Haze-day Trends from 2013 to 2020 and Analysis of Spatiotemporal Characteristics of a Haze Process in Ningbo, China

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Abstract. Air quality in Ningbo continues to improve with a constant decrease in the PM\textsubscript{2.5} concentration. However, pollution levels occasionally increase during autumn and winter. To understand the regional and seasonal distributions and the interannual variation during haze days, we analyzed the haze monitoring data from 2013 to 2020 and the haze weather process during January 18–19, 2016. Our results showed a downward trend in the major pollutant concentrations. High PM\textsubscript{2.5} concentrations persist in certain areas of Ningbo during winter owing to seasonal haze conditions. However, the annual number of haze days has decreased between 2013 and 2020. Regional variations in pollutant concentrations appear mainly in winter, especially in December and January. The observed concentrations were higher in the north and west, and lower in the south and east. The haze process during January 18–19, 2016, occurred within a height of 0–1.5 km, with high PM\textsubscript{2.5} concentrations mainly occurring as small and spherical particles. A higher relative humidity, temperature drop, and stable weather assist in accumulating and sinking pollutants, which cause long-term effects and render diffusion difficult. Although recent national initiatives have been effective, the air quality in northern Ningbo requires further improvement during autumn and winter.

Keywords. Haze-days, air quality, PM\textsubscript{2.5} concentrations, seasonal variations, Ningbo.

1. Introduction
Haze has detrimental effects on human health, agricultural production, transportation, and economic development. Furthermore, atmospheric particulate matter (PM) is a major air contaminant [1–3]. Considerable research has been conducted over the last decade on the diffusion of air pollutants in the atmosphere [4–7]. Fine particulate matter (PM\textsubscript{2.5}), which refers to particles in the atmosphere that exhibit a diameter of 2.5 µm or less, is the primary air pollutant in China [8].

In China, air quality in the Ningbo urban area of eastern Zhejiang Province has been improving steadily in recent years, and the area was ranked among cities with good ambient air quality in 2018. The number of annual haze days has dropped, and the general trend in air quality has been increasing annually. Moreover, high air pollution days were relatively rare after 2014. However, high air pollution levels were experienced on December 7, 2013, with PM\textsubscript{10} concentrations well above 500 (AQI=500). At the time, the Environmental Bureau and the Meteorology Bureau jointly issued the first red warning for heavy pollution [9].
The improved local conditions could be attributed not only to an increase in awareness about environmental protection but also to the formulation of the PM$_{2.5}$ pollution control policy by the government [10, 11]. Since the implementation of the “Ten Atmospheric Items” and the “Three-Year Action Plan for Winning the Blue Sky War” in 2013 [12], the air quality in Ningbo has improved steadily, exceeding the class ii limit values (35 µg/m$^3$) of the National Ambient Air Quality Standard (NAAQS) over the last two years. These government initiatives included adjustment of industrial, energy, and transportation structures as well as treatment of both the symptoms and root causes of five major pollution sources, namely industrial emissions, coal burning, dust, vehicle emissions, and non-point source pollution [13].

The annual number of haze days from 2013 to 2020 was 138, 118, 74, 67, 38, 25, 29, and 15, respectively. Compared with that in 2015, the number of pollution days over the past two years has decreased significantly. The number of haze days in 2018 was 113, less than that in 2013; this was two years before the area featured in the list of cities with ambient air quality standards. Over the last decade, abundant research has been conducted on the seasonal variations in haze at Ningbo [14-16], whereas insignificant investigation has been conducted on regional variations.

Despite government interventions, seasonal and regional changes in pollutant concentrations persist. High pollution levels are observed mostly in winter, with dangerous haze conditions and high PM$_{2.5}$ concentrations.

Air pollution is related closely to meteorological conditions. A case in point is the persistent haze process that occurred at Ningbo during January 18–19, 2016. In this study, we aimed to analyze the haze monitoring data from 2013 to 2020 and the haze weather process during January 18–19, 2016, to understand the regional and seasonal distributions and the interannual variation during haze days.

