



1 **Decadal Evolution of Visibility in Beijing: Sources and Their**
2 **Implications for Shifting Perspectives on Haze**

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Submitted by

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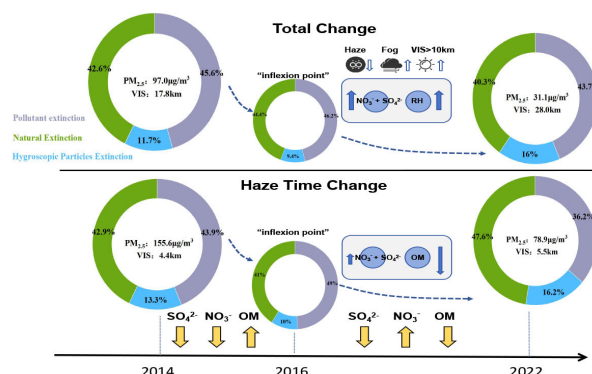


23 **Abstract**

24 Atmospheric visibility is a fundamental indicator of air quality, and its
25 degradation is governed by aerosol light extinction, with implications for radiation
26 balance, climate, and public health. Over the past decade, PM_{2.5} in China has declined
27 substantially, yet visibility has often improved more slowly, and how changing
28 aerosol composition and atmospheric water, through hygroscopic growth and
29 hydrometeorological extinction, contribute to this lag remains incompletely quantified.
30 Here we quantify the sources and decadal evolution of atmospheric extinction in
31 Beijing (2013 – 2022) using hourly observations of meteorology, PM_{2.5} and aerosol
32 chemical composition within an improved IMPROVE framework that explicitly
33 accounts for hydrometeorological extinction. PM_{2.5} decreased from 97.0 to 31.1 µg/m
34 ³ and annual visibility rose from 12.8 to 28.0 km, while haze frequency declined and
35 fog frequency increased. Particulate extinction remained dominant (55.6 % – 59.7 %),
36 but its structure shifted: dry pollutant extinction decreased while hygroscopic
37 extinction, driven by rising nitrate and humidity, rose from 9.4 % to 16.0 %. By 2022,
38 hydrometeorological and hygroscopic extinction together accounted for 73.3 % of the
39 residual extinction. During haze, particulate extinction proportion has declined since
40 2016 as the rise in nitrate extinction did not offset the larger decline in organic matter,
41 weakening the visibility – PM_{2.5} correlation. These results show that natural and
42 composition driven extinction increasingly controls visibility, implying that existing
43 haze criteria may need revision and revealing a nitrate-amplified hygroscopic
44 feedback with global relevance for cities dominated by secondary inorganic aerosols.

45 **Keywords:** Atmospheric visibility; Light extinction coefficient; Particulate
46 matter components; Beijing.

47 **Synopsis:** This study reveals Beijing's fog-haze interaction mechanisms, providing
48 insights for precise air pollution control, refining haze classification, and guiding
49 environmental policies.



50

51 1. Introduction

52 Visibility, an essential parameter for characterizing atmospheric transparency,
 53 serves as a straightforward and easily understood indicator for the public to assess air
 54 pollution.(Watson, 2002) Particulate pollution is a significant contributor to visibility
 55 reduction. In recent years, the relationship between the light absorption effects of
 56 atmospheric particulates, extinction coefficients, and visibility has garnered increasing
 57 attention.(Cheng et al., 2017)

58 Studies have reported notable regional differences in visibility trends despite
 59 reductions in PM_{2.5} concentrations. For example, PM_{2.5} levels in southern China
 60 decreased significantly from 52 μg/m³ to 33 μg/m³ between 2013 and 2018, yet the
 61 frequency of low-visibility events did not show a substantial decline.(Xu et al., 2020)
 62 Similarly, in eastern China, a significant reduction in PM_{2.5} levels during the same
 63 period did not correspond to a marked improvement in the frequency of low-visibility
 64 haze.(Liu et al., 2020) Research on the relationship between particulate matter and
 65 meteorological conditions in Hefei revealed that, under low-visibility conditions, the
 66 correlation between visibility and the main components of PM_{2.5} weakened
 67 significantly. In Shijiazhuang, the impact of PM_{2.5} mass concentration on visibility
 68 varied with relative humidity: at lower humidity, visibility was primarily influenced
 69 by PM_{2.5} mass concentration, while at higher humidity, the decrease in visibility was
 70 attributed to the increased hygroscopicity of particulates. (Wang et al., 2019a)

71 Further analyses of PM_{2.5} components have shown that secondary aerosols, such
 72 as sulfate, nitrate, and ammonium, are the primary contributors to particulate



73 extinction.(Cao et al., 2012, Xia et al., 2017) For instance, in Beijing, organic mass
74 (OM), NH_4NO_3 , and $(\text{NH}_4)_2\text{SO}_4$ were found to play critical roles in summer visibility
75 changes, contributing 32.2%, 25.9%, and 24.4%, respectively, to the extinction
76 coefficient.(Zou et al., 2018) Similarly, in the Pearl River Delta region during summer,
77 the contributions of $(\text{NH}_4)_2\text{SO}_4$, OM, elemental carbon (EC), and NH_4NO_3 to
78 atmospheric extinction were reported as 39%, 31%, 12%, and 13%,
79 respectively.(Kong et al., 2020)

80 China's air pollution control measures in recent years have led to noticeable
81 changes in particulate components. For example, in Xi'an, $\text{PM}_{2.5}$ concentrations
82 during autumn and winter have decreased significantly over the past two decades.
83 However, the proportion of nitrate in $\text{PM}_{2.5}$ has increased, while sulfate has shown a
84 marked decline.(Ju et al., 2022) During periods of heavy pollution in autumn and
85 winter, mass concentrations of sulfate and organic components in particulate matter
86 decreased significantly in key regions of China between 2013 and 2017.(Wang et al.,
87 2019b)

