Visibility Variation in Zhengzhou from 2008–2017

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Abstract. Visibility is closely related to air quality and is therefore a source of concern. Using data from the National Basic Weather Station (NBWS), this study measured visibility variation in Zhengzhou from 2008 to 2017. The effects of PM$_{2.5}$ and meteorological parameters on visibility were also assessed. Results indicated that the mean annual visibility fluctuated between 8.07 km and 14.02 km, decreasing during the period from 2008 to 2013 and then increasing slightly after 2013. The seasonal mean visibility was 11.69 km in spring (the highest value), 11.37 km in summer, 9.42 km in autumn, and 8.98 km in winter (the lowest value). The mean annual concentrations of PM$_{2.5}$ from 2015 to 2017 were 90.83 μg m$^{-3}$, 79.89 μg m$^{-3}$, and 66.69 μg m$^{-3}$, respectively. These were 159.51%, 128.26%, and 90.54% higher than 35 μg m$^{-3}$ of the second grade of China National Ambient Air Quality Standards (CNAAQS). Additionally, direct radiation, total radiation, temperature, and relative humidity were positively correlated with visibility, whereas PM$_{2.5}$ mass concentration, scattered radiation, and wind velocity were negatively correlated with visibility. Further research is needed to analyse the effect of PM$_{2.5}$ on visibility and the mechanism through which this occurs.

1. Introduction

Visibility is closely related to air quality and is widely used to quantify aerosol loadings [1]. Increasing public concern regarding visibility levels has initiated a series of studies on this topic. For instance, Zou et al. [2] identified different nonlinear correlations between visibility and mass concentrations of PM$_{2.5}$ (particulate matter with an aerodynamic diameter of less than 2.5 μm) in varying conditions of relative humidity. Deng et al. [3] found that aerosol hygroscopic growth led to the further degradation of visibility. Similarly, Peng et al. [4] found that a decrease in visibility was closely related to an increase in the mass concentration of aerosol particles, whereas Wang et al. [5] found that secondary aerosols played a principal role in determining total PM$_{2.5}$ mass and decreasing visibility. Several studies have also focused on polluted areas such as the Pearl River Delta region [6], the Yangtze River Delta region [7], and the Beijing–Tianjin–Hebei region [8]. Zhengzhou, which is the capital of Henan Province in central China, has experienced serious atmospheric pollution problems and poor visibility [5]. The primary pollutant is PM$_{2.5}$, which causes low visibility [9]. However, few studies have been conducted on visibility in Zhengzhou, and long–term variations in visibility have never been reported. To address
this gap in the literature, visibility variation in Zhengzhou from 2008 to 2017 and the effect of PM$_{2.5}$ and meteorological parameters on visibility were analysed.

2. Methods and data
Atmospheric visibility and meteorological data for the last 10 years, including solar radiation, temperature, relative humidity, wind speed, and PM$_{2.5}$, were obtained from the National Basic Weather Station (NBWS, N34°42′, E113°40′) in Zhengzhou. This source was selected because its data are the most complete. Additionally, professional observers conducted frequent measurements of the visual range by using reference objects at known distances from the meteorological location. Daily visibility was averaged from a minimum of four synoptic observations per day. The data were correctly decoded as much as possible to eliminate random error.

To investigate the effect of PM$_{2.5}$ and meteorological parameters on visibility, rainy and foggy days were screened out. Additionally, only visibility data with relative humidity (RH) <90% were selected for analysis [7].

3. Results and discussion

3.1. Annual and seasonal changes in visibility
Mean visibility from 2008 to 2017 and the 10–year trend in Zhengzhou are summarised in Table 1. This shows that the 10–year mean visibility was 10.37 km, and the annual mean visibility for 2008–2012 was 10.06 km, 9.49 km, 9.74 km, 9.37 km, and 9.25 km, respectively; the annual mean visibility for 2013 was 8.07 km, and the annual mean visibility for 2014–2017 was 10.05 km, 14.02 km, 11.24 km, 12.38 km, and 9.25 km, respectively. Thus, the mean annual visibility increased slightly after 2013, which may have been the point at which Zhengzhou began executing Ambient Air Quality Standard (BG3095–12) [10]. Overall, the mean annual visibility fluctuated between 8.07 km and 14.02 km, markedly lower than the national mean of 26.00 km, indicating that Zhengzhou experienced poor visibility.