2. Materials and Methods

2.1. Sectoral Cooperation

To manage haze weather conditions, Ningbo Meteorological Bureau and Ningbo Municipal Bureau of Ecology and Environment (formerly known as Ningbo Environmental Protection) have implemented a series of measures, such as coordinated layout, real-time monitoring, information sharing, and joint media releases. The meteorological department has set up 10 atmospheric component monitoring stations in various districts (counties and cities) to monitor PM$_{2.5}$, as shown in figure 1. At the same time, the vertical distributions of pollutants and optical characteristics are monitored continuously using atmospheric remote sensing technologies, such as aerosol lidar [17–20]. In 2013, cooperation with environmental protection authorities was strengthened in response to the growing haze threat, and cooperation agreements were signed to enable the sharing of monitoring data in real time from 27 monitoring sites. Monitoring data are uploaded to the data center every hour through optical fiber technology.

Figure 1. Map of the monitoring stations for PM and Lidar in Ningbo (CX: CiXi; YY: YuYao; ZH: ZhenHai; HS: HaiShu; BL: BeiLun; YZ: YinZhou; FH: FengHua; NH: NingHai; XS: XiangShang).
Haze days in Ningbo occur mainly in winter, with the highest occurrences in December and January; however, fewer haze days are observed in summer. For example, at Yuyao County in 2016, there were 39, 6, 3, and 22 haze days each quarter, respectively. In January and December, there were 15 haze days. From 2013 to 2020, the number of haze days decreased annually, and the number of urban haze days showed a significant downward trend (figure 2). The highest annual number of haze days was 138 (2013) and the lowest was 15 (2020).

The annual number of haze days in the Ningbo urban areas and districts (counties and cities) from 2014 to 2020 is shown in table 1 and figure 3. The seasonal trends were similar to those observed in urban areas; however, they were significantly lower than those observed before 2014. The distribution of haze days over this region is typically “north more and south less, west more and east less,” with more such days in Cixi and Yuyao and less in Beilun. Over the past three years, except for Cixi, Yuyao, Fenghua, and Xiangshan, the annual haze days in other counties were all within 40 d. Since the launch of the three-year action plan of “five gas (coal burning flue gas, industrial waste gas, automobile exhaust gas, urban dust, and oil fume) co-governance” in Zhejiang Province and the “blue Sky Defense war” in Ningbo City in 2015, the effects of these government initiatives have been evident with the air quality improving significantly. Over the last five years, more than 40 haze days occurred only in Cixi and Yuyao.

### Table 1. Annual number of haze days in urban and county (city, district) areas in 2014–2020.

| Year | Urban | CX | YY | ZH | YZ | BL | FH | XS | NH |
|------|-------|----|----|----|----|----|----|----|----|
| 2014 | 118   | 115| 144| 129| 118| 31 | 38 | 73 | 67 |
| 2015 | 74    | 95 | 85 | 68 | 74 | 12 | 53 | 83 | 53 |
| 2016 | 67    | 87 | 43 | 49 | 67 | 19 | 37 | 58 | 28 |
| 2017 | 38    | 71 | 44 | 29 | 33 | 12 | 9  | 46 | 4  |
| 2018 | 25    | 42 | 34 | 18 | 25 | 6  | 35 | 25 | 22 |
| 2019 | 29    | 29 | 70 | 20 | 28 | 33 | 59 | 41 | 35 |
| 2020 | 15    | 47 | 62 | 13 | 32 | 25 | 40 | 27 | 34 |
| 2016–2020 Avg | 35 | 55 | 51 | 26 | 37 | 19 | 36 | 39 | 25 |

Note: “Five gas co-governance” was proposed in 2015, and the average value was calculated from 2016. CX: CiXi; YY: YuYao; ZH: ZhenHai; YZ: YinZhou; BL: BeiLun; FH: FengHua; XS: XiangShang; NH: NingHai.
2.2. Methods and Data Sources

The Ministry of Environmental Protection of the State defined haze pollution in 2014 as follows: A haze pollution day refers to an air pollution episode in which the average concentration of fine particulate matter (PM$_{2.5}$) becomes greater than 75 µg/m$^3$, while the visibility is reduced to less than 5.0 km for at least 6 h, owing to the increase in the concentration of fine particles in the air. Haze Identification for Meteorological Observation Identification Standard (GB/T 36542-2018) came into inception on July 13, 2018, thereby setting the criteria for haze and haze days. These criteria include: abundant atmospheric aerosol particles of sizes below a few microns, which limit horizontal visibility to less than 10.0 km; general cloudy weather conditions; and haze lasting 6 h or more over one day. The Observation and Forecasting Levels of Haze standard (Standard QX/T 113-2010) defines four types of haze based on the extent of visibility, as presented in table 2.

