Isotopic constraints on heterogeneous sulfate production in Beijing haze

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Abstract. Discerning mechanisms of sulfate formation during fine-particle pollution (referred to as haze hereafter) in Beijing is important for understanding the rapid evolution of haze and for developing cost-effective air pollution mitigation strategies. Here we present the first observations of the oxygen-17 excess of $PM_{2.5}$ sulfate ($\Delta^{17}O(SO_4^{2-})$) collected in Beijing haze from October 2014 to January 2015 to constrain possible sulfate formation pathways. Throughout the sampling campaign, the 12h-averaged $PM_{2.5}$ concentrations ranged from 16 to 323 μg m^{-3} with a mean of (141±88 (1σ)) μg m^{-3}, with SO_4^{2-} representing 8–25 % of $PM_{2.5}$ mass. The observed $\Delta^{17}O(SO_4^{2-})$ varied from 0.1 ‰ to 1.6 ‰ with a mean of (0.9±0.3) ‰. $\Delta^{17}O(SO_4^{2-})$ increased with $PM_{2.5}$ levels in October 2014 while the opposite trend was observed in November 2014 to January 2015. Our estimate suggested that in-cloud reactions dominated sulfate production in polluted days (PD, $PM_{2.5} \geq 75$ μg m^{-3}) of Case II in October 2014 due to the relatively high cloud liquid water content (LWC), with a fractional contribution up to 68 %. However, heterogeneous sulfate production (P_{het}) on aerosols was estimated to dominate sulfate formation during PD of other cases, with a fractional contribution of (48±5) %. For the specific mechanisms of heterogeneous oxidation of SO_2, chemical reaction kinetics calculations suggested S(IV) (= $SO_2 H_2O + HSO_3^- + SO_3^{2-}$) oxidation by H_2O_2 in aerosol water accounted for 5–13 % of P_{het}. The relative importance of heterogeneous sulfate production by other mechanisms was constrained by our observed $\Delta^{17}O(SO_4^{2-})$. Heterogeneous sulfate production via S(IV) oxidation by O_3 was estimated to contribute 21–22 % of P_{het} on average. Heterogeneous sulfate production pathways that result in zero-$\Delta^{17}O(SO_4^{2-})$, such as

S(IV) oxidation by NO_2 in aerosol water and/or by O_2 via a radical chain mechanism, contributed the remaining 66–73 % of P_{het}. The assumption about the thermodynamic state of aerosols (stable or metastable) was found to significantly influence the calculated aerosol pH (7.6 ±0.1 or 4.7 ±1.1, respectively), and thus influence the relative importance of heterogeneous sulfate production via S(IV) oxidation by NO_2 and by O_2. Our calculation suggests sulfate formation via NO_2 oxidation can be the dominant pathway in aerosols at high pH-conditions calculated assuming stable state while S(IV) oxidation by O_2 can be the dominant pathway providing that highly acidic aerosols (pH ≤ 3) exist. Our results also illustrate the utility of $\Delta^{17}O(SO_4^{2-})$ for quantifying sulfate formation pathways and its inclusion in models may improve our understanding of rapid sulfate formation during haze events.

1 Introduction

Frequent occurrence of haze events in Beijing and throughout the North China Plain (NCP) during cold seasons is a health threat for round 400 million people living there. High concentrations of $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm), of which the daily average can exceed 300 μg m^{-3} during severe haze (He et al., 2014; Jiang et al., 2015), contribute to cardiovascular morbidity and mortality (Brook et al., 2010; Cheng et al., 2013). As one of the major components of $PM_{2.5}$, sulfate is of particular concern due to its high concentrations in haze days (Zheng et al., 2015b; Zheng et al., 2015a) and its key role in the climate system (Seinfeld and Pandis, 2012). Hourly sulfate concentrations can exceed 100 μg m^{-3} and account for up to one quarter of $PM_{2.5}$ mass during severe haze (Zheng et al., 2015a). However, due to the generally low solar radiation and cloud liquid water content (LWC) during haze (Zheng et al., 2015a; Wang et al., 2014), conventional sulfate formation via OH oxidation in the gas-phase and from aqueous-phase SO_2 (referred to as S(IV) = $SO_2 \cdot H_2O + HSO_3^- + SO_3^{2-}$) oxidation by H_2O_2 (McArdle and Hoffmann, 1983), O_3 (Hoffmann and Calvert, 1985), and O_2 via a radical chain mechanism initiated by transition metal ions (TMIs) in clouds (Ibusuki and Takeuchi, 1987; Alexander et al., 2009; Harris et al., 2013) cannot explain the observed high sulfate concentrations (Zheng et al., 2015a). To explain the observed high sulfate concentrations during haze in Beijing and NCP, recent studies have suggested that heterogeneous reactions on/in aerosols/aerosol water are potentially important (He et al., 2014; Hung and Hoffmann, 2015; Cheng et al., 2016; Wang et al., 2016; Zheng et al., 2015a; Zheng et al., 2015b; Wang et al., 2014). In particular, Zheng et al. (2015a) largely improved the underestimate of modelled sulfate concentrations in 2013 Beijing haze by using a relative humidity (RH)-dependent uptake coefficient (γ) of SO_2 on aerosols, without knowing the specific mechanisms of heterogeneous oxidation of SO_2. Calculations by Guo et al. (2017) suggest heterogeneous oxidation of SO_2 in Beijing maybe dominated by O_2 via a radical chain mechanism initiated by TMIs. Laboratory work has suggested SO_2 oxidation by O_3 on mineral dust is a significant pathway for sulfate production (Li et al., 2006), but its role in Beijing haze has not been determined. More recently, Hung and Hoffmann (2015) proposed that rapid S(IV) oxidation by O_2 via a radical chain mechanism on acidic microdroplets (pH ≤ 3) could be responsible

for heterogeneous sulfate production in Beijing haze, while Cheng et al. (2016) suggested that S(IV) oxidation by NO_2 (Lee and Schwartz, 1982; Clifton et al., 1988) in aerosol water could be important due to the high RH and NO_2 concentrations during severe haze in NCP. Due to the strong pH-dependence of SO_2 oxidation and the large variability of model calculated aerosol pH in Beijing haze (Cheng et al., 2016; Wang et al., 2016; Liu et al., 2017), the relative importance of heterogeneous SO_2 oxidation is difficult to constrain.

