine-particle enhancement and growth-like feature. Variations in nucleation-mode particles on that day were more likely associated with local or regional pollution accumulation.

4. Discussion

On 29 March 2024, a pronounced ABL-FT exchange event occurred over Shanghai and was accompanied by an increase in near-surface ultrafine-particle concentrations. Under the influence of a northeastern cold vortex, strong northwesterly winds transported dust aerosols and cold air into the region. The associated cold advection also produced a relatively low-temperature FT environment, which could have enhanced the thermodynamic stability of low-volatility molecular clusters and thereby favored the survival of newly formed or pre-existing nucleation-mode particles aloft. At lower levels, warm-moist advection and daytime surface heating helped establish a relatively warm and moist boundary layer beneath drier and more stably stratified air aloft. This vertical contrast in moisture and stability, together with the boundary-layer jet and marked changes in wind structure with height, created favorable conditions for dynamical disturbances near the ABL top. These disturbances appeared as intermittent upward and downward motions, thereby enhancing cross-boundary exchange between the ABL and the lower FT. The morning radiosonde sounding further supports this interpretation by showing negligible SBCAPE, strong CIN, and a dry layer above the shallow moist surface layer, implying that the subsequent ABL-FT exchange was unlikely to be driven by deep moist convection.

To clarify the relationship among dust transport, the possible FT fine-particle reservoir, ABL-FT exchange, and the surface particle response, Figure S9 in Supporting Information S1 summarizes the proposed process framework. Although the present observations do not directly demonstrate that the dust layer observed near 3.2 km was itself the direct source of the near-surface nucleation-mode particles, the co-occurrence of dust-influenced FT air, vigorous intermittent entrainment, enhanced 12–20 nm particles, and a weak simultaneous sub-10 nm response supports an interpretation more consistent with FT-to-ABL particle influence followed by boundary-layer mixing and growth than with a purely local near-surface formation mechanism.

During this event, strong winds in the FT during the morning may have reduced preexisting aerosol loading, thereby maintaining a relatively low condensation sink which was more favorable for NPF. In the afternoon, long-range transported dust aerosols arrived over Shanghai under the influence of persistent northwesterly flow. In general, dust outbreaks can substantially enhance coagulation loss and the condensation sink, thereby suppressing NPF (De Reus et al., 2000; Ndour et al., 2009; Zamora & Kahn, 2020). However, several studies have suggested that NPF can still occur under long-range dust transport conditions far from the source regions (Baalbaki et al., 2021; Casquero-Vera et al., 2020). Catalytically active mineral components within dust particles may promote the formation of hydroxyl radicals (OH) and other oxidants, thereby enhancing the atmospheric oxidation capacity and indirectly facilitating NPF (Nie et al., 2014). More broadly, heterogeneous photochemistry on atmospheric particles can modify oxidant production, multiphase reactions, and aerosol aging, providing a general chemical framework for interpreting dust-related particle formation and growth under irradiated conditions (George et al., 2015). Casquero-Vera et al. (2023) further suggested that frequent NPF events can occur even during strong dust outbreaks, particularly in downwind regions influenced by dust transport. Therefore, under the meteorological conditions of this study, dust transport may not necessarily have suppressed particle formation aloft. Instead, it might have interacted with the evolving oxidative and dynamical environment in a way that remained compatible with particle formation or survival aloft. Nevertheless, this interpretation remains tentative and requires further examination using targeted observations and modeling analyses.

During the period of strong vertical exchange, a pronounced increase in the near-surface concentration of 12–20 nm nucleation-mode particles was observed. One plausible explanation is that particles present aloft were transported downward and subsequently mixed and grew within the ABL. However, neither the enhancement in this size range nor the growth-like size-distribution pattern is source-specific. Similar particle evolution may also result from regional advection of an evolving NPF plume, the arrival of an elevated upwind urban plume, or a

local or regional NPF event in which the smallest particles were below the lower detection limit of the Nano-SMPS, were rapidly lost by coagulation, or grew rapidly through the smallest detectable size range. The absence of a preceding or simultaneous increase in 5–10 nm particles weakens, but does not completely exclude, a surface-initiated local NPF explanation. Typical surface-observed NPF events generally exhibit an initial increase in sub-10 nm particles followed by progressive growth toward larger sizes (Dai et al., 2017; Lv et al., 2018; Shen et al., 2023; Wang et al., 2017), whereas the enhancement observed here was concentrated mainly in the 12–20 nm range. More importantly, this size-dependent particle evolution occurred simultaneously with pronounced vertical motions extending across the evolving ABL top and with large observation-constrained air-mass exchange fluxes. Previous modeling studies have also shown that enhanced vertical mixing can transport particles formed or present aloft downward and produce a more vertically homogeneous particle distribution (Lai, Hai, et al., 2022; Lai, Huang, et al., 2022). The combined particle and dynamical evidence therefore suggests that downward entrainment from an aloft particle reservoir likely contributed to the near-surface enhancement. Nevertheless, the present observations cannot uniquely determine whether this reservoir was located in the lower FT, the residual layer, or an elevated upwind plume, nor can they completely exclude contributions from local or regional NPF.