| Level     | Extent of visibility          |
|-----------|-------------------------------|
| Slight    | $5.0 \text{ km} \leq V < 10 \text{ km}$ |
| Mild      | $3.0 \text{ km} \leq V < 5.0 \text{ km}$ |
| Moderate  | $2.0 \text{ km} \leq V < 3.0 \text{ km}$ |
| Severe    | $V < 2.0 \text{ km}$          |

The data we used in this research were derived from the data center of the Ningbo Meteorological Bureau. The statistical span was 2014–2020, and the statistical data were obtained from the environmental monitoring stations of the Ningbo Municipal Bureau of Ecology and Environment. Haze events occurred locally on January 18 and 19, 2016, and the relevant analysis data included wind speed (WS), rainfall (R), visibility (Vi), and relative humidity (RH) from Zhenhai (Station No 58561) and FH (No 58565) National Monitoring Station. In addition, PM data were obtained from atmospheric composition monitoring stations. The extinction coefficient and depolarization ratio data were derived from dual wavelength lidar measurements at 532 nm and 355 nm (performed once every 5 min at a spatial resolution of 7.5 m), which afforded high spatial resolution and a continuous measurement ability [21, 22] (Zhongke Optoelectronics, China).
3. Results and Discussion

3.1. Spatiotemporal Distribution and Trends
Weather conditions from January 17 to 19, 2016, were not conducive to the diffusion of pollutants, owing to the effects of cold air and input pollutants. Most regions of Ningbo experienced severe haze weather, except for the eastern coast. The conditions (presented in Table 3) on January 18 were more severe compared with those on the following day. The daily average PM$_{2.5}$ concentration in Ningbo City on January 18 was 126.1 (for 24 h); however, on January 19, it was 95.5 (for 18 h). The most severely affected area was CX, which is located in the north of Ningbo. The local PM$_{2.5}$ value was 147.4 on January 18 (for 24 h) and 95.5 on January 19 (for 24 h).

| Date | CX | YY | ZH | BL | YZ | FH | NH | XS |
|------|----|----|----|----|----|----|----|----|
| D18  | 147.4 | 126.3 | 118.1 | 60.1 | 126.1 | 125.4 | 113.3 | 81.6 |
| D19  | 107.9 | 93 | 89.8 | 43.6 | 95.5 | 101.4 | 106.7 | 66.5 |

| Haze grade | D18 | Severe | Moderate | Slight | Normal | Mild | Slight | Normal | Slight | Normal | Slight |
|------------|-----|--------|----------|--------|--------|------|--------|--------|--------|--------|--------|
| Severe     |     |        |          |        |        |      |        |        |        |        |        |
| D19        | 2.4 | 3.2 | 2.8 | 2.4 | 4.1 | 3 | 2.5 | 2.1 |
| D19        | 1.8 | 2.8 | 2.8 | 2.4 | 3.8 | 3.5 | 3.5 | 1.2 |
| Avg WS (m/s) | D18 | 4.87 | 4.84 | 5.01 | 5.47 | 5.23 | 5.23 | 4.44 | 6.01 |
| D19 | 3.80 | 1.48 | 3.96 | 1.83 | 4.07 | 4.07 | 2.68 | 4.10 |
| Avg T (°C) | D18 | 1.5 | 2.4 | 1.9 | 3.0 | 3.0 | 3.0 | 2.2 | 3.8 |
| D19 | -1.5 | -1.2 | -3.2 | -1.4 | -0.7 | -0.9 | -1.2 | -1.2 |
| T$_{min}$ (°C) | D18 | (23:50) | (23:33) | (23:49) | (23:50) | (23:54) | (23:55) | (6:43) | (23:49) |
| D19 | (23:42) | (23:05) | (23:45) | (23:49) | (23:35) | (23:45) | (23:53) | (23:42) |
| V$_{min}$ (m) | D18 | 1130 | 2883 | 1006 | 4210 | 2705 | 2106 | 2240 | 2410 |
| D19 | 3159 | 5675 | 2197 | 9367 | 4209 | 3543 | 3387 | 3285 |

WS: wind speed; Vi: visibility.

