Characteristics of Turbulence and Aerosol Optical and Radiative Properties during Haze–Fog Episodes in Shenyang, Northeast China

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Abstract: The characteristics of turbulence in the planetary boundary layer (PBL) and the aerosol optical and radiative properties during haze and haze–fog mixed episodes on 22–27 January 2021, in Shenyang, a provincial city in Northeast China, were analyzed using meteorological and aerosol observations. During the haze episode, the hourly mean PM$_{2.5}$ concentration reached a maximum of 337 µg m$^{-3}$ and visibility decreased to 1.6 km. The PM$_{2.5}$ concentration decreased gradually during the haze–fog mixed episode as a result of the scavenging effects of fog, but visibility mostly remained below 1 km owing to high ambient relative humidity (>90%). During the haze–fog mixed episode, an increasing proportion of PM$_{2.5}$ led to a higher ratio of the backward to the total scattering coefficient. As fog occurred, downward shortwave radiation arriving at the surface was significantly reduced, and upward longwave radiation increased and almost equaled the downward longwave radiation, which can be used as a good indicator for distinguishing haze and fog. Mechanical turbulence was weak during both episodes, and latent heat flux varied within a wider range during the haze–fog mixed episode. The PBL dynamic structure affected the vertical distribution of aerosols/fog droplets. Aerosol-rich layers appeared at altitudes below 0.5 km and above 0.6 km during the haze episode. The elevated aerosol layer was related to the aerosol transport from upstream polluted areas caused by strong upper-level turbulence, and it began to mix vertically after sunrise because of convective turbulence. Aerosols and fog droplets were mostly trapped in a shallower PBL with a height of 0.2–0.4 km during the haze–fog mixed episode because of weaker turbulence.

Keywords: haze and fog; turbulence; radiative effect; optical property; planetary boundary layer; Northeast China

1. Introduction

Haze and fog events typically characterized by high PM$_{2.5}$ (particulate matter with aerodynamic diameters of 2.5 µm and smaller) concentrations have occurred frequently during the past few decades in China, particularly in the most developed and highly populated regions [1–3]. Severe haze and fog events can damage human and ecological health [4–6], cause low visibility and traffic safety issues [7–9], and even produce weather and climate change [10,11].

To understand the formation mechanisms and climate/radiation effects of haze and fog, researchers have investigated the physical and chemical properties of aerosols/fog droplets and meteorological conditions during severe haze and fog events over different regions in China [12–17]. As haze and fog events both occur in the planetary boundary layer (PBL), turbulence in the PBL can directly affect the horizontal transport and vertical mixing of aerosols/fog droplets and thus alter the near-surface visibility and air quality [18–20].
Turbulence observations during two haze episodes in Shenyang showed that the PM$_{2.5}$ concentration was well correlated with the friction velocity ($u^*$; positive and negative correlations in local-accumulation- and long-transport-related haze episodes) but did not have an obvious relationship with the scaling potential temperature, which means that the haze events were affected more by the dynamic effects of turbulence and less affected by its thermal effects [21]. The PBL experiment conducted in northern China in December 2016 indicated that the evolution of fog–haze episodes during the daytime was controlled by the intensity of vertical turbulence and wind speed, while at night the atmospheric vertical mixing capacity was mainly controlled by the percentage of large-scale eddies [22]. Turbulence caused by nocturnal low-level jets can influence the dispersion/transport of air pollutants and modify air quality in the North China Plain [23] and Northeast China [19]. Ambient relative humidity (RH) affects the formation and evolution of haze/fog and visibility mainly through the hygroscopic growth of aerosols. Previous observations have shown that the PM$_{2.5}$ concentration dominates the variation in atmospheric visibility under dry conditions or a low PM$_{2.5}$ concentration, and that the contribution of RH to visibility becomes increasingly important as the PM$_{2.5}$ concentration and RH increase [24,25]. It has been observed that atmospheric visibility was critically reduced as aerosols grew from the uptake of water when the RH was higher than 95% [7]. As the RH continuously increases, some of the hygroscopic aerosols can be activated and form fog droplets [26].