88 Based on previous studies, this paper explores the long-term evolutionary
89 mechanism between atmospheric visibility and $\text{PM}_{2.5}$ concentration in Beijing. Using
90 hourly observations of meteorological parameters, particulate concentrations, and
91 chemical components from 2013 to 2022, it reveals the long-term variation
92 characteristics of atmospheric extinction components. By incorporating
93 hydrometeorological extinction into the modified IMPROVE model, this study
94 quantifies the contribution ratios of particulate and natural extinction coefficients
95 under different visibility conditions, and analyzes the evolution of particle chemical
96 components. The findings provide a scientific foundation for improving atmospheric
97 visibility and advancing precise air pollution prevention and control measures in
98 Beijing.

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100 **2. Methods**

101 *2.1. Description of sites and data sources*



102 Long-term hourly observations of visibility (VIS) and meteorological parameters
103 (e.g., relative humidity, precipitation) were obtained from the Comprehensive
104 Observatory and Research Station for Atmospheric Environmental Sciences
105 (SUACOR) under the Chinese Academy of Environmental Sciences (116.40°E,
106 40.03°N). (Gao et al., 2016) Hourly urban PM_{2.5}, PM₁₀, and NO₂ mass concentration
107 data were obtained from audited datasets of the Beijing Olympic Sports Center
108 state-controlled site 1011A and the National Agricultural Exhibition Center site
109 1006A, measured by Thermo FH62 C-14 analyzer and Ecotech 9841 NO₂ analyzer,
110 following the “Technical Specification for Evaluation of Ambient Air Quality (for
111 Trial Implementation)” (HJ663-2013).

112 Hourly observations of PM_{2.5} chemical components (e.g., SO₄²⁻, NO₃⁻, NH₄⁺, Cl⁻,
113 Na⁺, Ca²⁺) from 2013 to 2020 were sourced from SUACOR. Organic carbon (OC) and
114 elemental carbon (EC) data from this period were derived from previously published
115 studies due to equipment limitations (Table S1). Some of the data has been validated
116 and utilised in previous studies. (Huo et al., 2022) For 2021–2022, PM_{2.5} chemical
117 composition data were obtained from the Particulate Component Station of the China
118 Environmental Monitoring General Station (116.41°E, 40.04°N).
119 Hydro-meteorological data were sourced from the ERA5 atmospheric reanalysis
120 dataset released by the European Centre for Medium-Range Weather Forecasts
121 (ECMWF) at 0.25° spatial and 1-hour temporal resolution, covering the region
122 116.2°E–116.45°E, 39.9°N–41.5°N.

123 2.2. Division of fog and haze weather

124 Fog and haze were classified following Chinese national standards for fog
125 forecasting and haze observation. Low-visibility events were defined as visibility <
126 10.0 km, excluding interference from precipitation, sandstorms, sand dust, and
127 floating dust. Haze was identified when relative humidity (RH) < 80%, or 80% ≤
128 RH ≤ 95% with PM_{2.5} > 75 µg/m³. Fog was distinguished under the same visibility
129 threshold but not meeting the haze criteria. Haze intensity was divided into four levels:
130 slight (5 ≤ VIS < 10 km), light (3 ≤ VIS < 5 km), moderate (2 ≤ VIS < 3 km),



131 and heavy (VIS < 2 km).

132 2.3. Data analysis

133 Atmospheric extinction is a fundamental indicator used to assess the impact of
 134 air pollution on visibility.(Pitchford et al., 2007) The original IMPROVE algorithm
 135 for estimating extinction was developed from the U.S. IMPROVE particle monitoring
 136 data. The light extinction coefficient (b_{ext}) is expressed as the sum of particle
 137 scattering (b_{sp}), particle absorption (b_{ap}), gas scattering (b_{sg}), and gas absorption
 138 (b_{ag}). In this calculation, gas absorption (b_{ag}) is assumed to be zero, and a Rayleigh
 139 scattering coefficient of 10 Mm^{-1} is applied for each monitoring point.¹ Regardless of
 140 site-specific and meteorological conditions, particle scattering (b_{sp}) and particle
 141 absorption (b_{ap}) are derived by multiplying the concentrations of six major particulate
 142 constituents by their respective mass-specific scattering efficiencies.

$$143 \quad b_{ext} \approx 3 \cdot f(RH) \cdot [Sulfate] + 3 \cdot f(RH) \cdot [Nitrate] + 4 \cdot [Organic Mass] + \\ 144 \quad 10 \cdot [Elemental Carbon] + 1 \cdot [Fine Soil] + 6 \cdot [Coarse Mass] + 10 \quad (1)$$

145 where b_{ext} is the total atmospheric extinction coefficient, corresponding to visible
 146 wavelengths ($\lambda \sim 550 \text{ nm}$) in Mm^{-1} , and $f(RH)$ is the growth function. The six major
 147 components are sulfate ($(\text{NH}_4)_2\text{SO}_4$), nitrate (NH_4NO_3), organic compounds (based on
 148 measured organic carbon (OC)), elemental carbon (or black carbon (EC)), fine soil
 149 (crustal elements plus oxides (FS)), and coarse mass (the difference between the mass
 150 concentrations of PM_{10} and $\text{PM}_{2.5}$ (CM)). The mass scattering efficiencies (MSEs) of
 151 the components are constants. Particulate component concentrations are
 152 dimensionless in $\mu\text{g} \cdot \text{m}^{-3}$ and MSE in $\text{m}^2 \cdot \text{g}^{-1}$. Rayleigh scattering (b_{sg}) is taken directly
 153 as a constant 10 Mm^{-1} .