Analysis of the situation field at 500 hPa, as shown in figure 4(a–c), indicated that an East Asia trough was established over the central and eastern parts of China from January 17 to 19 (this was a stable situation) and that a steady stream of cold air was spreading south. As the bottom of the trough was located over Zhejiang Province, its influence was already weak when the cold air reached Ningbo. The situation field at 925 hPa, shown in figure 4(d–f), indicated that weak cold air from the bottom started to influence Ningbo during the day of January 17; this phenomenon ended on the night of January 19. Under the influence of the weak cold air, the WS at the Ningbo surface was low, with the average daily WS being 2–4 m/s in most areas on January 18 and 19. Overall, the air pollution diffusion conditions in Ningbo were poor. During January 18 and 19, the conditions during pollutant imports from North China to the south of the Yangtze River were consistent with north or northwest airflow. The pollutants accumulating in Ningbo between January 18 and 19 were derived from the area north of the Yangtze River, which is heavily polluted and experiences frequent northerly currents from the northern pollutant transport channel to the south. The temperature in Ningbo started to drop on January 18 (table 3), with the average daily temperature decreasing from approximately 5 °C to approximately 3 °C on January 19; the minimum temperature was −1 °C at 23:00. As the temperature dropped, the air density increased and a sinking motion emerged, which facilitated the increase in pollutant concentration as well as the sinking of pollutants.
In summary, from January 18 to 19, 2016, severe pollution was observed in the region. The leading causes of this condition were the transit inputs to the pollution in the north, adverse weather conditions, high PM$_{2.5}$ concentrations in most of Ningbo, and high levels of haze (especially in the CX area).

![Figure 4](image_url)

**Figure 4.** Situation fields at 500 hPa: (a) January 17, 20:00; (b) January 18, 08:00; (c) January 19, 20:00. Situation fields at 925 hPa: (d) January 17, 20:00; (e) January 18, 08:00; (f) January 19, 20:00.

### 3.2. Analysis of Meteorological Elements

Haze can be determined preliminarily by employing Vi and RH data combined with surface meteorological elements. When haze occurs, the Vi drops below 10 km and the RH becomes lower than 90%. We analyzed precipitation and WS values under haze weather conditions. For the persistent haze event over the Ningbo urban area during January 18 and 19, 2016, we selected surface meteorological data from FH (Station No 58565) and Zhenhai (Station No 58561) for analyses of the haze process (figure 5 and 6).

**Wind speed.**

During the haze event, WS was low and the accumulated particulate matter could not diffuse, resulting in reduced Vi and exacerbation of the haze conditions. However, as the WS increased, the particles were blown away easily, leading to an increase in the Vi and alleviation of the haze conditions. Wind speed is negatively correlated with particle concentration, and low wind speeds cannot diffuse particles easily, thereby leading to persistent haze conditions. With static winds or breezes, fine particles easily accumulate on the ground and play a crucial role in haze formation. Figure 5 shows the variation in WS from 14:00 on January 17 to 20:00 on January 20 at stations 58565 and 58561. The WS was approximately 3 m/s, which indicated light, wind or breeze, and gentle winds. The observed low WS at stations 58565 and 58561 contributed to prolonging the haze conditions.
3.3. Relative Humidity and Visibility
From 14:00 on January 17 to 20:00 on January 20, stations 58565 and 58561 experienced no rainfall. However, atmospheric humidity remained high because of the recent rain, and persisted at approximately 90% at 06:00 on January 18. As shown in Figure 6, overall, similar trends in Vi and RH changes were observed at stations 58565 and 58561. From 0:00 on January 18 to 08:30 on January 19, the RH was over 60%. This condition is beneficial to the moisture absorption and sinking of atmospheric particles, and conducive to the formation and persistence of haze for more than 30 h. Such conditions led to a Vi of less than 10 km for an extended duration, with the lowest value being 3 km. From 08:30 to 16:30 on January 19, the RH decreased from 70% to 30%, the haze abated, and the Vi increased to more than 10 km. However, as the humidity rose again, the haze reemerged and Vi decreased again. After 18:10, the RH measured at Station 58565 was below 70%, the haze continued to emerge, and Vi decreased continuously; however, the RH measured at Station 58561 increased continuously to more than 90%.