Seasonal mean visibility over this 10–year period is also shown in Table 1. Specifically, the mean visibility for spring (Mar, Apr, and May), summer (Jun, Jul, and Aug), autumn (Sep, Oct, and Nov), and winter (Dec, Jan, and Feb) was 11.69 km, 11.37 km, 9.42 km, and 8.98 km, respectively. The best visibility was recorded in the summer of 2016 (12.02 km), and the worst in the winter of 2013 (4.93 km). The mean visibility in winter was worst in Zhengzhou (8.98 km), which was in line with the worst visibility of other cities in winter. According to Chang et al. [6], low visibility is related to PM$_{2.5}$ pollution, coal combustion, secondary sulphates, and biomass burning, especially in winter. Better visibility in spring may have been caused by cold air arising from a frequent high wind speed.

3.2. Effect of PM$_{2.5}$ on visibility
The degradation of visibility was primarily attributable to air pollution, which is caused by coal combustion, vehicle exhausts, and industry emissions [11-12]. PM$_{2.5}$ plays a key role in reducing visibility [13-15]. Using continuous measurements from 2015 to 2017 (Table 2), full–scale data on PM$_{2.5}$ mass concentrations were obtained, which showed that the mean annual concentrations of PM$_{2.5}$ in 2015–2017 were 90.83 μg m$^{-3}$, 79.89 μg m$^{-3}$, and 66.69 μg m$^{-3}$, respectively. These values were 159.51%, 128.26%, and 90.54% higher, respectively, than the second grade of China National Ambient Air Quality Standards (CNAAPS) for PM$_{2.5}$ annual mass concentration (35 μg m$^{-3}$). Furthermore, the PM$_{2.5}$ mass concentration in 2015 was significantly higher than that in 2016 and 2017 by 13.69% and 36.20%, respectively. Moreover, the annual concentration of PM$_{2.5}$ was approximately 1–2 times higher than that in Shanghai (54 μg m$^{-3}$) [16] and Fuzhou (44 μg m$^{-3}$) [17].

In this study, the concentration of PM$_{2.5}$ revealed a clear seasonal variation, with the maximum concentration in winter and the minimum concentration in summer. The mean seasonal concentrations of PM$_{2.5}$ were 122.45 μg m$^{-3}$ (winter) > 75.89 μg m$^{-3}$ (spring) > 68.29 μg m$^{-3}$ (autumn) > 49.91 μg m$^{-3}$ (summer), respectively. This indicates a considerable difference in the PM$_{2.5}$ concentration between winter and summer, which might be due to the combined effect of seasonal variations in emissions,
transport and dispersion of air mass, and chemical production loss and deposition. Thus, the PM$_{2.5}$ mass concentration in spring and winter was higher than that in summer and autumn. The maximum PM$_{2.5}$ concentration was 141.53 $\mu$g m$^{-3}$ in the winter of 2016, whereas the minimum PM$_{2.5}$ concentration was 41.36 $\mu$g m$^{-3}$, in the summer of 2016. The minimum level of visibility for 2015–2017 was 8.05 km, which was reported in the winter of 2016, whereas the maximum level of visibility was 18.02 km, which was reported in the summer of 2016. This indicates a negative correlation between the PM$_{2.5}$ mass concentration and visibility and is consistent with the results of previous studies [5, 18].

Table 1. Summary of mean annual and seasonal visibility in Zhengzhou from 2008–2017.

| Visibility (km) | Spring | Summer | Autumn | Winter | Annual |
|----------------|--------|--------|--------|--------|--------|
| 2008           | 11.01  | 10.14  | 9.86   | 9.21   | 10.06  |
| 2009           | 10.29  | 9.59   | 8.49   | 9.59   | 9.49   |
| 2010           | 11.23  | 8.89   | 9.15   | 9.67   | 9.74   |
| 2011           | 11.58  | 9.11   | 8.18   | 8.61   | 9.37   |
| 2012           | 10.78  | 10.50  | 10.23  | 5.48   | 9.25   |
| 2013           | 9.33   | 11.41  | 6.60   | 4.93   | 8.07   |
| 2014           | 10.63  | 9.29   | 7.84   | 12.44  | 10.05  |
| 2015           | 15.71  | 18.02  | 12.46  | 9.89   | 14.02  |
| 2016           | 11.89  | 15.25  | 9.77   | 8.05   | 11.24  |
| 2017           | 14.45  | 11.53  | 11.63  | 11.90  | 12.38  |

Table 2. Summary of mean seasonal PM$_{2.5}$ mass concentration and visibility in Zhengzhou from 2015–2017.