The oxygen-17 excess ($\Delta^{17}O$) of sulfate, defined as $\Delta^{17}O = \delta^{17}O - 0.52 \times \delta^{18}O$ wherein $\delta^{X}O = (({}^{X}O/{}^{16}O)_{sample}/({}^{X}O/{}^{16}O)_{VSMOW} - 1)$ with X = 17 or 18 and VSMOW referring to Vienna Standard Mean Ocean Water (Matsuhisa et al., 1978), is a useful tool for estimating the relative importance of different sulfate formation pathways because each oxidant transfers its $\Delta^{17}O$ signature to the product (Table 1) through SO_2 oxidation (Savarino et al., 2000). SO_2 has $\Delta^{17}O$ = 0 ‰ due to the rapid isotopic exchange with abundant vapour water whose $\Delta^{17}O$ is near 0 ‰ (Holt et al., 1981). S(IV) oxidation by H_2O_2 and O_3 leads to $\Delta^{17}O(SO_4^{2-}) = 0.7$ ‰ and 6.5 ‰, respectively, on the basis of $\Delta^{17}O(H_2O_2) = 1.4$ ‰ (Savarino and Thiemens, 1999) and assuming $\Delta^{17}O(O_3) = 26$ ‰ (Vicars and Savarino, 2014; Ishino et al., 2017). Other sources of sulfate exhibit $\Delta^{17}O(SO_4^{2-})$ at or near 0 ‰. Specifically, sulfate directly emitted from natural and anthropogenic sources or formed by OH and O_2 oxidation has $\Delta^{17}O(SO_4^{2-})$ values at or near 0 ‰ (Dubey et al., 1997; Luz and Barkan, 2005; Lee et al., 2002; Bao et al., 2000). Sulfate produced by NO_2 oxidation is suggested to occur either via a radical chain mechanism (Shen and Rochelle, 1998), via oxygen-atom transfer from OH^- (Clifton et al., 1988), or from O_2 based on experimental results of He et al. (2014), resulting in $\Delta^{17}O(SO_4^{2-}) = 0$ ‰. Once formed, atmospheric sulfate does not undergo further isotopic exchange, and $\Delta^{17}O(SO_4^{2-})$ will not be altered by mass-dependent processes such as deposition.

In this work, first observations of $PM_{2.5}$ $\Delta^{17}O(SO_4^{2-})$ during haze events from October 2014 to January 2015 in Beijing are reported, contributions of O_3 and H_2O_2 oxidation in heterogeneous sulfate formation are quantified, and the roles of NO_2 and O_2 oxidation are explored.

2 Materials and Methods

2.1 Sampling and atmospheric observations

A high volume air sampler (model TH-1000C II, Tianhong Instruments Co., Ltd, China) with quartz microfiber filter (Whatman Inc., UK, pre-combusted at 450 °C for 4 h) was used to collect $PM_{2.5}$ samples at a flow rate of 1.05 m^3 min^{-1} from October 2014 to January 2015. The collections lasted for 12 h (08:00–20:00 LT or 20:00–08:00 LT) for each sample. The sample site is located on the rooftop of the First Teaching Building at the campus of University of the Chinese Academy of Sciences (40.41 °N, 116.68 °E, around 20 m from the ground) in Beijing, around 60 km northeast of downtown. Hourly $PM_{2.5}$, SO_2, NO_2 and O_3 concentrations were observed at Huairou station (40.33 °N, 116.63 °E) by Beijing Municipal Environmental Monitoring Center, which is about 10 km from our aerosol sampling site. The concentration of atmospheric H_2O_2 was not

observed in our campaign, but long-term observations from March to November in Beijing shows a good correlation between H_2O_2 concentrations (ppb) and air temperature (T, in °C) according to $[H_2O_2] = 0.1155 \times e^{(0.0846 \times T)}$ (Fu, 2014). In the present study, H_2O_2 concentration was estimated from our measured T with the above empirical equation. Our calculated H_2O_2 concentration based on this formula in October and November 2014 is respectively (0.32 ±0.08) ppb and (0.17 ±0.04) ppb, comparable to the observed values of (0.44 ±0.18) ppb and (0.38 ±0.11) ppb, respectively in October and November 2013 (Fu, 2014). Meteorological data including T and relative humidity (RH) were recorded by an automatic weather station (model MetPak with integrated wind sonic, Gill Instruments Limited, UK). Time reported in this paper is local time (LT = UTC + 8).

2.2 Measurements of ions and isotope ratios

The measurements of ions were conducted in Anhui Province Key Laboratory of Polar Environment and Global Change in the University of Science and Technology of China. A detailed description of the method for chemical analysis of NH_4^+, K^+, Ca^{2+}, Na^+, Mg^{2+}, SO_4^{2-}, NO_3^- and Cl^- can be found in the literature (Ye et al., 2015). Briefly, ions were extracted from a part (2 cm × 2 cm) of each filter with 20 ml of Millipore water (≥ 18 MΩ) by sonication for 80 min in an ice water bath. Insoluble substances in the extract were filtered with 0.45 μm filters before analysis. The pH of filtrates was measured by an ion activity meter (model PXS-215, Shanghai INESA Scientific Instrument Co., Ltd., China). And the ion concentrations were analysed using Dionex ICS-2100 ion chromatograph system (Thermo Fisher Scientific Inc., USA). Typical analytical precision by our instrument is better than 10 % RSD (relative standard deviation) for all ions (Chen et al., 2016). The preparation and measurements of $\Delta^{17}O(SO_4^{2-})$ were conducted in Isolab (https://isolab.ess.washington.edu/isolab/) at the University of Washington, USA. A detailed description of the method can be found in the literature (Savarino et al., 2001; Geng et al., 2013; Chen et al., 2016; Alexander et al., 2012). Briefly, $PM_{2.5}$ sample filters were dissolved in Millipore water (≥ 18 MΩ) and the insoluble substances were filtered. Pre-packed ion capture cartridges (Alltech Maxi-Clean IC-RP SPE) were used for the first step of removal of organics. Cations in the samples were replaced with sodium using a cation exchange resin and 30 % H_2O_2 solution was added as the second step of removal of organics. Excess H_2O_2 was removed via evaporation and SO_4^{2-} was separated from other anions (e.g., NO_3^-) by ion chromatography. After ion separation, SO_4^{2-} was converted to Ag_2SO_4, dried, and then pyrolyzed at 1000 °C in an elemental analyzer to form Ag(s), SO_2(g), and O_2(g). The produced gases were carried by He gas to pass through a liquid nitrogen trap to remove SO_2, and then a GC to further purify the O_2 gas which was finally induced to a mass spectrometer (Thermo Scientific MAT 253). Masses of 32, 33 and 34 of O_2 were measured to determine $\delta^{17}O$ and $\delta^{18}O$ and then $\Delta^{17}O$ was calculated. The precision of $\Delta^{17}O$ measurements in our method is ±0.3 ‰ based on replicate analysis of standards, which is consistent with previous studies (Alexander et al., 2005; Sofen et al., 2014; Chen et al., 2016). To quantify the uncertainty in each sample, 30 samples were measured in triplicate, 2 samples in quadruplicate, and 2 samples in duplicate depending on the limitation of sample size. In total, 10 filters sampled in non-polluted days (NPD, $PM_{2.5} < 75$ μg m^{-3}) and 24 filters sampled in polluted days (PD, $PM_{2.5} \geq 75$ μg m^{-3}) were analysed.