![Figure 5. Wind speed at stations 58565 (a) and 58561 (b) from 14:00 on January 17 to 20:00 on January 20.](image-url)
Figure 6. Relative humidity, visibility, and concentration of PM$_{2.5}$ at stations 58565 (a) and 58561 (b), PM$_{2.5}$, PM$_{1.0}$, and PM$_{1.0}$/PM$_{2.5}$ at stations 58565 (c) and 58561 (d) from 14:00 on January 17 to 20:00 on January 20.
3.4. Temporal Variations in PM$_{2.5}$.

Temporal variations in PM$_{2.5}$ concentration at stations 58565 and 58561 from 0:00 on January 18 to 0:00 on January 20 are shown in figure 6a–b.

Analyses of the change trend in pollutant concentrations have shown that a RH higher than 60% is conducive to the accumulation of haze, thereby leading to poor visibility. However, a RH below 60% decreases accumulation and increases Vi rapidly. In Ningbo, the maximum measured PM$_{2.5}$ concentration exceeded 180 µg/m$^3$ on January 18. From 0:00 on January 18 to 08:30 on January 19, the PM$_{2.5}$ concentration remained above 100 µg/m$^3$. The haze pollution grade on January 19 was 1 to 2 levels lower than that on January 18, as shown in table 3. Visibility was below 6 km over the same period, as shown in figure 6a–b; this indicated that a higher humidity is beneficial to moisture absorption and subsidence of atmospheric particles, which easily leads to reduced Vi. From 08:30 to 15:00 on January 19, the PM concentration decreased to approximately 60 µg/m$^3$, Vi continued to rise rapidly, and humidity dropped sharply. After 15:00, the concentration of PM increased rapidly and the haze worsened, with Vi declining rapidly and relative humidity rising continuously (figure 6a–b). Such a significant increase in aerosol particle concentrations could lead to a rapid decline in Vi. However, in this particular haze process, an increase in atmospheric RH was a redeeming factor.

Figure 6c–d shows, in this case, that PM$_{2.5}$ and PM$_{1.0}$ concentrations seem to follow the same temporal pattern, and both PM$_{1.0}$/PM$_{2.5}$ ratios were around 0.9. Both PM$_{2.5}$ and PM$_{1.0}$ concentrations were high, and the haze process was dominated by fine particles.

3.5. Optical Characteristics of Haze.

![Image](image_url)  
**Figure 7.** Extinction coefficient at 532 nm (a), depolarized coefficient at 532 nm (b), and extinction coefficient at 355 nm (c) at Station 58565 between January 18 and 19, 2016.
We analyzed the spatial distribution and variation characteristics of aerosols based on the lidar data of PM at Station 58565 in the FH area from January 18 to 19, 2016. Particulate lidar measurements were performed using two wavelengths (532 nm and 355 nm), which exhibit different sensitivities for the detection of large and small particles.

At 14:00 on January 17, as the rain stopped, the influence of the weak cold airflow started. Changes in the 532 nm extinction coefficient (figure 7a) indicated that the lower layer of pollutants started to affect conditions on the ground from 18:40; that is, the vertical distribution of pollutants ranged from 0 to 1 km, with a maximum value of 1.5 km. These conditions are in accordance with the fact that atmospheric pollutants are concentrated mainly within the planetary boundary layer (PBL); that is, the atmospheric layer, which is 1−2 km above the ground [23]. The extinction coefficient of pollutants was 0.4 km$^{-1}$, and the depolarization coefficient was 0.005. When a boundary layer depression existed between 21:30 and 23:00, a polluted air mass was observed (0.5–1 km), the concentration of pollutants near the ground increased, humidity exceeded 80%, and the moisture absorption increase. These factors led to a continuous decline in $V_i$.