Haze and fog events can alter the radiation balance and even the PBL structure because of the light scattering and absorbing of aerosols/fog droplets; these processes largely depend on the particle number and properties such as size, shape, and chemical composition [27,28]. For example, the particle size distribution, optical properties, and chemical composition of aerosols were analyzed during a severe haze–fog episode in the Yangtze River Delta on 16–27 November 2018 [13]. The radiation characteristics on haze, fog, and clean days were compared using longwave and shortwave radiation data measured at a 325 m meteorological tower in Beijing from October to December 2004 [14]. Although haze and fog are routinely observed at meteorological stations, considerable problems remain in haze and fog observations. Because fog and haze are frequently mixed, they are difficult to distinguish by operational observation [29]. Thus, comparison of the characteristics of haze, fog, and their transition or mixed episodes would be useful for better identifying haze and fog.

In this study, we analyzed the characteristics of turbulence and aerosol optical and radiative properties during haze and haze–fog mixed episodes on 22–27 January 2021, in Shenyang, Northeast China, using meteorological and aerosol observations. The reminder of this paper is organized as follows. Section 2 introduces the study area, observational data, and methods of this study. Section 3 compares the characteristics of turbulence and aerosol optical and radiative properties between a haze episode and a haze–fog mixed episode and discusses the impact of the PBL dynamic structure on the vertical distribution of aerosols. Conclusions are provided in Section 4.

2. Materials and Methods

2.1. Observational Site and Data

Shenyang is a provincial city in Northeast China and a key city in the Northeast Asia Economic Rim and Bohai Economic Rim (Figure 1a). Haze and haze–fog mixed episodes occur frequently in cold seasons in Shenyang because of high anthropogenic emissions, high relative humidity, and poor dispersion conditions [19]. Meteorological and aerosol data for the period of 22–27 January 2021 were obtained from two stations in the southern urban region of Shenyang (Figure 1b) to investigate the characteristics of turbulence and aerosol optical and radiative properties during wintertime haze and fog episodes. Table 1 summarizes the accuracy of the observational variables and information about the devices used in this study.

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Figure 1. (a) Geographic location of Shenyang and (b) locations of two observation sites in Shenyang.

Table 1. Observational variables and devices at the two stations in Shenyang.

| Station | Variable | Interval | Height (AGL) | Device | Accuracy/Resolution |
|---------|----------|----------|--------------|--------|---------------------|
| NWS     | Vis      | 1 h      | 2.8 m        | DQNI; Huayun, Beijing, China | ±10%, 10 m–10 km ± 15%, 10–35 km |
|         | WS, WD, $T_a$, RH, $P_a$ | 1 h      | 2 m          | ZQZ-CII Automatic weather station, Jiangsu Radio, Wuxi, China | Resolution: WS: 0.1 m s$^{-1}$, WD: 3°, $T_a$: 0.1 °C, RH: 0.1%, $P_a$: 0.1 hPa |
|         | WS, WD, $w$, $C_n^2$ | 5 min | 0–10 km      | TWP8-L, Beijing Metstar Radar Co. Ltd., Beijing, China | Resolution: WS: 0.2 m s$^{-1}$, 0–60 m s$^{-1}$; WD: 0.5°, 0–360° |
| IAE     | $\sigma_t$ and $\sigma_b$ | 5 min | 1 m          | Aurora3000, Ecotech, Melbourne, Australia | Resolution: $<0.3$ M m$^{-1}$, 0.25–2000 M m$^{-1}$ |
|         | $\sigma_{\text{ext}}$ | 5 min | 105 m–5 km   | AGHJ-I-LIDAR; Wuxi CAS Photonics, Wuxi, China | Accuracy: $<30\%$, 0–0.1 km$^{-1}$ $<10\%$, >0.1 km$^{-1}$ |
|         | $R_n$, DSW, USW, DLW, and ULW | 10 min | 60 m        | NR-Lite, Kipp & Zonen, Delft, The Netherlands | Sensitivity: $10 \mu$V/W/m$^2$ for 40 °C–80 °C |
|         | $u'$, $v'$, $w'$ | 10 Hz | 60 m | CSAT3, Campbell Scientific, Inc., Logan, UT, USA | Resolution: 1 mm s$^{-1}$ for $u'$ and $v'$, 0.5 mm s$^{-1}$ for $w'$ |