154 Since the original IMPROVE equation exhibited significant biases under
 155 extreme conditions, Pitchford et al. developed a corrective algorithm. It added the
 156 contributions of sea salt and NO_2 light absorption in coastal areas, and modified the
 157 mass scattering efficiencies for organic compounds and organic carbon. However,
 158 both the original and revised IMPROVE equations only calculate aerosol extinction



coefficients. In fact, atmospheric water such as free water droplets, fog droplets and hydrometeors also strongly affects visibility. Conventional instrumental monitoring adopts heating and dehumidification pretreatment, which ignores this part of extinction and seriously underestimates actual total extinction under high humidity and foggy conditions. To address this limitation, this study incorporates additional extinction contributions beyond particulate matter hygroscopic growth. Specifically, it includes the influence of water vapor and other natural extinction factors not captured by traditional monitoring systems (b_{other}), such as the extinction caused by hydrometeors ($b_{ext-hyd}$). The improved formula for calculating the total atmospheric extinction coefficient (b_{ext}) is given as:

$$b_{ext} = b_{sp} + b_{ap} + b_{ag} + b_{sg} + b_{other} \quad (2)$$

$$b_{sp} = \alpha_1 \cdot f(RH) \cdot [(NH_4)_2SO_4] + \alpha_2 \cdot f(RH) \cdot [NH_4NO_3] + \alpha_3 \cdot [OM] + \alpha_4 \cdot [EC] + \alpha_5 \cdot [FS] + \alpha_6 \cdot [Other] + \alpha_7 \cdot [CM] \quad (3)$$

$$b_{ap} = 10 \cdot [EC] \quad (4)$$

$$b_{ag} = 0.33 \cdot [NO_2] \quad (5)$$

$$b_{other} = b_{ext} - b_{sp} - b_{ap} - b_{ag} - b_{sg} \quad (6)$$

where b_{other} encompasses particle hygroscopic extinction as well as extinction attributable to other factors, including hydrometeorological extinction. *Other* is related to the difference between the actual PM_{2.5} concentration and the reconstructed PM_{2.5} concentration. Organic mass (OM) was estimated by multiplying the OC by 1.6. b_{ag} was estimated from the absorption efficiency for NO₂ (ppb) uptake. α_1 - α_7 for the MSE of each major extinction component of particulate was taken from the empirical values of regression calculations of b_{sp} and PM_{2.5} mass concentrations previously measured in actual Beijing, which is $4.5 \pm 1.7 \text{ m}^2\text{g}^{-1}$, $4.9 \pm 1.6 \text{ m}^2\text{g}^{-1}$, $6.4 \pm 2.3 \text{ m}^2\text{g}^{-1}$, $3.6 \pm 1.3 \text{ m}^2\text{g}^{-1}$, $1.1 \pm 0.6 \text{ m}^2\text{g}^{-1}$, $3.2 \pm 1.2 \text{ m}^2\text{g}^{-1}$ and $0.6 \pm 0.2 \text{ m}^2\text{g}^{-1}$ respectively. (Tao et al., 2015)

Among these, the extinction coefficient attributed to the internal water content of



186 particulate matter is defined as b_{ext-w} and is calculated using the following formula:

$$187 \quad b_{ext-w} = (\alpha_1[(NH_4)_2SO_4] + \alpha_2[NH_4NO_3]) \times (f(RH) - 1) \quad (7)$$

188 The hydrometeor extinction coefficient is calculated by combining the methods
 189 of Stoelinga et al. (1999) and Gultepe et al. (2009), with slight modifications to the
 190 coefficients as proposed by subsequent studies.(Xie et al., 2024) The formulation is
 191 expressed as follows:

$$192 \quad b_{ext-hyd} = \frac{-\ln \varepsilon}{0.87706} (N_d LWC)^{0.49034} + 2.24 C_{rw}^{0.75} + 327.8 C_{ci}^{1.00} + 10.36 C_{sw}^{0.7776} \quad (8)$$

193 Where LWC is the liquid water content (in $g \cdot m^{-3}$), and N_d is the cloud droplet
 194 number concentration (in cm^{-3}). In this calculation, the default N_d value of 100 cm^{-3} ,
 195 as adopted in the Thompson microphysics scheme, is used. Additionally, C_{rw} , C_{ci} ,
 196 and C_{sw} represent the mass concentrations (in $g \cdot m^{-3}$) of rainwater, cloud ice, and
 197 snow, respectively.

198 In addition, since the visibility wavelength measured by the sensor in this study
 199 is 880 nm, it is necessary to transform the light scattering measured at 880 nm to 550
 200 nm to ensure comparability between the extinction coefficient measured by the
 201 visibility sensor and the extinction coefficient calculated using the IMPROVE
 202 equation. This transformation is performed using the following relationship:

$$203 \quad Mb_{sca}(550nm) = Mb_{sca}(880nm) \cdot (\lambda(550nm)/\lambda(880nm))^{-\alpha} \quad (9)$$

204 where α is the scattering index. The mean value of α of 1.18 was used in this study.

205 According to Kirchmid's law, the meteorological optical range of view (MOR) is
 206 expressed as:

$$207 \quad MOR = -(\ln(\varepsilon))/\sigma \quad (10)$$

208 where ε is the contrast threshold, σ is the extinction coefficient. When $\varepsilon=0.05$,
 209 $MOR = 3.00/\sigma$.

210 2.4. Uncertainty and Sensitivity Analysis

211 To assess the robustness of the extinction apportionment results to the
 212 uncertainties in mass scattering efficiency (MSE) parameters, a Monte Carlo
 213 simulation was performed separately for haze-time and annual-average conditions.