2.3 Estimate of the overall rate of heterogeneous sulfate production

Heterogeneous sulfate production (P_{het}) is commonly parameterized in models according to Eq. (1) (Jacob, 2000; Zheng et al., 2015a):

$$P_{\mathrm{het}} = \frac{3600\times 96}{RT}\left(\frac{R_{\mathrm{p}}}{D_{\mathrm{g}}} + \frac{4}{v\gamma}\right)^{-1} S_{\mathrm{p}}[\mathrm{SO_2(g)}] \quad (1)$$

where P_{het} is in unit of μg m^{-3} h^{-1}, 3600 is a time conversion factor (s h^{-1}), 96 is the molar mass of SO_4^{2-} (g mol^{-1}), R is the gas constant (0.082 atm L K^{-1} mol^{-1}), and T is temperature in K. R_p is the radius of aerosol particles (m), D_g is the gas-phase molecular diffusion coefficient of SO_2 (m^2 s^{-1}), v is the mean molecular speed of SO_2 (g) (m s^{-1}), γ is the uptake coefficient of SO_2 on aerosols (unitless), [SO_2 (g)] is the gas-phase concentration of SO_2 (ppb) and S_p is the aerosol surface area per unit volume of air (m^2 m^{-3}). The typical tropospheric value of D_g and v is 2×10^{-5} m^2 s^{-1} and 300 m s^{-1}, respectively (Jacob, 2000). Observations of $PM_{2.5}$ mass concentrations (μg m^{-3}) and $PM_{2.5}$ mean radius (m) during Beijing haze roughly follows an empirical formula: $R_p = (0.254\times PM_{2.5}+10.259)\times10^{-9}$ (Guo et al., 2014). By using the volume and surface area formulas of a sphere and the mean density of particles (ρ = 1.5×10^6 g m^{-3} (Guo et al., 2014)), S_p can be estimated from Eq. (2). A RH-dependent γ (= $(2–5)\times10^{-5}$, Eq. (3)) derived from Zheng et al. (2015a) during 2013 Beijing haze was used. This range of γ is also consistent with the estimated values of γ from (1.6 ± 0.7) to $(4.5\pm1.1)\times10^{-5}$ by Wang et al. (2016).

$$S_{\mathrm{p}} = \frac{\mathrm{PM_{2.5}}\times10^{-6}}{4/3\times\pi {R_{\mathrm{p}}}^3\times\rho}\times 4\pi {R_{\mathrm{p}}}^2 \quad (2)$$

$$\gamma = \begin{cases} 2\times10^{-5}, \mathrm{RH}\le 50\ \% \\ 2\times10^{-5} + \frac{5\times10^{-5}-2\times10^{-5}}{100-50}\times(\mathrm{RH}-50), \ 50\ \%\le \mathrm{RH}\le 100\ \% \end{cases} \quad (3)$$

2.4 Estimate of primary sulfate

The primary sulfate, which is directly emitted into air, includes the sea salt source, terrigenous source and anthropogenic source (Li et al., 2013; Faloona, 2009). The concentration of sea salt sulfate was calculated by using the observed concentrations of SO_4^{2-} and Na^+ and the mass ratio of (SO_4^{2-}/Na^+) = 0.252 in seawater (Calhoun et al., 1991). The terrigenous sulfate was estimated using the observed concentrations of SO_4^{2-} and Ca^{2+} and the mass ratio of (SO_4^{2-}/Ca^{2+}) = 0.18 in soil (Legrand et al., 1997), where (Ca^{2+}/Na^+) = 0.038 in seawater was used to calculate the fraction of observed Ca^{2+} from soil (Legrand and Mayewski, 1997). The anthropogenic primary sulfate is estimated as 3 % of anthropogenic SO_2 emissions in models (Faloona, 2009; Alexander et al., 2009). Supposing all the observed concentrations of SO_2 and precursors of secondary sulfate are anthropogenic, we have $n_{ap} = 3\% \times (n_{SO2} + n_{sas})$, where $n_{sas} = n_{tos}–n_{ss}–n_{ts}–n_{ap}$ and n_{ap}, n_{sas}, n_{tos}, n_{ss} and n_{ts} is the molar concentrations of anthropogenic primary sulfate (ap), secondary sulfate (sas), total sulfate (tos), sea salt sulfate (ss) and terrigenous sulfate (ts). The estimated concentration of total primary sulfate is the sum of primary sulfate from all these sources.

2.5 Estimate of sulfate production rate from OH oxidation in the gas-phase

The sulfate production rate from OH oxidation in the gas-phase (P_{SO2+OH}) can be expressed as:

$$P_{SO_2+OH} = \frac{3600 \times 96 \times R_{SO_2+OH}}{RT} \quad (4)$$

where P_{SO2+OH} is in unit of μg m^{-3} h^{-1}, 3600, 96, R and T is the same as Eq. (1). R_{SO2+OH} is the chemical reaction rate (ppb s^{-1}), calculated as shown in Table S1 and S2.

2.6 Estimate of in-cloud sulfate production rate

The main in-cloud sulfate formation pathways considered here include S(IV) oxidation by H_2O_2, O_3, NO_2 (Wang et al., 2016) and O_2 via a radical chain mechanism initiated by TMIs (Alexander et al., 2009). Their chemical reaction rate expressions ($R_{S(IV)+oxi}$) and rate constants (k) are summarized in Table S3. The rate of in-cloud sulfate production by a certain oxidant ($P_{cloud,\ S(IV)+oxi}$) can be expressed as (Seinfeld and Pandis, 2012):

$$P_{cloud,S(IV)+oxi} = 3600 \times 96 \times LWC \times R_{S(IV)+oxi} \quad (5)$$

where $P_{cloud,\ S(IV)+oxi}$ is in unit of μg m^{-3} h^{-1}, 3600 and 96 is the same as Eq. (1), and $R_{S(IV)+oxi}$ is in unit of M s^{-1}. Cloud liquid water content (LWC, in unit of mg m^{-3}) was derived from a global reanalysis, GEOS-FP (https://gmao.gsfc.nasa.gov/products/).

2.7 Isotopic constraints on sulfate formation pathways

Since S(IV) oxidation by O_3 and H_2O_2 are the sole sources of non-zero $\Delta^{17}O(SO_4^{2-})$ (Table 1) (Savarino et al., 2000), the relative importance of different sulfate formation pathways can be calculated as follows (Alexander et al., 2012):

$$\Delta^{17}O_{obs} = \left(6.5 \times f_{S(IV)+O_3}\right) + \left(0.7 \times f_{S(IV)+H_2O_2}\right) + \left(0 \times f_{zero-\Delta^{17}O}\right) \quad (6)$$

where $f_{S(IV)+O3}$ and $f_{S(IV)+H2O2}$ are the fractional contributions of S(IV) oxidation by O_3 and H_2O_2 oxidation to total sulfate production, respectively, and $f_{zero-\Delta17O}$ represents the fractional contribution of sulfate with zero-$\Delta^{17}O$ processes such as primary sulfate, secondary sulfate formed via OH oxidation, NO_2 oxidation, and O_2 oxidation. By definition, we have $f_{S(IV)+O3}$ + $f_{S(IV)+H2O2}$ + $f_{zero-\Delta17O}$ = 100 %.