1 Full names for abbreviations and symbols in Table 1 are listed in Abbreviations part.

The national weather station (41.7352° N, 123.5100° E) provided conventional surface meteorological data, including hourly mean wind speed (WS), wind direction (WD), RH, air temperature ($T_a$), air pressure ($P_a$) at 2 m above ground level (AGL), and visibility (Vis) at 2.8 m. In addition, the aerosol backward/total scattering coefficients ($\sigma_t$ and $\sigma_b$) were measured by a three wavelength integrating nephelometer (Aurora 3000, Ecotech, Melbourne, Australia). An L-band wind profiler radar (TWP8-L; Beijing Metstar Radar, Beijing, China) simultaneously measured vertical profiles of WS, WD, vertical velocity ($w$), and the atmospheric structure constant of the refractive index ($C_n^2$), with a temporal resolution of 5 min and with 48 vertical layers ranging from 150 m to 9630 m. Among these radar-retrieved parameters, $C_n^2$ is an important parameter describing the turbulence in the atmosphere and can be expressed as follows [30,31]:

$$C_n^2(z) = a^2(K_H/K_M)L_0^{4/3}M^2$$  \hspace{1cm} (1)
where $a$ is an empirical constant, $z$ is observational height, $K_H$ and $K_M$ are the exchange coefficients for heat and momentum, $L_0$ is the turbulent mixing length that characterizes turbulent eddies, and $M$ is a function of the vertical gradient of air temperature or potential temperature. For the radar detection, $C_n^2$ is proportional to the backward-scattered energy of the radar to detect turbulence [32].

The atmospheric environment monitoring station was built on top of the Institute of Atmospheric Environment (IAE), China Meteorological Administration building. The IAE station (about 60 m high; 41.7388° N, 123.4256° E) provided hourly mean data for downward shortwave radiation (DSR), upward shortwave radiation (USR), downward longwave radiation (DLR), upward longwave radiation (ULR), and net radiation ($R_n$) with a four-component radiometer (NR-Lite; Kipp & Zonen, Delft, The Netherlands). Vertical distributions of the aerosol extinction coefficient ($\sigma_{ext}$) were measured with a ground-based LiDAR with a temporal resolution of 5 min and a vertical resolution of 7.5 m [19]. Turbulence data of wind speed (including $u'$, $v'$, and $w'$) were detected with a three-dimensional sonic anemometer–thermometer device (CSAT3; Campbell Scientific, Logan, UT, USA).

Moreover, to analyze air quality during the study period, hourly mean mass concentrations of PM$_{2.5}$ and PM$_{10}$ in Shenyang were obtained from the China National Environmental Monitoring Center.

2.2. Calculations

Turbulence kinetic energy (TKE) and friction velocity ($u_*$) were calculated using Equations (1) and (2), respectively:

$$TKE = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}),$$

$$u_* = \left[ (\overline{uw'})^2 + (\overline{vw'})^2 \right]^{1/4}$$

where $u'$, $v'$ and $w'$ are fluctuating values respect to the average values of the two horizontal wind speeds $u$, $v$ and vertical wind speed $w$.

2.3. Identification of Haze and Fog Events

Different criteria to identify haze and fog events were summarized in Quan et al. [16]. Here, we followed criteria mentioned in Hao et al. [18] that consider both meteorological indicators (i.e., Vis and RH) and the PM$_{2.5}$ concentration. Haze is defined as visibility less than 10 km with RH less than 80% or RH 80–95% and PM$_{2.5}$ concentrations higher than 75 µg m$^{-3}$. Fog is defined as visibility less than 1 km and RH higher than 95%. Some researchers have further divided fog into clean fog and polluted fog according to the PM$_{2.5}$ level [3]. In this study, a PM$_{2.5}$ concentration of 75 µg m$^{-3}$ was taken as the threshold value to distinguish polluted haze and clean haze. Other phenomena with visibility less than 10 km were considered as haze–fog mixed or transition episodes, including visibility within 1–10 km and RH higher than 95%, or visibility less than 10 km and PM$_{2.5}$ lower than or equal to 75 µg m$^{-3}$ (see Table 2).