The extinction coefficients associated with the 532 nm and 355 nm wavelengths of the polluted air mass were both approximately 1.6 km$^{-1}$, thereby indicating high humidity and severe pollution (figure 6a). Moreover, the $V_i$ was less than 4 km at 03:00 on January 18. With the rapid decrease in humidity, fine particles were observed to be the main pollutants in the vertical spatial range of 1 km between 0:00 and 03:00 on January 18. The extinction coefficient intensity at 355 nm was approximately 0.8 km$^{-1}$ near the ground; however, it was between 1.5 and 2 km$^{-1}$ within the vertical spatial range of 0.4 to 1.3 km. At the same time, the decrease in humidity was not sufficient for large particles to accumulate. The intensity of the 532 nm extinction coefficient was approximately 0.8 km$^{-1}$ at the same height. However, the concentration of large particulate pollutants generated by moisture absorption near the ground was slightly higher than that of the fine particulate pollutants. The intensity of the 532 nm extinction coefficient was between 0.3 and 0.4 km$^{-1}$ near the ground, whereas the intensity of the 355 nm extinction coefficient was between 0.2 and 0.3 km$^{-1}$. As shown in Figure 6a, the concentration of PM$_{2.5}$ was 110 µg/m$^3$. Figure 7a shows that the pollution intensified after 07:00 on January 18 and lasted for more than 16 h. As the pollutants sank, the extinction coefficient intensity of the 532 nm wavelength in the entire vertical spatial range was generally above 1.2 km$^{-1}$ due to the humidity exceeding 65% (figure 6a), which is consistent with the reflection of the forward-scattered visibility. $V_i$ was maintained within 5 km, and the corresponding concentration of PM$_{2.5}$ was 130−150 µg/m$^3$. The extinction coefficient at 355 nm was similar to that at 532 nm, but its intensity was slightly lower. The results showed that fine particles were evidently deposited; however, no secondary moisture absorption occurred to form large particles. Consequently, the extinction coefficient at 532 nm remained at approximately 0.4 km$^{-1}$.

As shown in figure 6, after 02:00 on January 19, the humidity dropped rapidly from 70% to 32% at 15:36, and the corresponding $V_i$ increased rapidly from 3,977 km to 17,831 km. As shown in figure 7(c), the concentration of fine particle pollutants was relatively high; it was approximately 1.2 km$^{-1}$ at 1 km height, approximately 0.3 km$^{-1}$ near the ground (with the concentration of large particle pollutants being small), approximately 0.4 km$^{-1}$ over the entire height range, and approximately 0.2 km$^{-1}$ near the ground. These results indicated weakened input pollution. After the humidity decreased and the secondary settlement of pollutants disappeared, there were fewer pollutants near the ground. Furthermore, the extinction coefficient gradually decreased, and the $V_i$ started increasing rapidly. After 17:00 on January 19, the boundary layer had depressed and the pollution reappeared (mainly fine particles). After 14:00, the degree of depolarization at 532 nm was 0.03–0.04 near the ground. Figure 7(b) shows that the depolarization coefficient of the entire process was within 0.04, indicating that the pollutants were almost spherical. A large proportion of the pollutants transported from January 17 to 19 comprised mainly spherical fine particles. The intensities of the 532 nm extinction coefficient and 355 nm extinction coefficient were both in the range of 1−3 km$^{-1}$, indicating severe pollution and that the accumulation of aerosol particles was greater under humid conditions. Before 06:00 on January 19,
when the humidity was high, the particles exhibited hygroscopic growth and secondary generation. After 08:30 on January 19, the humidity dropped rapidly, the degree of air pollution declined, and fine particles were present at high altitudes.

**Figure 8.** The extinction coefficient at 532 nm (a), depolarized coefficient at 532 nm (b), and extinction coefficient at 355 nm (c) in ZH area between January 18 and 19, 2016.

During the period of influence, variation in the extinction coefficient in the Zhenhai area was similar to that in the FH area. Figures 8(a) and (c) show the variations in the extinction coefficient at Station 58561, thereby demonstrating that the aerosol particles were concentrated mainly below 1.5 km. At 14:00 on January 17, the rain stopped and the pollutants absorbed moisture and subsequently subsided. The influence range was similar to that at Station 58565 (within 1.5 km). Vi was below 4 km; the extinction coefficient of pollutants was 2.00 km\(^{-1}\) near the ground and 1 km\(^{-1}\) in the middle, with the depolarization coefficient being 0.04. After moisture absorption, the concentration of aerosols near the surface increased gradually to 0.5 km until 21:00; the extinction coefficient of 532 nm was approximately 2 km\(^{-1}\) in the range of 0.2–0.5 km, and 1 km\(^{-1}\) in the range of 0.5–1.2 km. At 0:00 on January 18, the RH was 83% (figure (6b)) and Vi was 3.2 km. Subsequently, the RH gradually increased to more than 95% at approximately 03:00, while the Vi gradually decreased to 1 km (3.9 km in the FH area). Pollution at Station 58561 was more severe than it was at Station 58565. This situation persisted until 21:00, in which the humidity exceeded 70%, Vi remained below 5 km, almost all concentrations of PM\(_{2.5}\) remained above 100 μg/m\(^3\), and the intensity of the 532 nm extinction coefficient was 2.00 km\(^{-1}\) (from the ground to high altitude). Clearly, pollution was severe during this period.