In addition, as sulfate with non-zero $\Delta^{17}O(SO_4^{2-})$ is produced either via in-cloud reactions or via heterogeneous reactions or both, Eq. (6) can also be written as follows:

$$\Delta^{17}O_{obs} = f_{het} \times \Delta^{17}O_{het} + f_{cloud} \times \Delta^{17}O_{cloud} + f_{SO_2+OH} \times \Delta^{17}O_{SO_2+OH} + f_p \times \Delta^{17}O_p \quad (7)$$

where f_{het}, f_{cloud}, f_{SO2+OH} and f_p respectively represents the fractional contribution of heterogeneous sulfate production, in-cloud sulfate production, gas-phase sulfate production and primary sulfate to the observed sulfate. $\Delta^{17}O_{het}$, $\Delta^{17}O_{cloud}$, $\Delta^{17}O_{SO2+OH}$ and $\Delta^{17}O_p$ respectively represents $\Delta^{17}O$ of corresponding sulfate produced via above pathways. Both $\Delta^{17}O_{SO2+OH}$ and $\Delta^{17}O_p$ are

equal to 0 ‰. $\Delta^{17}O_{cloud}$ can be calculated as shown in Eq. (8) as the lifetime of sulfate produced in clouds will not depend on the specific S(IV) oxidant.

$$\Delta^{17}O_{cloud} = \frac{6.5\times P_{cloud,S(IV)+O_3} + 0.7\times P_{cloud,S(IV)+H_2O_2}}{P_{cloud}} \quad (8)$$

where P_{cloud} is the rate of total in-cloud sulfate production, which was calculated as the sum of in-cloud S(IV) oxidation by H_2O_2, O_3, NO_2 and O_2 initiated by TMIs.

2.8 Calculation of aerosol water content (AWC), aerosol pH and ionic strength (I_s)

AWC, aerosol pH and I_s was calculated by the ISORROPIA II model, which is a thermodynamic equilibrium model for NH_4^+-K^+-Ca^{2+}-Na^+-Mg^{2+}-SO_4^{2-}-NO_3^--Cl^--H_2O aerosols (Fountoukis and Nenes, 2007). The ISORROPIA II model can solve forward problems in which *T*, RH and the concentrations of gas + aerosols are known (e.g., NH_3 + NH_4^+), and reverse problems in which *T*, RH and the concentrations of aerosol (but not gas) species are known. We used the forward method to calculate AWC, aerosol pH and I_s as this method has been shown to best predict aerosol pH (Hennigan et al., 2015). The AWC, pH and I_s was first calculated in metastable mode (assuming that bulk aerosol solution is supersaturated), which is consistent with previous studies about Beijing haze (Liu et al., 2017; Guo et al., 2017). However, the work of Rood et al. (1989) in California, USA suggested that not all aerosols are in metastable state, even though the fractional occurrence of metastable aerosols increases with increasing RH in urban sites (i.e., from near 0 at RH < round 30 % to near 100 % at RH > round 80 %, roughly following Eq. (9)). We also calculated the AWC, pH and I_s assuming stable mode (assuming that bulk aerosols crystallize once saturation is exceeded), which is consistent with Wang et al. (2016). The input of observed inorganic ion concentrations and meteorological parameters are summarized in Table S4. Since gaseous NH_3 was not measured in our campaign, we used the empirical equation NH_3 (ppb) = 0.34 ×NO_X (ppb) + 0.63, derived from observations of Meng et al. (2011) in Beijing winter, to estimate the NH_3 concentrations. We used NO_2 concentrations instead of NO_X as input due to the lack of NO_X observations in our study, which would give a lower end of the NH_3 concentrations. Given the importance of AWC for reaction rates and the fact that ISORROPIA II underestimates AWC at low RH (Bian et al., 2014), samples with RH < 40 % are excluded from analysis (Hennigan et al., 2015). This excludes 8 out of the total 34 samples (24 %), with 6 of them in NPD. A total of 4 samples in NPD and 22 samples in PD were analysed for AWC, aerosol pH and I_s using observations and the ISORROPIA II model. Due to that the predicted I_s is high (I_s > 10 M, Table S4), which suggests aerosol water is non-ideal, the influence of I_s on reaction rate constants (Table S3) and effective Henry's law constants (Table S5) is taken into consideration when the influence is known.

$$MF = \begin{cases} 0, & RH < 30\ \% \\ -0.024 \times RH^2 + 4.18 \times RH - 89.13, & 30\ \% \le RH \le 80\ \% \\ 100\ \%, & 80\ \% < RH \le 100\ \% \end{cases} \quad (9)$$

where MF (in %) is the fraction of metastable aerosols to total aerosols.

2.9 Estimate of aqueous concentrations of trace species

The aqueous concentrations of SO_2, O_3, H_2O_2 and NO_2 were calculated as described in Table S5. The determination of in-cloud concentrations of TMIs (here only Fe(III) and Mn(II) (Alexander et al., 2009)) is described below.

The concentration of soluble Fe(III) follows Eqs. (10)–(13) (Liu and Millero, 1999):

$$\log_{10}[\mathrm{Fe(III)}] = \log_{10} K^*_{\mathrm{Fe(OH)_3}} + 3 \times \log_{10}[\mathrm{H^+}] + \log_{10}(1 + \beta_1^*[\mathrm{H^+}]^{-1} + \beta_2^*[\mathrm{H^+}]^{-2}) \quad (10)$$

where

$$\log_{10} K^*_{\mathrm{Fe(OH)_3}} = -13.486 - 0.1856 \times I_s^{0.5} + 0.3073 \times I_s + 5254/T \quad (11)$$

$$\log_{10} \beta_1^* = 2.517 - 0.8885 \times I_s^{0.5} + 0.2139 \times I_s - 1320/T \quad (12)$$

$$\log_{10} \beta_2^* = 0.4511 - 0.3305 \times I_s^{0.5} - 1996/T \quad (13)$$

and [Fe(III)] is the aqueous concentration of Fe(III) in unit of M, T is temperature in unit of K, and I_s is ionic strength in unit of M, $K^*_{\mathrm{Fe(OH)3}}$ is the solubility product constant of $Fe(OH)_3$, and β^*_1 and β^*_2 is respectively first-order and second-order cumulative hydrolysis constants of Fe^{3+}.

Our calculation suggested in-cloud [Fe(III)] was in the range of 0.6 to 6.1 μM with a mean of (2.6±1.8) μM, which is similar to the observed values in NCP (Guo et al., 2012; Shen et al., 2012). The concentration of soluble Mn(II) in cloud water was set to be 1 μM in the present study, which is the general value observed in cloud water in NCP (Guo et al., 2012; Shen et al., 2012).