| Classification | Sub-Classification | Visibility | Relative Humidity | PM$_{2.5}$ Concentration |
|----------------|--------------------|------------|-------------------|--------------------------|
| Haze           | <10 km             | <80%       | 80–95%            | >75 µg m$^{-3}$          |
|                | <10 km             | >80%       |                   |                          |
| Fog            | Clean fog           | <1 km      | >95%              | ≤75 µg m$^{-3}$          |
|                | Polluted fog        | <1 km      | >95%              | >75 µg m$^{-3}$          |
| Mixed episode  | 1–10 km            | >95%       |                   |                          |
|                | <10 km             | >95%       |                   | ≤75%                     |
3. Results

3.1. Overview of the Haze and Haze–Fog Mixed Episodes in Shenyang

A severe haze and fog event occurred on 22–27 January 2021 in Shenyang. Figure 2 shows the variation in surface PM concentrations and meteorological parameters during the study period. According to the criteria for haze and fog mentioned in Section 2.3, a haze episode occurred from 07:00 local time (LT) on 22 January to 21:00 LT on 25 January (lasting 87 h) and subsequently turned into a haze–fog mixed episode that ended at 12:00 LT on 27 January (lasting 39 h). Note that a polluted fog episode occurred from 23:00 LT on 25 January to 03:00 LT on 26 January, which was not separated from the haze–fog mixed episode because of its short duration (less than 1 h).

Figure 2. Variation in hourly mean (a) mass concentrations of PM$_{2.5}$ and PM$_{10}$, (b) atmospheric visibility and relative humidity, (c) wind speed and direction, and (d) air temperature and air pressure at 2 m height in Shenyang on 22–27 January 2021.

During the haze episode, Shenyang was first located in front of a high pressure system, and northeasterly winds prevailed at 900 hPa on 22 January (Figure 3a). As the high pressure system weakened, Shenyang was controlled by a saddle pressure pattern on 23 January (Figure 3b), and weak winds favored the aerosols’ accumulation in Shenyang (Figure 2a). On 24–25 January, the high pressure system over the Yellow Sea was enhanced, and southwesterly flows were dominant (Figure 3c,d). Because of the change of large-scale synoptic conditions, aerosol concentrations near the surface experienced obvious fluctuations, basically opposite to the fluctuation of wind speed (Figure 2a–c). The first concentration peaks of PM$_{2.5}$ and PM$_{10}$ occurred at 00:00 LT on 24 January, when they reached 248 and 316 µg m$^{-3}$, respectively. Correspondingly, visibility decreased to at least 1.6 km. PM$_{2.5}$ and PM$_{10}$ were higher (337 and 420 µg m$^{-3}$) during the night of 25 January, leading to lower visibility (close to 1 km).
After the haze episode, a low pressure system over Inner Mongolia was enhanced and moved continuously southward on 26 January (Figure 3e). Massive cold air intruded into Shenyang, resulting in a decrease in $T_a$ from 5 to 15 °C on 26–27 January (Figure 2d). The rapid cooling process caused strong surface radiation cooling at night and moist ambient conditions, contributing to the formation of a haze–fog mixed episode after 21:00 LT on 25 January. During the haze–fog episode, the PM concentration gradually decreased as the result of the scavenging effects of fog [33]. As the strong low pressure moved eastward, Shenyang was located in the transition zone of the northern low pressure system and a southern high pressure system (Figure 3f). Strong winds favored the dispersion of air pollutants and the cessation of the haze–fog mixed episode.

3.2. Different Characteristics of the Haze and Haze–Fog Mixed Episodes

3.2.1. Relationships among PM$_{2.5}$ Concentration, Visibility, and RH

We first compared the variation in the PM$_{2.5}$ concentration, visibility, and RH during the haze and haze–fog mixed episodes (Figure 2). During the haze episode, the RH showed obvious diurnal variation on most days (except for 22 January), with relatively higher values (about 80–90%) at nighttime and lower values (50–70%) during the daytime. The diurnal variation in visibility was weaker and opposite to the variation in RH. Compared to the haze episode, moister ambient conditions occurred during the haze–fog mixed episode, with RH >90% at night and >75% during the day. Visibility during the haze–fog mixed episode did not show obvious diurnal variation and remained below 1 km most of the time. The PM$_{2.5}$ concentration during the haze and haze–fog mixed episodes did not show diurnal variation, reflecting the complexity of PM$_{2.5}$ variation during air pollution events.