| The mass concentration of PM$_{2.5}$ (μg/m$^3$) | Spring | Summer | Autumn | Winter | Annual |
|-------------------------------------------------|--------|--------|--------|--------|--------|
| 2015                                             | 95.49  | 64.22  | 77.07  | 126.54 | 90.83  |
| 2016                                             | 65.47  | 41.36  | 71.19  | 141.53 | 79.89  |
| 2017                                             | 66.71  | 44.16  | 56.62  | 99.28  | 66.69  |

3.3. Effect of meteorological parameters on visibility

3.3.1. Solar radiation. Visibility depends largely on the concentration of atmospheric aerosols [19]. These can absorb, scatter, and reflect solar radiation, significantly reducing its intensity (including direct radiation and scattered radiation). Thus, solar radiation is an important determinant of visibility. Fig.1 shows that the mean annual total radiation from 2008 to 2017 was 436.47 MJ m$^{-2}$, within which the mean annual scattered radiation was 218.76 MJ m$^{-2}$ and the mean annual direct radiation was 217.70 MJ m$^{-2}$. Total radiation and direct radiation from 2008 to 2017 exhibited a steady uptrend, whereas scattered radiation over the same period exhibited a steady downtrend. A positive correlation was also found between direct radiation and visibility, and a negative correlation was found between scattered radiation and visibility. Because the range of direct radiation was greater than that of scattered radiation, total radiation exhibited an upward trend, and a positive correlation was observed between total radiation and visibility. The trend in total solar radiation in this study is the same as that in the western region of Beijing–Tianjin–Hebei [20].
Seasonal and annual changes in solar radiation are shown in Table 3 and Figs. 2–6. As explained in Table 3, the seasonal climate tendency for direct radiation was 0.9621 MJ m⁻² a⁻¹ in spring, 1.9354 MJ m⁻² a⁻¹ in summer, and 2.4491 MJ m⁻² a⁻¹ in winter, respectively, whereas the seasonal climate tendency for direct radiation was –0.5044 MJ m⁻² a⁻¹. However, the seasonal climate tendency for scattered radiation was remarkable, with values of –0.2688 MJ m⁻² a⁻¹, –0.1057 MJ m⁻² a⁻¹, 0.2038 MJ m⁻² a⁻¹, and –0.2861 MJ m⁻² a⁻¹, respectively. Therefore, the seasonal climate tendency for total radiation was 0.6933 MJ m⁻² a⁻¹, 1.8297 MJ m⁻² a⁻¹, –0.3006 MJ m⁻² a⁻¹, and 2.1630 MJ m⁻² a⁻¹, respectively, in which the annual tendency for direct radiation, scattered radiation, and total radiation was 4.8423 MJ m⁻² a⁻¹, –0.4569 MJ m⁻² a⁻¹, and 4.3854 MJ m⁻² a⁻¹, respectively. Moreover, Figs. 2–5 illustrate that trends in the seasonal variation of total radiation, direct radiation, and scattered radiation were basically consistent with trends in annual variation. Both total radiation and direct radiation initially decreased and then rose, whereas scattered radiation initially rose and then decreased. All were significantly correlated with visibility, indicating that solar radiation had an important effect on visibility.

The regression equation slope for direct radiation and visibility (8.1494 MJ km⁻¹) was significantly higher than that for scattered radiation and visibility (–2.1086 MJ km⁻¹), indicating that the effect of direct radiation on visibility was stronger than that of scattered radiation. It also indicated that inflection points for solar radiation and visibility occurred in 2013. This may be because the PM₂.₅ mass concentration had decreased, which resulted in a steady increase in scattered radiation and a decrease in direct radiation [21].

Table 3. The seasonal and annual tendency equation and climate tendency for solar radiation in Zhengzhou.

| Solar Radiation | Annual | Spring | Summer | Autumn | Winter |
|-----------------|--------|--------|--------|--------|--------|
| Direct Radiation | \( Y = 4.8423x - 9527.4 \) | \( Y = 0.9621x - 1874.7 \) | \( Y = 1.9354x - 3848.6 \) | \( Y = -0.5044x + 1065.2 \) | \( Y = 2.4491x - 4869.3 \) |
| \( R^2 = 0.3802 \) | \( R^2 = 0.4276 \) | \( R^2 = 0.3664 \) | \( R^2 = 0.0482 \) | \( R^2 = 0.4276 \) |
| Scattered Radiation | \( Y = -0.4569x + 1138.3 \) | \( Y = -0.2688x + 605.13 \) | \( Y = -0.1057x + 283.82 \) | \( Y = 0.2038x - 364.85 \) | \( Y = -0.2861x + 614.66 \) |
| \( R^2 = 0.0461 \) | \( R^2 = 0.0735 \) | \( R^2 = 0.0349 \) | \( R^2 = 0.0337 \) | \( R^2 = 0.1098 \) |
| Total Radiation | \( Y = 4.3854x - 8389.2 \) | \( Y = 0.6933x - 1269.6 \) | \( Y = 1.8297x - 3565.3 \) | \( Y = -0.3006x + 700.31 \) | \( Y = 2.163x - 4254.6 \) |
| \( R^2 = 0.4286 \) | \( R^2 = 0.0762 \) | \( R^2 = 0.4276 \) | \( R^2 = 0.0089 \) | \( R^2 = 0.2320 \) |
| \( 4.3854 \) | \( 0.6933 \) | \( 1.8297 \) | \( -0.3006 \) | \( 2.1630 \) |
Figure 1. Variation in solar radiation from 2008–2017.