214 The MSE values (α_1 – α_7) and their standard deviations were adopted from Tao et al. At
215 each iteration ($n = 10,000$), MSE values were randomly sampled from normal
216 distributions. Negative values were discarded and re-sampled. The extinction
217 contributions were recalculated following Equations (2)–(7). Linear regression was
218 applied to obtain trend slopes. The 95% confidence intervals were computed. A trend
219 was considered robust if its 95% CI did not include zero.

220 Sensitivity analysis confirms that the key findings are statistically robust (Fig.
221 S1a,b). For annual-average conditions, all four components show robust trends:
222 nitrate ($+0.98\% \text{ yr}^{-1}$), OM ($-0.61\% \text{ yr}^{-1}$), sulfate ($-0.35\% \text{ yr}^{-1}$), and EC ($-0.99\% \text{ yr}^{-1}$).
223 Under haze conditions, nitrate shows a robust increasing trend (median: $+2.31\% \text{ yr}^{-1}$,
224 95% CI: $[+1.43, +2.80]$), while OM exhibits a robust decreasing trend (median:
225 $-2.23\% \text{ yr}^{-1}$, 95% CI: $[-2.93, -1.20]$). Notably, the nitrate increasing rate under haze
226 conditions is ~ 2.4 times higher than annual-average conditions ($+0.98\% \text{ yr}^{-1}$). These
227 results demonstrate that our conclusions are insensitive to MSE parameter choices.

228 **3. Results and discussion**

229 *3.1. Trends of $\text{PM}_{2.5}$ concentration and changes in fog and haze in the past 10 years*

230 From 2013 to 2022, the $\text{PM}_{2.5}$ concentration in Beijing has shown a continuous
231 and significant decline. The $\text{PM}_{2.5}$ concentration decreased from $97.0 \mu\text{g}/\text{m}^3$ to 31.1
232 $\mu\text{g}/\text{m}^3$, with an average annual reduction of 11.9%. Correspondingly, the annual
233 average visibility increased from 12.8 to 28.0 km, rising by 9.1% per year. The
234 narrowing variability of $\text{PM}_{2.5}$ and expanding variability of visibility indicate more
235 stable air quality and fewer severe pollution events.

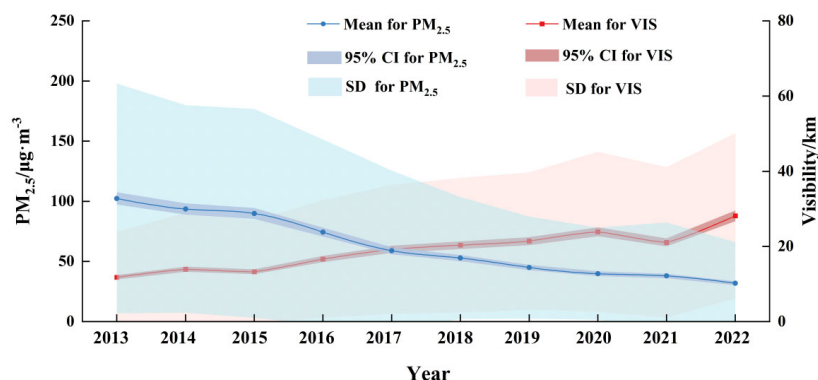


Figure 1 Changes in visibility and PM_{2.5} concentration in Beijing over the past 10 years from 2013 to 2022

The weather statistics for Beijing from 2013 to 2022 are presented in Fig. 2a. The frequency of visibility exceeding 10 km shows an annual increase, whereas occurrences of total low-visibility events (haze + fog + other events) exhibit a continuous decline. The peak frequency of haze was recorded in 2014 (53.9%), and it declined steadily in other years except for a partial rebound in 2021, dropping to 21.8% in 2022. The minimum fog frequency appeared in 2014 (1.9%), followed by an overall upward trend. This trend can be attributed, on one hand, to the reduction in PM_{2.5} mass concentrations resulting from regional emission control measures and, on the other hand, to a potential increase in fog occurrences driven by climate change. In addition, the rebound of haze frequency in 2021, corresponding to the declined visibility, was attributed to the reduced precipitation in spring and winter and the weakened wet deposition effect in that year.

As shown in Fig. 2b, the frequency order of haze intensities during 2013-2017 was: slight haze > light haze > heavy haze > moderate haze. After 2018, heavy haze frequency decreased markedly to the lowest level, with the largest decline among all categories. Specifically, heavy haze occurrences dropped from 13.5% in 2014 to 2.0% in 2022. Haze frequency generally coincided with PM_{2.5} concentrations. Although haze frequency rebounded in 2021, PM_{2.5} showed no significant change, which may



reflect stricter intensity classification and altered particle extinction characteristics during haze.

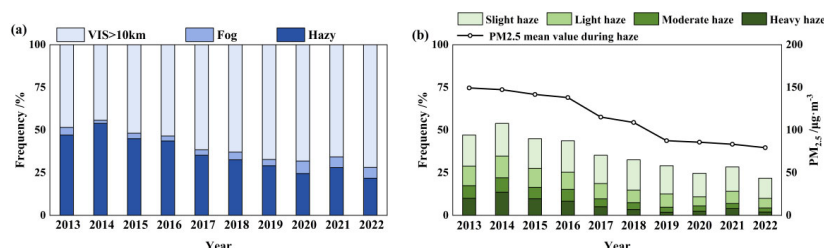


Figure 2 (a) Frequency of haze, fog and visibility >10km from 2013 to 2022. (b) Frequency of different levels of haze and PM_{2.5} concentration during haze from 2013 to 2022.