2.10 Estimate of sulfate production rate in aerosol water

The reaction rate expressions, rate constants (k) and the influence of I_s on k for sulfate production in aerosol water are summarized in Table S3. The overall rates for S(IV) oxidation in aerosol water depend not only on chemical reaction rates (Table S3) but also on mass transport limitations. A standard resistance model was used to estimate effects of mass transport following the work of Cheng et al. (2016):

$$\frac{1}{R_{\mathrm{H,S(IV)+oxi}}} = \frac{1}{R_{\mathrm{S(IV)+oxi}}} + \frac{1}{J_{\mathrm{aq,lim}}} \quad (14)$$

where $R_{\mathrm{H,\,S(IV)+oxi}}$ is the overall reaction rate for S(IV) oxidation by a certain oxidant (oxi) such as O_3, H_2O_2, NO_2 and O_2 on acidic microdroplets (M s^{-1}), $R_{\mathrm{S(IV)+oxi}}$ is the chemical reaction rate (M s^{-1}) and $J_{\mathrm{aq,\,lim}}$ is the rate limited by mass transfer from the gas to the aqueous phase (M s^{-1}). Due to the large decrease in the aqueous-phase reaction rate constant for TMI-initiated S(IV) oxidation by O_2 with increasing I_s (Martin and Hill, 1967) and the high I_s of aerosols (Table S4), combined with the fact that the rate constant for the S(IV) + O_2 mechanism on acidic microdroplets proposed by Hung and Hoffman (2015) likely includes the effect of TMIs, we do not directly consider TMI-initiated S(IV) oxidation by O_2 in aerosol water. $R_{\mathrm{S(IV)+oxi}}$ was calculated as described in Table S3. The limiting mass transfer $J_{\mathrm{aq,\,lim}}$ was calculated by Eqs. (15) and (16).

$$J_{\mathrm{aq,lim}} = \min\{J_{\mathrm{aq}}(\mathrm{SO_2}), J_{\mathrm{aq}}(\mathrm{oxi})\} \quad (15)$$

$$J_{aq}(X) = k_{MT}(X) \times [X(aq)] \quad (16)$$

where X = SO_2, O_3, H_2O_2 or NO_2 and k_{MT} (s^{-1}) is the mass transfer rate coefficient and was calculated as Eq. (17) (Cheng et al., 2016; Seinfeld and Pandis, 2012):

$$k_{MT}(X) = \left[\frac{R_p^2}{3D_g} + \frac{4R_p}{3\alpha v}\right]^{-1} \quad (17)$$

where R_p, D_g and v are the same as Eq. (1). The α used in our calculation is respectively 0.11 for SO_2, 0.23 for H_2O_2, 2.0×10^{-3} for O_3 and 2.0×10^{-4} for NO_2 (Seinfeld and Pandis, 2012; Jacob, 2000). The term on the left hand side of Eq. (17) is the gas-phase diffusion limitation while the term on the right hand side of Eq. (17) is the interfacial mass transport limitation. k_{MT} was limited by interfacial mass transport in our study.

The rate of heterogeneous sulfate production by a certain oxidant ($P_{het,\,S(IV)+oxi}$) in aerosol water can be expressed as:

$$P_{het,S(IV)+oxi} = 3600 \times 96 \times AWC \times R_{H,S(IV)+oxi} \quad (18)$$

where $P_{het,\,S(IV)+oxi}$ is in the unit of μg m^{-3} h^{-1}, 3600 and 96 is the same as Eq. (1). AWC is in the unit of mg m^{-3} and $R_{H,\,S(IV)+oxi}$ is in the unit of M s^{-1}.

3 Results and Discussion

3.1 Characteristics of haze events in Beijing

Figure 1a shows the temporal evolution of concentrations of $PM_{2.5}$ and SO_4^{2-} during our sampling period. The 12h-averaged $PM_{2.5}$ concentrations ranged from 16 to 323 μg m^{-3} with a mean of (141±88 (1σ)) μg m^{-3}. In comparison, the Grade II of the Chinese National Ambient Air Quality Standard of daily $PM_{2.5}$ is 75 μg m^{-3}. The SO_4^{2-} concentrations varied from 1.5 to 56.4 μg m^{-3} with a mean of (21.2±15.4) μg m^{-3}. As shown in Fig. 1a, SO_4^{2-} concentrations presented a similar temporal trend as $PM_{2.5}$ concentrations, i.e., increased from a mean of (3.9±1.8) μg m^{-3} in non-polluted days (NPD, $PM_{2.5}$ < 75 μg m^{-3}) to (28.4±12.5) μg m^{-3} in polluted days (PD, $PM_{2.5}$ ≥ 75 μg m^{-3}). The fraction of SO_4^{2-} to $PM_{2.5}$ mass concentration ranged from 8–25 %, and increased from a mean of (11±2) % in NPD to (15±5) % in PD. The sulfur oxidation ratio (SOR = $nSO_4^{2-}/(nSO_4^{2-}+nSO_2)$, where nSO_4^{2-} and nSO_2 represents the molar concentration of SO_4^{2-} and SO_2, respectively), a proxy for secondary sulfate formation (Sun et al., 2006), also increased rapidly with $PM_{2.5}$ levels, from a mean of (0.12±0.04) in NPD to (0.41±0.17) in PD (Fig. 1b).

Observed $\Delta^{17}O(SO_4^{2-})$ ($\Delta^{17}O_{obs}$) ranged from 0.1 ‰ to 1.6 ‰ with a mean of (0.9±0.3) ‰ (Fig. 1b). The highest $\Delta^{17}O_{obs}$ = 1.6 ‰ occurred during PD of Case II in October 2014 while the lowest $\Delta^{17}O_{obs}$ = 0.1 ‰ occurred during PD of Case IV in December 2014. $\Delta^{17}O_{obs}$ reported here is similar in magnitude to previous observations of $\Delta^{17}O(SO_4^{2-})$ in aerosols and rainwater collected in China (Lin et al., 2017; Li et al., 2013) and other mid-latitude sites (Table S6). The overall $\Delta^{17}O_{obs}$ levels during our entire sampling time are similar for NPD and PD, being (0.9±0.1) ‰ and (0.9±0.4) ‰, respectively. However, the NPD to PD difference of $\Delta^{17}O_{obs}$ can be case-dependent. For Case I and II in October 2014, $\Delta^{17}O_{obs}$ increased from NPD to PD,

while the opposite trend was observed for Case III to V in November 2014 to January 2015 (Fig. 1b). These $\Delta^{17}O_{obs}$ variations are generally similar to variability in concentrations of observed O_3 and calculated H_2O_2 (Fig. 1c), which is consistent with the fact that O_3 and H_2O_2 are the sole sources of non-zero $\Delta^{17}O(SO_4^{2-})$ (Table 1).

3.2 Direct estimate of sulfate formation pathways based on $\Delta^{17}O_{obs}$

Figure 2 shows the calculated possible fractional contributions of each formation pathway ($f_{S(IV)+H2O2}$, $f_{S(IV)+O3}$, and $f_{zero\text{-}\Delta17O}$) for each sample using Eq. (6). On average over all samples collected, $f_{S(IV)+O3}$ = 4–13 %, $f_{S(IV)+H2O2}$ = 0–88 %, and $f_{zero\text{-}\Delta17O}$ = 8–87 %. For samples during PD of Case IV in December 2014 with the three lowest $\Delta^{17}O_{obs}$ values (Fig. 1b), $f_{zero\text{-}\Delta17O}$ was respectively in the range of 57–95 %, 86–98 % and 57–95 %, corresponding to $f_{S(IV)+H2O2}$ being in the range of 0–43 %, 0–14 % and 0–43 % respectively, which clearly suggests zero-$\Delta^{17}O$ pathways dominated sulfate formation during PD of Case IV. However, for other samples, the maximum possible $f_{S(IV)+H2O2}$ ranged from 71 to 100 % with a mean of (93±7) % while the maximum possible $f_{zero\text{-}\Delta17O}$ was 75 to 92 % with a mean of (86±4) %, implying that sulfate formation during these sampling periods were dominated by H_2O_2 oxidation and/or zero-$\Delta^{17}O$ pathways.