Figure 2. Variation in solar radiation in Spring from 2008–2017.

Figure 3. Variation in solar radiation in Summer from 2008–2017.

Figure 4. Variation in solar radiation in Autumn from 2008–2017.
3.3.2. Wind velocity. Fig. 7 depicts the effect of wind velocity on visibility. First, it shows that wind velocity fluctuated from 2.19 m s\(^{-1}\) to 2.56 m s\(^{-1}\) and slightly decreased from 2008 to 2017, whereas visibility fluctuated from 8.07 km to 14.02 km and slightly increased after 2013. Wind velocity and visibility were therefore negatively correlated, which is consistent with previous research. For instance, Liu et al. [22] investigated factors exerting a long-term effect on atmospheric visibility and found that a reduction in wind velocity was unfavourable for diluting and diffusing near-surface atmospheric pollutants; a significant positive correlation was also observed between visibility and wind velocity. This is supported by Liu et al. [23] who found that increased wind velocity led to the rapid spread of dust and pollutants in the atmosphere, which increased visibility. In this study, the phenomenon may be due to the effect of another factor on visibility, the effect of which is much greater than that of wind velocity.

3.3.3. Temperature. As shown in Fig. 8, the annual mean temperature for 2008–2017 ranged from 16.64 °C to 18.09 °C in Zhengzhou, which represents a slight upward trend, and was significantly positively correlated with visibility. This indicates that an increase in temperature was conducive to diffusing atmospheric pollutants and increasing visibility, a finding that is consistent with previous research [22]. However, some researchers have identified a positive correlation between temperature and visibility, although the effect of temperature on visibility was only slight, which suggests that another factor had a greater effect on visibility [23].

3.3.4. Relative humidity. Because the scattering cross section of a hygroscopic particle in a humid environment can increase by five or more times in a dry environment, data on visibility with RH < 90% were selected for analysis. In this study, the trend in RH was consistent with that of visibility, as both initially decreased and then subsequently increased, and they were positively correlated (Fig. 9). This result is consistent with previous research [21], although some studies have also found a negative correlation between RH and visibility [24].
4. Conclusions
This study explored the long-term trend in visibility variation in Zhengzhou and the factors that influence this. Based on 10-year observations, the annual mean visibility fluctuated between 8.07 km and 14.02 km, decreasing from 2008 to 2013 and then increasing slightly after 2013. The seasonal mean visibility was 11.69 km in spring, 11.37 km in summer, 9.42 km in autumn, and 8.98 km in winter, respectively. It was thus the highest in spring, lowest in winter, and markedly lower than the national average (26.00 km), suggesting that Zhengzhou experienced a striking degradation in visibility. The mean annual PM$_{2.5}$ concentrations for 2015–2017 were 90.83 $\mu$g m$^{-3}$, 79.89 $\mu$g m$^{-3}$, and 66.69 $\mu$g m$^{-3}$, respectively. These values were 159.51%, 128.26%, and 90.54% higher, respectively, than the second grade of China National Ambient Air Quality Standards (CNAAQS, 35 $\mu$g m$^{-3}$). The mean seasonal PM$_{2.5}$ concentrations were 122.45 $\mu$g m$^{-3}$ (winter) > 75.89 $\mu$g m$^{-3}$ (spring) > 68.29 $\mu$g m$^{-3}$ (autumn) > 49.91 $\mu$g m$^{-3}$ (summer), respectively. Correlation analyses suggested that direct radiation, total radiation, temperature, and relative humidity were positively correlated with visibility, whereas PM$_{2.5}$ mass concentration, scattered radiation, and wind velocity were negatively correlated with visibility. Additional studies are needed to assess the effect of the chemical characteristics of PM$_{2.5}$ on visibility and to determine the mechanism through which this occurs in Zhengzhou.
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