3.2. Visibility Response to PM_{2.5} Concentration Change

Hourly observations show a significant power-law correlation between visibility and PM_{2.5} concentration, which is weakened by higher humidity. The overall correlation coefficient remained stable between -0.65 and -0.56 throughout the study period (Figure 3). However, the correlation under low-visibility conditions (VIS < 10 km) was notably weaker and declined annually to -0.48 in 2022, suggesting shifts in the dominant factors controlling atmospheric extinction.

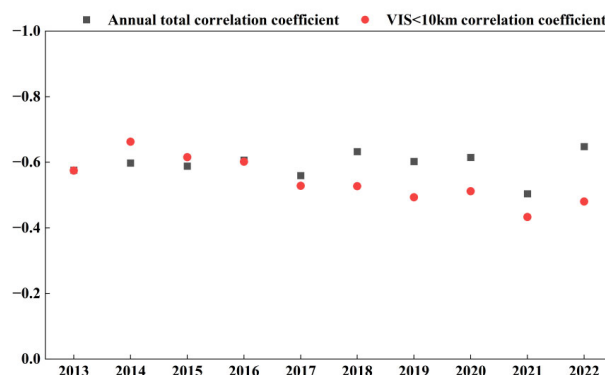


Figure 3 Changes in the correlation between visibility and hourly PM_{2.5} concentration in Beijing from 2013 to 2022

Statistics on the mean PM_{2.5} concentrations corresponding to specific visibility



intervals and the visibility corresponding to identical $PM_{2.5}$ concentration ranges (Figure 4a). For a fixed visibility range of 9.5–10.5 km, the corresponding $PM_{2.5}$ concentration decreased from $76.8 \mu\text{g}/\text{m}^3$ in 2013 to $42.1 \mu\text{g}/\text{m}^3$ in 2022, with an annual decline of $3.9 \mu\text{g}/\text{m}^3$ (6.5% per year). For a fixed $PM_{2.5}$ range of 115–150 $\mu\text{g}/\text{m}^3$, the corresponding visibility decreased from 5.0 km in 2013 to 3.0 km in 2022, at an annual rate of 0.2 km (5.9% per year). These trends confirm that the contribution of $PM_{2.5}$ to atmospheric extinction has changed substantially over the decade.

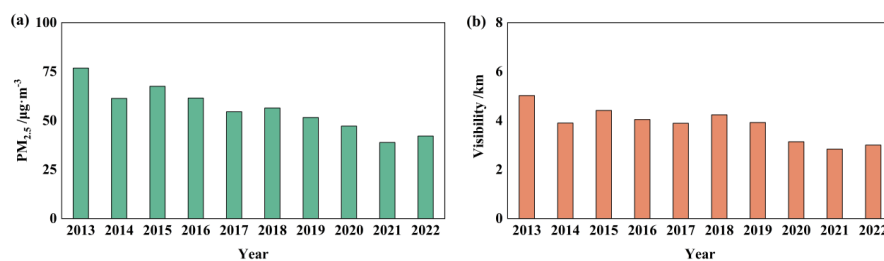


Figure 4 (a) $PM_{2.5}$ concentration corresponding to visibility of 9.5 – 10.5 km (b) Visibility corresponding to the $PM_{2.5}$ concentration range of 115-150 $\mu\text{g}/\text{m}^3$

3.3. Sources and changes in total atmospheric extinction

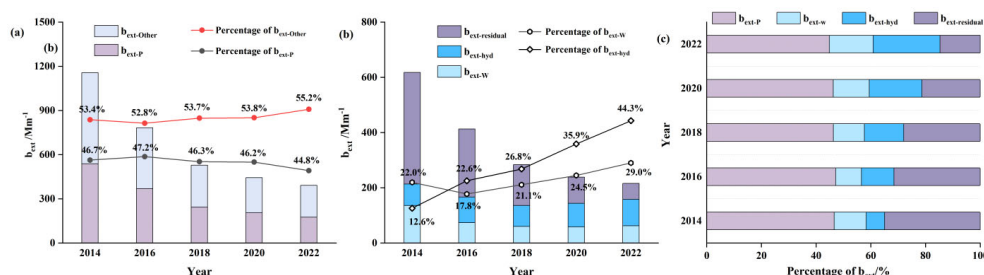
The total atmospheric extinction was partitioned into two components. The first is dry particulate matter extinction ($b_{\text{ext-P}}$, also termed pure pollutant extinction), which corresponds to particulate extinction after excluding particulate water uptake extinction. The second is extinction attributable to other factors ($b_{\text{ext-Other}}$), which comprises particulate water uptake extinction ($b_{\text{ext-W}}$), hydrometeorological extinction ($b_{\text{ext-hyd}}$), and the residual term ($b_{\text{ext-Residual}}$) arising from various other uncertain factors.

The results (Fig. 5) indicate that the total atmospheric extinction coefficient decreases from 2014 to 2022, declining by 66.2% in 2022 relative to its peak value in 2014. Particulate matter extinction shows an annual decrease in absolute terms, yet its contribution ratio to total extinction remains dominant and demonstrates an increasing trend, rising from 56.6% to 60.8%. After water correction, pollutant extinction declined from 47.2% in 2016 to 44.8%. Particulate hygroscopic extinction was the main driver, rising from 9.4% to 16.0% over the same period, with a much larger



299 increase than the decrease in pollutant extinction.