3.3 Chemical kinetic calculations with the constraint of $\Delta^{17}O_{obs}$

The good correlation between RH and SOR in Fig. 3a ($r = 0.76$, $p < 0.01$) suggests heterogeneous reactions played an important role in sulfate formation. Our calculations show that overall heterogeneous sulfate production (P_{het}, see Sect. 2.3) presented similar trends with SO_4^{2-} concentrations except for Case II (Fig. 3b) and increased from a mean of (0.6±0.3) μg m^{-3} h^{-1} in NPD to (2.0±1.1) μg m^{-3} h^{-1} in PD during our entire sampling period. In comparison, Cheng et al. (2016) reported that the missing sulfate production rate required to explain the observed sulfate concentration is around 0.07 μg m^{-3} h^{-1} when $PM_{2.5}$ < 50 μg m^{-3} and around 4 μg m^{-3} h^{-1} when $PM_{2.5}$ > 400 μg m^{-3} during 2013 Beijing haze. We also calculated the contribution from primary sulfate and performed chemical kinetic calculations including SO_2 oxidation by OH in the gas-phase and in-cloud sulfate production (Fig. 4 and Table S7, see Sect. 2.4–2.6) to estimate the relative importance of heterogeneous sulfate production in our sampling period. Heterogeneous reactions were found to dominate sulfate formation during PD in four out of the total five cases (except for Case II) with fractional contributions of 42 to 54 % and a mean of (48±5) % (Fig. 4). This is consistent with Zheng et al. (2015a) who modelled that about half of the observed sulfate was from heterogeneous reactions during 2013 Beijing haze. In contrast, we found that during PD of Case II in October 2014, heterogeneous sulfate production only accounted for 23 % of total sulfate production while in-cloud sulfate production predominated total sulfate production with an estimated fraction of 68 %. The predominant role of in-cloud sulfate production in PD of Case II was supported by the relative high LWC during this time period (Fig. 5a). Our calculations also suggest the in-cloud sulfate production was dominated by H_2O_2 oxidation throughout our sampling period (Fig. 5b), which is consistent with previous findings that H_2O_2 oxidation is the most important in-cloud sulfate production pathway globally (Alexander et al., 2012) and in

NCP (Shen et al., 2012). In addition, the $\Delta^{17}O$ of sulfate produced in clouds ($\Delta^{17}O_{cloud}$) was estimated to range from 0.5 ‰ to 0.8 ‰ with a mean of (0.6±0.1) ‰ during our sampling period and showed similar variations with $\Delta^{17}O_{obs}$ (Fig. 5c). The mean value of $\Delta^{17}O_{cloud}$ calculated here is close to $\Delta^{17}O(SO_4^{2-})$ in rainwater observed in central China (0.53±0.19 ‰) (Li et al., 2013) and at Baton Rouge, USA (0.62±0.32 ‰) (Jenkins and Bao, 2006). In addition, by using Eq. (7), the $\Delta^{17}O$ of sulfate produced via heterogeneous reactions ($\Delta^{17}O_{het}$) was calculated to range from 0.1 ‰ to 3.1 ‰ in our study.

To explore the specific mechanisms of heterogeneous oxidation of SO_2, we calculated aerosol parameters such as aerosol water content (AWC), pH and ionic strength (I_s) by using the ISORROPIA II thermodynamic model (Fountoukis and Nenes, 2007) (Fig.6, see Sect. 2.8). It was found that the assumptions about aerosol thermodynamic state (salts crystallize once saturation is exceeded, termed as "stable state" or aerosol solution is supersaturated, termed as "metastable state") significantly influence the calculated aerosol pH, but have little impact on the calculated AWC and I_s (Fig. 6). Calculated AWC increased with $PM_{2.5}$ concentrations, from (5.3±7.4) μg m^{-3} in NPD to (63.5±54.6) μg m^{-3} in PD when assuming stable state and from (9.6±6.0) μg m^{-3} in NPD to (84.2±49.2) μg m^{-3} in PD when assuming metastable state (Fig. 6a). Calculated I_s was similar for stable and metastable assumptions, ranging from 11.3 to 51.6 M (Fig. 6b). The high I_s suggested aerosol water was non-ideal and thus the influence of I_s on reaction rate constants (Table S3) and effective Henry's law constants (Table S5) was taken into consideration when the influence is known. The bulk aerosol pH predicted in stable state was in the range of 7.5 to 7.8 with a mean of (7.6±0.1), consistent with bulk aerosol pH (7.63±0.03) calculations during a haze event in Beijing 2015 predicted by Wang et al. (2016). The bulk aerosol pH calculated assuming metastable state was in the range of 3.4 to 7.6 with a mean of (4.7±1.1), consistent with the mean value of 4.2 calculated in metastable aerosol assumption during severe haze in Beijing 2015–2016 by Liu et al. (2017). The calculated aerosol pH assuming metastable state decreased with increasing $PM_{2.5}$ levels, from a mean of (6.5±1.3) in NPD to (4.4±0.6) in PD, while that assuming stable state shows no relationship with $PM_{2.5}$ concentrations (Fig. 6c). Our measured pH of filtrate ranged from 4.6 to 8.2 with a mean of (5.7±1.0), similar to pH of filtrate from $PM_{2.5}$ in Beijing reported by Wang et al. (2005). The measured pH of filtrate shows similar trends with bulk aerosol pH calculated assuming metastable state (Fig. 6c), with a mean value (6.9±0.7) in NPD and (5.1±0.6) in PD, which suggests that bulk aerosols are in metastable state with moderate acidity in PD. This is also consistent with our estimate that most aerosols are in metastable with a fraction of (74±17) % in PD by using Eq. (9) and our cognition that the mixture of major acidic aerosols with minor neutral aerosols would lead to the bulk being acidic. However, as the effective Henry's law constant of SO_2 at pH = 7.6 (stable state) can be 3 orders magnitude higher than that at pH = 4.4 (metastable state in PD) rendering even a small fraction of aerosol at this high pH value being potentially significant active sites for heterogeneous sulfate production during PD.