The relationships among visibility, PM$_{2.5}$ mass concentration, and RH during the two episodes are compared further in Figure 4. During the haze episode (Figure 4a), the reduction of visibility depended on the increase in both the RH and PM$_{2.5}$ concentration under a low PM$_{2.5}$ level, whereas the dependence of visibility on RH increased as the PM$_{2.5}$ concentration increased. For instance, when the PM$_{2.5}$ concentration was between 200 and 250 µg m$^{-3}$, visibility hardly varied as RH varied within a small range (85–90%), but it decreased rapidly from 7.5–8.0 km to 2–3 km as RH increased from less than 60%
to more than 80%. The dependence of visibility on RH was more obvious when the PM$_{2.5}$ concentration exceeded 300 µg m$^{-3}$. However, during the haze–fog mixed episode, poor visibility depended more on the RH and less on the PM$_{2.5}$ concentration (Figure 4b). Although PM$_{2.5}$ concentration decreased from 300 to 100 µg m$^{-3}$, visibility decreased and remained below 1 km because of high ambient RH. The lower PM$_{2.5}$ concentration but poorer visibility in the haze–fog mixed episode indicates that a haze–fog mixed episode can lead to worse visibility [27].

A negative exponential function between visibility and PM$_{2.5}$ concentration was observed in haze and haze–fog mixed events in Beijing, for example, by Han et al. [34] using daily averaged data from October 2013 to September 2014 and by Luan et al. [27] using hourly mean data in 2014 and 2015. A negative correlation between visibility and PM$_{2.5}$ concentration was also observed in this study, but the relationship was not an obvious exponential function. This is probably attributable to the limited time range of this study, resulting in fewer cases than in the results reported in these previous studies [27,34]. Li et al. [35] observed a negative exponential function between visibility and PM$_{2.5}$ concentration in Shenyang from 2014 to 2015 in all sky conditions, however, they did not distinguish fog and haze. Additional observations are needed to examine the quantitative relationships among visibility, PM$_{2.5}$ concentration, and RH during haze, fog, and their transition periods in different regions in China.

3.2.2. Optical Properties of the Haze and Haze–Fog Mixed Episodes

Aerosol optical properties, such as scattering and extinction, play a significant role in the Earth’s radiation budget, thereby influencing the atmospheric environment and climate. In particular, the scattering of light by atmospheric aerosols in the visible and near-visible spectral regions influences Earth’s climate through changing shortwave radiative forcing [36]. In this study, the aerosol extinction coefficient $\sigma_{\text{ext}}$ was measured by a ground-based LiDAR, which represents the loss of light per unit distance from scattering and absorption by particles and gases in the atmosphere. As parts of $\sigma_{\text{ext}}$, the total scattering coefficient $\sigma_t$ and the backward scattering coefficient $\sigma_b$ are simultaneously measured, representing the loss of light per unit distance from total and backward scattering by aerosols in the atmosphere, respectively. Here we examined the scattering properties of aerosols and their dependence on particle size and analyzed the vertical distribution of $\sigma_{\text{ext}}$ and its relation to PBL structure.

There were strong positive correlations between $\sigma_t$ and $\sigma_b$ and PM concentration (Figure 2a or Figure 5). As PM$_{2.5}$ reached its peak, $\sigma_t$ and $\sigma_b$ reached their maxima of 1.87 and 0.25 km$^{-1}$, respectively. The ratio $\sigma_b/\sigma_t$, which roughly represents the size
distribution of aerosols, was negatively correlated with the ratio PM$_{2.5}$/PM$_{10}$, with a correlation coefficient ($R$) of –0.57 during the haze and haze–fog mixed episodes (Figure 6). This means that $\sigma_b/\sigma_t$ increased with the increasing relative abundance of fine aerosols, which was consistent with theoretical expectations and previous observations [37,38]. On average, the proportion of fine aerosols increased by 7% in the haze–fog mixed episode compared to the haze episode, causing the ratio $\sigma_b/\sigma_t$ to decrease by approximately 8%. The increasing of fine aerosols during the haze–fog mixed episode was mainly due to hygroscopic growth of aerosols under high RH conditions and wet deposition owing to water vapor adhesion of coarse particles [39]. Previous studies in Xuzhou observed that coarse aerosols (PM$_{2.5}$–$^{10}$) decreased and aerosols with sizes of 1–1.6 $\mu$m dominated during the haze–fog mixed episode [39].