300 An analysis of $b_{\text{ext-Other}}$ reveals that the proportion of particulate water uptake
 301 extinction increased substantially, rising from 12.6% to 44.3%. Hydrometeorological
 302 extinction exhibited a trend of initial decrease followed by increase, accounting for
 303 29.0% of $b_{\text{ext-Other}}$ in 2022. Together, these two components became the principal
 304 constituents of $b_{\text{ext-Other}}$, with a combined proportion of 73.3%, while the residual
 305 fraction declined. Furthermore, within natural extinction (defined here as $b_{\text{ext-Other}}$
 306 excluding particulate water uptake extinction), the proportion of hydrometeorological
 307 extinction increased steadily from 16.2% to 62.4%, establishing it as the primary
 308 factor driving natural extinction.



309

310 **Figure 5** (a) Total Atmospheric Extinction and Proportion of Different Components in
 311 Beijing from 2013 to 2022. (b) Fractional contributions of particulate hygroscopic
 312 extinction and hydrometeorological extinction to $b_{\text{ext-Other}}$. (c) The proportions of
 313 different extinction components in total atmospheric extinction.

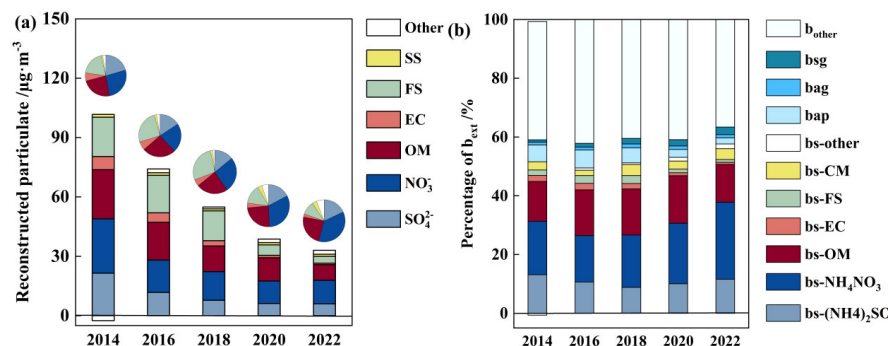
314 To evaluate whether the determined chemical components can represent the
 315 measured $\text{PM}_{2.5}$, $\text{PM}_{2.5}$ mass was reconstructed. The reconstructed $\text{PM}_{2.5}$ agreed well
 316 with observations ($R^2=0.99$), accounting for over 94% of the measured mass,
 317 confirming the rationality of component selection.

318 The particulate matter water absorption extinction is primarily related to nitrates,
 319 sulphates, and RH. Since 2016, the sum proportion of nitrate and sulfate increased
 320 obviously, reaching 54.3% in 2022 and becoming the dominant components (Figure
 321 6a). The proportion of nitrate components ranges from 22.1% to 36.1% and exhibits
 322 an upward trend. During the period, the annual average RH in Beijing also shows a



323 trend of first decreasing and then increasing. The annual average RH in Beijing rises
 324 to 48.2% in 2022. The increase in RH enhances particle hygroscopic growth and
 325 extinction efficiency. The frequency of wind direction occurrences and their
 326 corresponding variations in relative humidity further validate the reliability of this
 327 observed trend. Over the past decade, the dominant wind directions each year have
 328 been southeast and southwest winds, both of which show an increasing trend in
 329 occurrence frequency and associated relative humidity. (Wang et al., 2016)

330 In recent decade, particle hygroscopicity and meteorological factors have exerted
 331 growing impacts on total atmospheric extinction. Meteorology-related extinction
 332 became more prominent. Traditional emission reduction alone can hardly offset the
 333 extinction contribution from hydrometeorological factors, making continuous
 334 visibility improvement increasingly difficult.



335
 336 **Figure 6** (a) Reconstructed particulate concentrations and component shares in
 337 Beijing from 2014 to 2022. (b) Percentage of extinction contribution of different
 338 components in total atmospheric extinction.

340 3.4. Atmospheric extinction and changes during haze-polluted weather

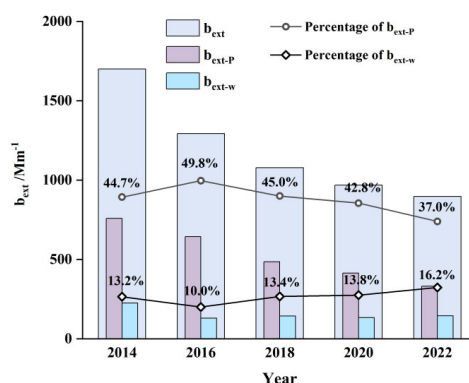
341 3.4.1. Sources and changes of extinction during haze

342 The corresponding mean values of particulate matter concentration and visibility
 343 during haze events indicate that $\text{PM}_{2.5}$ concentrations have decreased significantly
 344 over the past decade, from $155.6 \mu\text{g}/\text{m}^3$ to $78.9 \mu\text{g}/\text{m}^3$, with an average annual
 345 decrease of $8.5 \mu\text{g}/\text{m}^3$ ($7.3\% \text{ yr}^{-1}$). Concurrently, average visibility has improved,



346 increasing from 4.4 km to 5.5 km, with an average annual increase of 0.12 km (2.5%
 347 yr^{-1}). Statistics on haze-period extinction sources (Fig. 7) show that haze extinction
 348 coefficient declined annually, similarly to annual total extinction: dropping by 20.3%
 349 yr^{-1} during 2014-2018 and slowing to 8.8% yr^{-1} afterward. Particulate extinction
 350 proportion rises from 2014 to 2016, then inflected and decreased to 53.2% in 2022,
 351 differing notably from annual total extinction evolution.