The main heterogeneous sulfate formation pathways considered include S(IV) oxidation by H_2O_2, O_3, NO_2 and O_2 on acidic microdroplets as proposed by Hung and Hoffmann (2015). Other sulfate formation pathways such as S(IV) oxidation by

NO_3 radical, methyl-hydrogenperoxide (MHP), peroxyacetic acid (PAA), and hypohalous acids in aerosol water (Feingold et al., 2002; Walcek and Taylor, 1986; Chen et al., 2017) is thought to be negligible during haze in NCP (Cheng et al., 2016), and thus is not considered here. We estimate the relative importance of these heterogeneous sulfate formation pathways as follows. First, the heterogeneous sulfate production rate via S(IV) oxidation by H_2O_2 ($P_{het,\ S(IV)+H2O2}$) was calculated with the influence of I_s being considered, which has been determined at high I_s in laboratories (Table S3 and S5). Then, the fractional contribution of H_2O_2 oxidation ($f_{het,\ S(IV)+H2O2}$) to overall heterogeneous sulfate production (P_{het}) calculated using apparent γ (see Sect. 2.3) was estimated. Large uncertainties exist in the influence of I_s on the reaction rate constant of S(IV) oxidation by O_3 in aerosol water (Table S3), renders the estimate of its fractional contribution ($f_{het,\ S(IV)+O3}$) to P_{het} from purely chemical kinetic calculations uncertain. Instead, $f_{het,\ S(IV)+O3}$ was estimated using our calculated $f_{het,\ S(IV)+H2O2}$ and $\Delta^{17}O_{het}$ values, on the basis that $\Delta^{17}O(SO_4^{2-}) > 0$ ‰ originates solely from H_2O_2 and O_3 oxidation. Then zero-$\Delta^{17}O$ pathways such as S(IV) oxidation by NO_2 and by O_2 was estimated to be the remaining part ($f_{het,\ zero\text{-}\Delta17O}$). At last, the potential importance of S(IV) oxidation by NO_2 and by O_2 is discussed.

Calculations show that $f_{het,\ S(IV)+H2O2}$ was 4–6 % with a mean of (5 ±1) % under stable aerosol assumptions, and 8–19 % with a mean of (13 ±4) % under metastable state assumptions for PD of all the cases. $f_{het,\ S(IV)+O3}$ was calculated to be 2–47 % with a mean of (22 ±17) % in stable state assumption and 0–47 % with a mean of (21 ±18) % in metastable state assumption. Correspondingly, $f_{het,\ zero\text{-}\Delta17O}$ was the remaining 73 % (47–94 %) in stable assumption, or 66 % (42–81 %) in metastable assumption for PD of all the cases (Fig. 7). Excluding PD of Case II, in which sulfate formation was predominated by in-cloud reactions, our calculations suggest zero-$\Delta^{17}O$ pathways such as S(IV) oxidation by NO_2 and/or by O_2 are important for sulfate formation during Beijing haze.

Cheng et al. (2016) suggested that S(IV) oxidation by NO_2 in aerosol water could largely account for the missing sulfate source in 2013 Beijing haze. In their study, the calculated mean aerosol pH is 5.8, while influence of I_s was not taken into account due to the lack of relevant experimental data. The calculated $P_{het,\ S(IV)+NO2}$ is highly sensitive to aerosol pH. In our study, when aerosol pH decreased from (7.6 ±0.1) assuming stable state to (4.7 ±1.1) assuming metastable state, mean $P_{het,\ S(IV)+NO2}$ decreased from (6.5±7.7) μg m^{-3} h^{-1} to (0.01±0.02) μg m^{-3} h^{-1} for PD of all the cases (Fig. 7). The former is much larger than our estimate of overall heterogeneous production rate, P_{het} = (2.0±1.1) μg m^{-3} h^{-1}, while the latter is too small. Moreover, the influence of I_s was not considered, which is expected to increase the reaction rate constant of S(IV) oxidation by NO_2 (Cheng et al., 2016). The treatment of aerosols as a bulk quantity, assuming that all aerosols are either in stable or metastable state, or that all aerosol particles have the same pH, may lead to errors in calculating heterogeneous sulfate production rates. As stated in Sect. 2.8, not all aerosols are in metastable state, even though the fractional occurrence of metastable aerosols increases with increasing RH (Rood et al., 1989). Fig. 8a shows that the fraction of metastable aerosols to total aerosols (MF in %), estimated by using Eq. (9), increases with $PM_{2.5}$ levels. However, when assuming a combination of stable and metastable state aerosol as

shown in Eq. (9), $P_{het, S(IV)+NO2}$ increases with $PM_{2.5}$ levels and reaches (0.9±0.7) μg m^{-3} h^{-1} during PD of all the cases (Fig. 8b), much higher than $P_{het, S(IV)+NO2}$ = (0.01±0.02) μg m^{-3} h^{-1} under sole metastable aerosol assumption. This estimate suggests that even though the majority of aerosols may be in metastable state during PD (74 ± 17 % in our calculation), the high pH of the minority of aerosols in stable state could render S(IV) oxidation by NO_2 a potentially significant pathway for heterogeneous sulfate production.

Since $P_{het, S(IV)+NO2}$ using calculated aerosol pH assuming metastable state was two orders of magnitude lower than P_{het} during PD, we further examined S(IV) oxidation by O_2 on acidic microdroplets under the metastable state assumption. A laboratory study suggested that SO_2 oxidation by O_2 on acidic microdroplets has a large aqueous-phase reaction rate constant of 1.5×10^6[S(IV)] (M s^{-1}) at pH ≤ 3, a pH range much lower than our calculated pH values. The rate constant was shown to decrease with increasing pH, however, no values of the rate constant at pH > 3 was reported (Hung and Hoffmann, 2015). Figure 7b shows heterogensous sulfate production rate via S(IV) oxidation by O_2 on acidic microdroplets ($P_{het, S(IV)+O2}$) with AWC calculated assuming metastable state and the aqueous-phase rate constant for pH ≤ 3 being used, even though the calculated aerosol pH is > 3. The estimated $P_{het, S(IV)+O2}$ is 1.5×10^3 to 1.3×10^5 μg m^{-3} h^{-1} with a mean of 2.5×10^4 μg m^{-3} h^{-1} during PD of all cases, which is four order of magnitude larger than P_{het}. This value should be an overestimate due to our calculated bulk aerosol pH predicted in metastable state being (4.4±0.6) during PD and the experimental results of He et al. (2014) and Wang et al. (2016) suggests O_2 oxidation pathway is negligible at higher pH conditions (e.g., on CaO and in NH_4^+ solution). However, some fraction of aerosols may have pH ≤ 3 due to the Kelvin effect (Hung and Hoffmann, 2015), rendering S(IV) oxidation by O_2 on acidic microdroplets a potentially important pathway for heterogeneous sulfate production even if it may occur on only a small fraction of the ambient aerosol.

4 Conclusions

Our study suggests that both in-cloud reactions and heterogeneous reactions can dominate sulfate formation during Beijing haze, with the fractional contribution of f_{cloud} = 68% in Case II and f_{het} = (48±5) % in Case I and III–V. The $\Delta^{17}O$-constrained calculation shows that the heterogeneous sulfate production during haze events in our observation was mainly (66 to 73 % on average) from reactions that result in sulfate with $\Delta^{17}O$ = 0 ‰, e.g., S(IV) oxidation by NO_2 and/or by O_2. S(IV) oxidation by H_2O_2 and O_3 accounted for the rest (27 to 34 %) of heterogeneous sulfate production. However, given the large difference in predicted aerosol pH assuming metastable aerosol state and stable aerosol state (pH = 7.6±0.1 and 4.7±1.1, respectively) and the strong dependence of SO_2 oxidation on aerosol pH, we cannot quantify the relative importance of these two pathways for heterogeneous sulfate production. S(IV) + NO_2 can be the dominant pathway when aerosols are in stable state with pH = 7.6±0.1, while S(IV) + O_2 can take over providing that highly acidic aerosols (pH ≤ 3) exist. To distinguish

which of these two mechanisms is more important for sulfate formation during Beijing haze, the heterogeneity of aerosol state and pH should be considered in future studies.