![Figure 5.](image-url)

Figure 5. Variation in hourly mean (a) aerosol total scattering coefficient ($\sigma_t$), (b) aerosol backward scattering coefficient ($\sigma_b$), and (c) the ratio of $\sigma_b$ to $\sigma_t$ at 525 nm observed at the IAE station, and (d) the ratio of mass concentrations of PM$_{2.5}$ to PM$_{10}$ in Shenyang during 22–27 January 2021.

In addition to surface aerosol optical properties, the vertical distribution of $\sigma_{ext}$ during the two episodes was also investigated based on LiDAR observations (Figure 7). Aerosols were mostly concentrated at altitudes lower than 0.5 km during the haze episode, but another aerosol layer appeared between 0.6–0.9 km after 15:00 LT on 22 January, with the maximum $\sigma_{ext}$ higher than 3 km$^{-1}$ (Figure 7a). The elevated aerosol layer was probably related to the aerosol transport from upstream polluted areas by strong northerly winds at the upper levels. Most northern regions in the Northeast China Plain were suffering from PM$_{2.5}$ pollution on 22 January (see the distribution of near real-time PM$_{2.5}$ concentrations on the website of Tracking Air Pollution in China, http://tapdata.org.cn/?page_id=523&lang=en, accessed on 1 October 2021). These transported aerosols were first trapped in the residual layer because of weak vertical mixing during the night, and then began to mix vertically toward the surface with the development of convective turbulence after sunrise, leading to an increase in surface PM concentration. Similar phenomena have been reported in other haze events in Shenyang [19,20].
3.2.3. Radiation Effects during the Haze and Haze–Fog Mixed Episodes

Radiation effects differed between the haze and haze–fog mixed episodes (Figure 8). First, without the cloud effects, the daytime maximum downward short radiation (DSR) was higher during the haze episode (485 and 434 W m\(^{-2}\) on 23 and 24 January, respectively) during the haze–fog mixed episode, the aerosol-rich layer was located below 0.4 km and at times even below 0.2 km, corresponding to the periods with Vis < 1 km (Figure 7b). This means that the vertical mixing process in the PBL was weaker during the haze–fog mixed episode than during the haze episode, and aerosols and fog droplets tended to accumulate in a shallower PBL. In Shenyang, the average PBL height during fog episodes from 2009 to 2012 was 379.5 ± 174.3 m, which was lower than the average height on haze days (467.7 ± 187.6 m) and clean days (585.5 ± 203.5 m) [17].
than during the haze–fog mixed episode (359 W m\(^{-2}\) on 26 January). Furthermore, the DSR during the haze episode showed a smoother diurnal variation than the DSR during the haze–fog mixed episode. The increase in DSR was delayed from 06:00 to 12:00 LT on 26 January because of the occurrence of fog (Figure 8a).

**Figure 8.** Variation in (a) downward shortwave radiation (DSR) and upward shortwave radiation (USR), (b) downward longwave radiation (DLR) and upward longwave radiation (ULR), and (c) net radiation (\(R_n\)) observed at the IAE station in Shenyang during 22–27 January 2021.