352 After water correction, the extinction contribution attributable solely to pollution
 353 components exhibits a trend similar to that of total particulate matter extinction,
 354 decreasing from 49.8% to 37.0%. Particulate hygroscopic extinction during haze
 355 increased from 10.0% to 16.2% after 2016, but its growth was far smaller than the
 356 decline in pollution-only extinction, leading to lower total particulate extinction —
 357 indicating significant changes in haze-period particle composition. In contrast to the
 358 average annual total extinction, the share of non-pollutant extinction (including
 359 natural extinction) has risen since 2016. The trend line ($R^2=0.9654$) projects natural
 360 extinction will become dominant (51.4%) by 2026. Combined with particle
 361 hygroscopic growth, its extinction contribution will be more prominent, reflecting the
 362 increasing weight of hydrometeorological factors in haze visibility variation over the
 363 decade.



364
 365 **Figure 7** Total Atmospheric Extinction and Proportion of Different Components
 366 during haze in Beijing from 2014 to 2022.



Reconstruction of $PM_{2.5}$ concentrations during haze events revealed a strong correlation between measured and reconstructed $PM_{2.5}$ levels ($R^2=0.97$). Reconstructed concentrations accounted for over 86% of measured concentrations. $PM_{2.5}$ component trends during haze (Fig. 8a) were generally consistent with annual averages, while their proportion changes differed greatly. OM decreased most obviously from 28.6% to 15.1% over the decade. In terms of extinction contribution, OM slightly rose from 27.8% to 32.9% during 2014-2016, then declined continuously at an annual rate of 5.6% to 16.0% in 2022. Sulfate extinction also presented a slight downward trend. By contrast, nitrate extinction showed a turning point in 2016, decreasing first and then rising steadily to 49.3% in 2022. The opposite variation of nitrate and OM dominated the structural change of particulate extinction during haze. After 2018, the annual increase of nitrate extinction ($2.9\% \text{ yr}^{-1}$) could not offset the sharp decline of OM extinction ($10.8\% \text{ yr}^{-1}$), eventually forming the inflection point of particulate extinction proportion in total atmospheric extinction during haze. The enhanced hygroscopic extinction efficiency of nitrate compared to OM creates a positive feedback: as the aerosol population shifts toward nitrate dominance, the same relative humidity increase produces greater water uptake and thus stronger light scattering per unit dry mass. This phenomenon explains why visibility improvement has lagged behind $PM_{2.5}$ reduction, particularly during high-RH haze events.

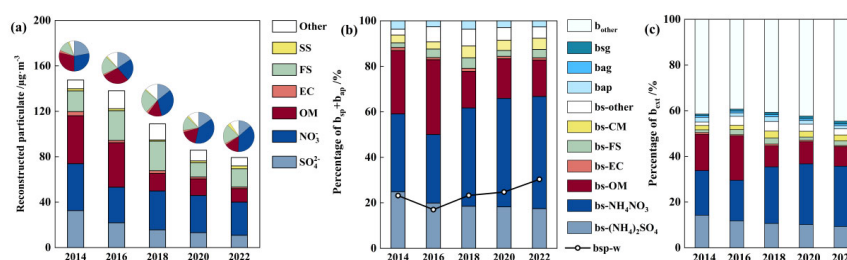


Figure 8 (a) Reconstructed particulate concentrations and component shares during haze in Beijing from 2014 to 2022. (b) Percentage of extinction contribution of different components in particulate extinction during haze. (c) Percentage of extinction contribution of different components in total atmospheric extinction during



392 haze.

393 Studies based on hourly observations across four seasons in Beijing show that
 394 with strengthened primary emission control, the extinction contribution of secondary
 395 inorganic salts, especially nitrate, has increased relatively, while the contribution of
 396 organic matter from traditional primary sources has decreased.(Li et al., 2022) In
 397 South China, low visibility events are also closely associated with the rising
 398 proportion of secondary inorganic salts. The amplified extinction effect of nitrate
 399 hygroscopic growth leads to lower visibility at the same $PM_{2.5}$ concentration.(Xu et al.,
 400 2020) The drop of OM after 2016 benefited from strict emission reduction of SO_2 and
 401 OC precursors driven by the coal-free policy in the Beijing-Tianjin-Hebei region, as
 402 well as energy structure adjustment and coal-to-gas transition in Beijing.(Han et al.,
 403 2016, Ji et al., 2019) The rising nitrate proportion highlights the urgency of mobile
 404 source control. Since 2018, nitrate pollution sources have shifted with increased
 405 contribution from southern industrial zones.(Qian and Liao, 2025) In general,
 406 Beijing's haze pollution characteristics have undergone obvious transformation, and
 407 the traditional haze classification criteria based on historical particulate extinction
 408 contributions can no longer accurately reflect current pollution features.

409 3.4.2. Comparison of typical haze-time changes

410 To further verify the changes in atmospheric extinction sources during haze over
 411 the past decade, typical haze pollution periods in winter 2014 (January 21–24) and
 412 winter 2022 (January 20–25) were selected for analysis (Fig. S2). Comparison of
 413 extinction sources for the two typical haze episodes (Fig. 9a) shows that total
 414 atmospheric extinction coefficients were similar between 2014 and 2022, yet the
 415 proportion of particulate extinction dropped sharply from 63.3% to 49.0%. The
 416 extinction due to polluting components decreased from 63.1% to 28.9%, while the
 417 extinction due to particle water absorption increased from 0.2% to 20.1%. Natural
 418 extinction excluding particle hygroscopic water increased from 36.7% to 51.0%.