After 21:30 on January 18, the humidity was below 70% and Vi remained at approximately 4 km. However, at 02:00 on January 19, the humidity dropped to approximately 65%, Vi gradually increased
by more than 7 km, and the extinction coefficient was 0.5 km\(^{-1}\) near the ground. From 02:00 to 14:00, the pollution near the ground was alleviated gradually, and the moisture absorption condition of the aerosol particles became insufficient. Consequently, the intensity of the extinction coefficient at 532 nm (Figure 8a) was clearly weaker than it was at 355 nm (Figure 8c). At this time, the upper air input was alleviated, and some accumulation was still observed near the ground, with the intensity of the extinction coefficient being approximately 1.2 km\(^{-1}\) and 0.8 km\(^{-1}\) at high altitudes. Subsequently, the RH decreased rapidly to below 30% at about 14:00 on January 19, and the corresponding Vi increased rapidly to above 1.5 km. After 19:00, the extinction coefficient at the 532 nm wavelength was approximately 0.40 below the boundary layer. The extinction coefficient at the 355 nm wavelength (figure 8c) revealed that because of the weakening pollution input near the boundary layer, the aerosol particles could not be decreased adequately after moisture absorption; this led to the formation of fog droplets and raindrop condensation nodules. There was no pollution at 02:00 on January 20, which is a condition conducive to subsequent rain accumulation.

Atmospheric particulate matter exhibits a long retention time in the air. In particular, particles smaller than 2.5 \(\mu m\) (PM\(_{2.5}\)) can stay in the air for several weeks [24–27]. However, the investigated pollution process lasted only 2 d because of two reasons: (1) the influx of cold air and the import of pollutants ceased; (2) after the input of pollutants had ceased during the rain break period, the humidity increased, rainfall started, and the air was purified.

4. Conclusions
Based on our analyses of the monitoring data obtained from the observation stations for 2013–2020 and the pollution process from January 18 to 19, 2016, the following conclusions could be drawn. The number of haze days from 2013 to 2020 showed a downward annual trend, which varied significantly. The regional and seasonal changes in pollutant concentrations were evident, appearing mostly in autumn and winter (especially in December, with most events in January); these changes were more frequent in the north and west and less in the south and east. The concentrations of PM\(_{2.5}\) were relatively high in Ningbo. Air pollution persisted in some areas in autumn and winter, and the influence of haze in winter was obvious. The haze process from January 18 to 19, 2016, led to an import of external pollutants, as the north or northwest wind is the main conveyance path that influences the variation in PM concentrations in Ningbo. A RH of more than 60% was conducive to the deposition and accumulation of pollution particles, which caused a decline in the Vi. The PM\(_{2.5}\) concentrations were higher under high humidity conditions, and the proportion of small particle pollutants was higher under low humidity conditions. Within a height of 2 km, the depolarization ratio was less than 0.04, indicating that the haze process was dominated by spherical fine particles. The high RH, decrease in temperature, and stable weather conditions were beneficial to the accumulation and subsidence of pollutants, which led to long-term effects as the particles could not be diffused easily.

Our results showed the change trends and distribution of haze in Ningbo in recent years. The temporal and spatial changes in pollutants could be obtained by analyzing the monitoring data of particulate lidar, meteorological elements, and PM\(_{2.5}\) pollutants. Currently, particulate lidar is not part of a network monitoring system. However, the use of particulate lidar measurements will be increased in the northern part of the haze-prone area in Ningbo over the next two years. Access to such network data would be helpful for further detailed analyses of pollutants in Ningbo.

5. Data Availability
The pollutant and meteorological data used in this study were obtained from the Data Center of Ningbo Meteorological Bureau. The statistical data were obtained from environmental monitoring stations in the ecological environment sector. The monitoring system included data from the regional monitoring stations.
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