Second, the upward longwave radiation (ULR) was much higher than the downward longwave radiation (DLR) at the surface during the haze episode, and the DLR remained lower than 250 W m\(^{-2}\); however, as fog formed from the night of 25 January to the early morning of 26 January, the DLR increased significantly and almost equaled the ULR (about 320 W m\(^{-2}\)) and the fluctuation of the DLR was stronger during the haze–fog mixed episode (Figure 8b). This could be a useful indicator for identifying haze and fog. The ULR depends on the variation in surface temperature, whereas the DLR depends mainly on the sky condition and air temperature. The DLR is typically lowest in clear sky conditions, higher on haze days, and highest in fog. The increase in the DLR during the haze–fog mixed episode indicated that the temperature within the fog layer almost remained in balance [14] because the vertical gradient of air temperature was weak within the fog layer owing to weak thermal dynamic turbulence, which made the stratification within the fog layer almost near-neutral.

Third, net radiation, or the sum of net shortwave radiation and net longwave radiation, can reflect the atmospheric radiation balance within the near-surface layer. The values of \(R_n\) at night during the haze episode remained negative (approximately \(-100\) W m\(^{-2}\)), which indicated radiation cooling of the surface at night, whereas during the haze–fog mixed episode the \(R_n\) increased to about \(-10\) W m\(^{-2}\) at night. The different radiation properties of the aerosols/fog droplets could modify the radiation balance and change the heating and cooling rates of the air layer and possibly the PBL structure [14].

3.2.4. Turbulence Characteristics during the Haze and Haze–Fog Mixed Episodes

The formation and evolution of haze and fog events were affected by turbulence activity in the PBL. Before the haze episode, the TKE and \(u^*\) were greater than 4.5 m\(^2\) s\(^{-2}\) and 0.6 m s\(^{-1}\), but they decreased gradually to less than 1.0 m\(^2\) s\(^{-2}\) and 0.2 m s\(^{-1}\) during the haze episode (Figure 9a). The weakened mechanical turbulence activity favored the local accumulation of aerosols, causing the PM\(_{2.5}\) concentration to increase from 49 to 248 µg m\(^{-3}\). There was a negative correlation between PM\(_{2.5}\) concentration and \(u^*\) during
both the haze and haze–fog mixed episodes, with \( R \) values of \(-0.44 \) and \(-0.31 \), respectively (Figure 10a). The diurnal variation in sensible heat flux was not clear during the pollution event, which had lower daytime values of sensible heat flux when the PM concentration increased (Figure 9b or Figure 10b). The variation range of the latent heat flux during the haze–fog mixed episode was larger than the range during the haze episode. The values of latent heat flux generally were below \( 50 \, \text{W m}^{-2} \) during the haze episode, but they exceeded \( 100 \, \text{W m}^{-2} \) during the haze–fog mixed episode (Figure 9c or Figure 10c). Latent heat is the heat transfer from the vapor phase transition. The increase and upward transport of latent heat flux during the fog episode was also observed in other cities, such as in Tianjin [18], meaning strong heat transfer caused by enhanced vapor phase transition occurs during fog episodes.

![Figure 9](image9.png)

**Figure 9.** Variation in hourly mean (a) friction velocity \( (u^*) \) and turbulent kinetic energy (TKE), (b) sensible heat flux \( (H_s) \), and (c) latent heat flux \( (LE) \) observed at the IAE station in Shenyang during 22–27 January 2021.

![Figure 10](image10.png)

**Figure 10.** Relationship of hourly mean \( \text{PM}_{2.5} \) concentration to (a) friction velocity, (b) sensible heat flux, and (c) latent heat flux during haze and haze–fog mixed episodes in Shenyang.

The variation in the atmospheric structure constant of refractive index \( C_n^2 \), WS, and vertical friction \( \nu \) near the surface was similar to the variation in \( u^* \) (Figure 11). At higher altitudes, the variation in \( C_n^2 \) was related to the vertical distribution and transport of aerosols. For instance, the \( C_n^2 \) at altitudes above \( 0.5 \, \text{km} \) increased in the afternoon of 22 January, contributing to the formation of the elevated aerosol layer at the same altitudes (Figure 7a). Around noon on 24 January, the WS within 1.5–2 km increased and then the strong momentum flux began to transport downward, reaching the surface during the
night of 24 January and causing the increase in WS and $C_n^2$ below 1 km and the dispersion of aerosols near the surface (the PM$_{2.5}$ concentration declined from 248 to 100 µg m$^{-3}$). Thereafter, the WS decreased at all heights on 25 January, and the PM$_{2.5}$ concentration increased gradually to its peak value.