Frequent NPF in the FT is particularly prominent during spring in Shanghai and is closely associated with regional meteorological conditions. Strong horizontal winds often reduced aerosol loadings in the FT, thereby lowering the condensation sink and enhancing the survival probability of newly formed nanoparticles, which favors their subsequent growth (Lai, Huang, et al., 2022). In addition, cold and dry conditions aloft may help sustain, or even enhance, hydroxyl radical (OH) concentrations (Hamed et al., 2011; Kerminen et al., 2018), promoting oxidation of gaseous precursors. Previous studies have further suggested that NPF in the FT depends not only on the upward transport of precursors from the boundary layer (Bianchi et al., 2016), but also that newly formed particles can subsequently be transported downward by subsidence between altitudes of 2 and 3.5 km, reaching the ABL-top transition zone and potentially being entrained into the boundary layer before shifting into the Aitken mode (Wang, 2023; Wang et al., 2016; Zhao et al., 2020). These findings provide important context for understanding particle exchange between the FT and the boundary layer in the present case.

Overall, the observational results of this study suggest that vertical exchange may play an important role in regulating springtime ultrafine-particle variability in Shanghai. Although the current evidence remains insufficient to fully quantify this process, the findings imply a possible linkage among particle processes aloft, dust transport, and vertical mixing. As a process-oriented case study, this work focuses on the mechanisms of one well-observed event rather than on the climatological frequency of such interactions. Future studies integrating high-altitude sounding observations, chemical precursor measurements, and numerical simulations are needed to further elucidate the mechanisms governing the downward transport of free-tropospheric particles and their impacts on regional aerosol number concentrations.

5. Conclusions

This study investigated an intense ABL-FT exchange event over Shanghai and its possible influence on the near-surface enhancement of ultrafine particles. The event evolved through two distinct stages: an initial period of strong exchange across the ABL top, followed by particle accumulation and growth within the boundary layer. During the exchange stage, the lower troposphere was characterized by a relatively warm and moist growing boundary layer, with drier and more stably stratified air above the ABL top. This vertical contrast in moisture and stability, together with a boundary-layer jet near the ABL top, favored dynamical disturbances that appeared as alternating upward and downward motions and drove intermittent ABL-FT exchange.

This case study provides three main insights. First, it documents a rare and well-observed intense ABL-FT exchange event over Shanghai using coordinated LiDAR, microwave-radiometer, particle-size, and WRF-based interface-flux diagnostics. Second, combined observations and numerical-simulation diagnostics indicate pronounced fluctuations in the estimated ABL-FT air-mass exchange flux, from -0.97 to $1.46 \text{ kg m}^{-2} \text{ s}^{-1}$. In the observation-constrained calculation, the vertical-motion term made the largest contribution, accounting for 58.5% of the estimated exchange, suggesting that vertical motions at the evolving ABL top were an important pathway for cross-boundary coupling during this event. Third, the timing and size-dependent particle response, together with the independently observed vertical-exchange pathway, is more consistent with a contribution from downward entrainment of an aloft particle reservoir than with a purely local surface-formation mechanism.

During the period of enhanced vertical coupling, ultrafine-particle concentrations increased markedly, whereas particles smaller than 10 nm did not show a corresponding increase. Although the arrival of long-range transported dust would generally be expected to increase the condensation sink and suppress NPF, the observations in this case are consistent with a possible linkage among particle processes aloft, dust intrusion, and subsequent downward transport during strong vertical mixing. However, direct confirmation of particle formation aloft and its quantitative contribution to the surface particle population remains uncertain. As a process-oriented case study, this work focuses on the mechanisms of one well-observed event. Further long-term, vertically resolved observations and process-oriented modeling are needed to better constrain the mechanisms of downward particle transport, assess the broader representativeness of such intense exchange events, and quantify their impacts on boundary-layer aerosol evolution.

Conflict of Interest

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

Availability Statement

The LiDAR, microwave radiometer, and particle size spectrometer data used in this study are publicly available from Figshare (F. Wei, 2025) at <https://doi.org/10.6084/m9.figshare.30142882>. The ERA5 reanalysis data are publicly available from the Copernicus Climate Change Service (C3S) Climate Data Store (Hersbach et al., 2023) at <https://doi.org/10.24381/cds.bd0915c6>. The Himawari-9 satellite data are publicly available from the Japan Meteorological Agency (2026) at <https://www.data.jma.go.jp/mscweb/en/>. Radiosonde observations from the Baoshan meteorological station in Shanghai (station ID: 58362) were obtained from the China Meteorological Data Service Centre (<https://data.cma.cn/>).

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