419 Particulate composition analysis (Fig. 9b) indicates obvious changes in $PM_{2.5}$
 420 chemical components during haze in 2022 relative to 2014. The shares of OM and



sulfate declined considerably, with their combined contribution decreasing from 52.0% to 33.1%. Meanwhile, the nitrate fraction's share increased evidently from 24.9% to 37.2%. Accordingly, nitrate's extinction contribution rose by nearly 7.8% (from 18.3% to 26.1%). However, the extinction contributions of OM and sulfate declined significantly, accounting for only 18.2% of the total haze extinction share in 2022 (with OM decreasing from 18.6% to 7.1% and sulfate from 17.3% to 10.6%). Their reduction offset the growth of nitrate extinction, resulting in a notable drop in overall particulate extinction proportion. Affected by atmospheric humidity variation, the extinction contribution of water vapor and other natural components also increased. Overall, the internal structure of haze pollution has undergone fundamental changes.

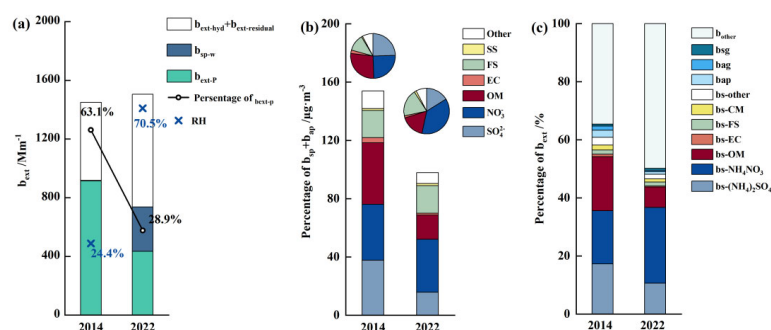


Figure 9 (a) Composition of extinction coefficients for typical haze hours in Beijing, 2014 and 2022. (b) Concentrations and component shares of reconstructed particulate during typical haze in Beijing, 2014 and 2022. (c) Percentage of extinction contribution of different components in total atmospheric extinction during typical haze in Beijing, 2014 and 2022.

4. Conclusions

Based on a decade of hourly observations (2013 – 2022) and an improved IMPROVE framework accounting for hydrometeorological extinction, we quantified the sources and evolution of atmospheric extinction in Beijing. Despite a marked $PM_{2.5}$ decline (97.0 to $31.1 \mu g/m^3$, $-11.9 \% yr^{-1}$) and visibility improvement (12.8 to



28.0 km), the visibility and $PM_{2.5}$ relationship weakened under low-visibility conditions. Particulate extinction remained dominant (55.6 % – 59.7 %) but shifted structurally: dry pollutant extinction declined while hygroscopic extinction, driven by rising nitrate and humidity, increased from 9.4% to 16.0%. By 2022, hydrometeorological and hygroscopic extinction together accounted for 73.3 % of the residual extinction, and during haze after 2016 nitrate-driven extinction rose (+0.8 % yr^{-1}) as organic matter declined (-5.6 % yr^{-1}). Thus, as controls reduced primary and sulfate aerosol, water and nitrate driven extinction increasingly control visibility, overtaking the historically dominant dry particulate scattering during haze.

This shift is consistent with, and extends, reports of lagging visibility improvement despite $PM_{2.5}$ reductions in eastern and southern China (Liu et al., 2020; Xu et al., 2020) and of nitrate and secondary inorganic aerosols dominating particle light extinction in Beijing (Li et al., 2022). Our decade-scale attribution provides a mechanistic explanation: the higher hygroscopic efficiency of nitrate, amplified by rising humidity and hydrometeorological feedbacks, creates a positive feedback whereby the same $PM_{2.5}$ mass scatters progressively more light over time.

This mechanism likely operates in many cities worldwide dominated by sulfate – nitrate – ammonium aerosols, affecting visibility, haze identification, aerosol direct radiative effects, and the interpretation of air-quality trends. As controls shift aerosol composition toward nitrate, projections of visibility, aerosol optical depth, and radiative forcing that assume composition-invariant optical properties may need reconsideration.

Several caveats limit the quantitative attribution: $b_{ext-residual}$ is a residual term whose interpretation is not unique and which absorbs uncertainties from $PM_{2.5}$ mass reconstruction, mass-scattering-efficiency assumptions, the hygroscopic growth function, wavelength conversion, and dataset mismatches; separating aerosol water uptake from hydrometeorological extinction at high relative humidity remains uncertain; and the single-site dataset limits generalization. These conclusions should therefore be regarded as indicative rather than definitive. Future work should constrain these processes with in-situ microphysical observations of droplet size



distributions and liquid water content, and extend the analysis to multi-site, regional, and global scales.

Author Contributions

Y.C. analyzed the data. **X.Y.** designed the study, performed data observation and processing. **J.G.** provided guidance on thesis ideas. **H.L.** guided and revised the structural content of the dissertation. **Y.C.** and **X.Y.** wrote the manuscript. **All authors** participated in relevant scientific discussions and provided comments on the manuscript.

Notes

The authors declare no competing financial interest.

Data availability

Hourly visibility and meteorological parameter data were obtained from the Comprehensive Observatory and Research Station for Atmospheric Environmental Sciences (SUACOR). Hourly urban particulate matter (PM_{2.5}, PM₁₀) and nitrogen dioxide data were obtained from the Beijing Olympic Sports Center (1011A) and National Agricultural Exhibition Center (1006A) state-controlled sites operated by the China National Environmental Monitoring Centre (CNEMC). Hourly PM_{2.5} chemical component data from 2013 to 2020 were obtained from SUACOR and are available on Zenodo under a CC BY 4.0 license (DOI: 10.5281/zenodo.23411459, <https://doi.org/10.5281/zenodo.23411459>). Hydrometeorological data were sourced from the ERA5 reanalysis dataset released by the European Centre for Medium-Range Weather Forecasts (ECMWF), which is publicly available (<https://doi.org/10.24381/cds.6860a573>) (Hersbach et al., 2023). All other data supporting the findings of this study are available from the corresponding authors upon reasonable request.

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