![Figure 11. Height-time crossing sections of (a) wind speed, (b) wind direction, (c) vertical wind speed ($w$), and (d) refractive rate log($C_n^2$) observed by wind radar in Shenyang during 22–27 January 2021.](image)

The $C_n^2$ values at all levels were distinctly lower during the haze–fog mixed episode than during the haze episode, which means that turbulence in the PBL was weaker. From 12:00 LT on 27 January, the $C_n^2$ values increased significantly compared to the period before (with the order of its magnitude increasing from about $10^{-40}$ to above $10^{-35}$), and the strong turbulence activity contributed to the cessation of this air pollution event.

### 4. Conclusions

We analyzed the characteristics of turbulence and aerosol optical and radiative properties during haze and haze–fog mixed episodes in Shenyang during severe haze and fog events on 22–27 January 2021 using meteorological and aerosol observations. During the haze episode (from 07:00 LT on 22 January to 21:00 LT on 25 January), the hourly mean PM$_{2.5}$ concentration reached a maximum of 337 µg m$^{-3}$ and the visibility decreased to 1.6 km. The reduction of visibility depended on the increases in both RH and PM$_{2.5}$ concentration under low PM$_{2.5}$-level conditions. Although the PM$_{2.5}$ concentration gradually decreased during the haze–fog mixed episode (from 21:00 LT on 25 January to 12:00 LT on 27 January) owing to the scavenging effect of fog, visibility mostly remained below 1 km because of higher ambient RH (>90%). Poor visibility depended more on the RH and less on the PM$_{2.5}$ concentration during the haze–fog mixed episode.

Both backward and total scattering coefficients $\sigma_b$ and $\sigma_t$ correlated positively with the PM$_{2.5}$ concentration during the two episodes. The ratio of $\sigma_b/\sigma_t$ increased by 8% on average during the haze–fog mixed episode because of the increasing proportion of fine aerosols (the ratio of PM$_{2.5}$/PM$_{10}$ increased by 7%). The downward shortwave radiation was weaker during the haze–fog mixed episode than during the haze episode, and the
upward longwave radiation increased to the values of the downward longwave radiation as fog formed, which could function as a useful indicator for distinguishing haze and fog.

During both episodes, the turbulent kinetic energy and friction velocity remained at low levels, much lower than before the pollution event. The values of latent heat flux generally were below 50 W m$^{-2}$ during the haze episode, whereas they could exceed 100 W m$^{-2}$ during the haze–fog mixed episode owing to high RH conditions. The PBL dynamic structure affected the vertical distribution of aerosols/fog droplets. Two aerosol layers, located at altitudes below 0.5 km and above 0.6 km, respectively, appeared during the haze episode. The latter was probably related to the transport of aerosols from upstream polluted areas because of strong upper-level turbulence. The elevated aerosol layer first overlaid the stable boundary layer during the night on 22 January and then began to mix vertically after sunrise because of convective turbulence, leading to higher aerosol concentrations the next day. During the haze–fog mixed episode, aerosols and fog droplets were mostly trapped in a shallower PBL within a height of 0.2–0.4 km because of weaker turbulence. This study facilitates understanding of the different characteristics of haze and fog events and the impact of the PBL on these events. It also provides reference for better identification of haze and fog.

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**Abbreviations**

List of abbreviations and symbols in Table 1 and elsewhere in this paper.

| Symbols | Full Name                        |
|---------|----------------------------------|
| Vis     | visibility                       |
| WS      | wind speed                       |
| WD      | wind direction                   |
| $T_a$   | air temperature                  |
| RH      | relative humidity                |
| $P_a$   | air pressure                     |
| $w$     | vertical velocity                |
| $C_n^2$ | atmospheric structure constant of refractive index |
| $\sigma_{\text{ext}}$ | aerosol extinction coefficient |
| $\sigma_t$ | aerosol total scattering coefficient |
| $\sigma_b$ | aerosol backward scattering coefficient |
| $R_n$  | net radiation                    |
| DSR     | downward shortwave radiation     |
| USR     | upward shortwave radiation       |
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