Supplementary Materials

Table S1. Reaction rate expression and constant for SO_2 oxidation by OH in the gas-phase.

Table S2. The daytime average OH concentration.

Table S3. Aqueous-phase reaction rate expressions, rate constants (k) and influence of ionic strength (I_s) on k for sulfate production in aerosol and cloud water.

Table S4. The input and output of ISORROPIA II model.

Table S5. Calculations of aqueous-phase concentrations, equilibrium constants and influence of ionic strength.

Table S6. Observed $\Delta^{17}O(SO_4^{2-})$ in aerosols or rainwater in mid-latitude areas.

Table S7. Estimated fractional contribution of different sulfate production pathways during Beijing haze.

Data availability

All data needed to draw the conclusions in the present study are shown in this paper and/or the Supplementary Materials. For additional data related to this study, please contact the corresponding author (zqxie@ustc.edu.cn).

Author contributions

Z.Q.X. initiated and led the study. P.Z.H. conducted oxygen isotope measurements supervised by B.A. and L.G.. P.Z.H., X.Y.C, S.D.F., H.C.Z., H. K. performed the field experiments and aerosol chemical composition measurements. P.Z.H., B.A., Z.Q.X., L.G., H.S. and Y.F.C. interpreted the data. H.S., Y.F.C. and G.J.Z. involved the discussion of oxidation pathway calculation. C.L. contributed to the field observation support. P.Z.H. wrote the manuscript with B.A., Z.Q.X. and L.G. inputs. All authors involved the discussion and revision.

Competing interests

The authors declare no competing interests.

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Figures and Tables

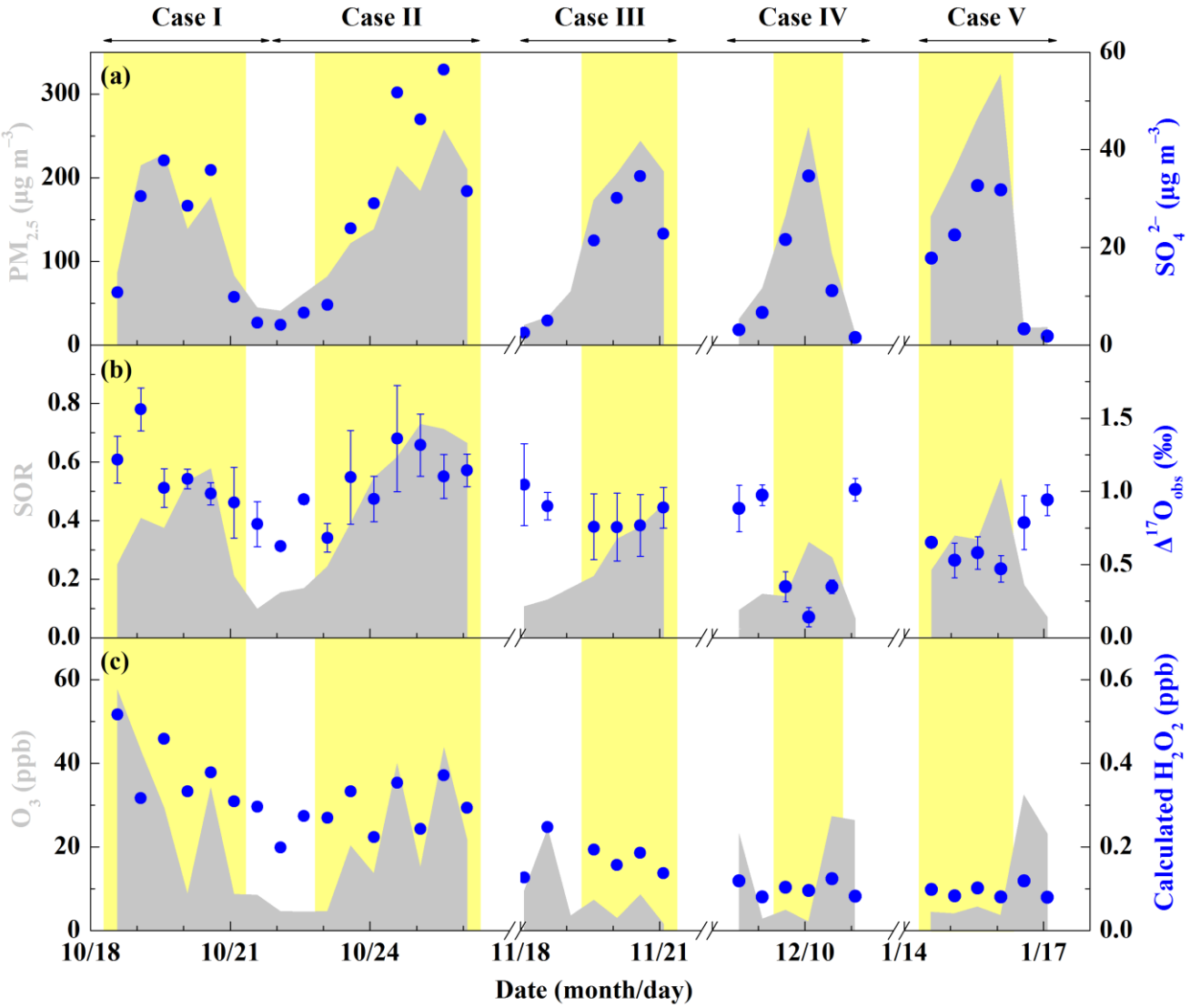
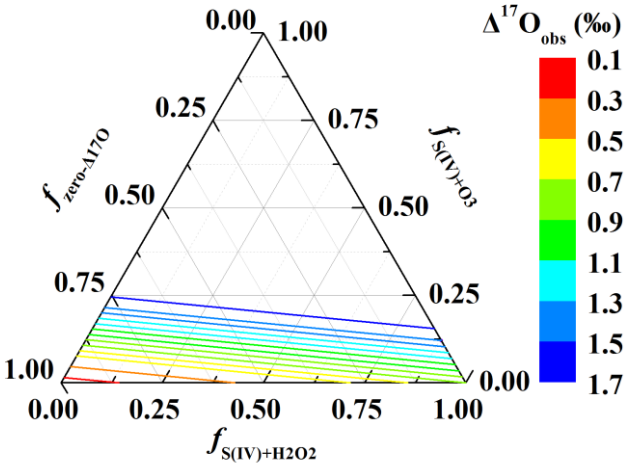


Figure 1. Characteristics of haze events in Beijing (October 2014–January 2015). **(a)** Temporal evolution of $PM_{2.5}$ and SO_4^{2-} concentrations. **(b)** Temporal evolution of sulfur oxidation ratio (SOR = $nSO_4^{2-}/(nSO_4^{2-}+nSO_2)$, n represents the molar concentration) and observed $\Delta^{17}O(SO_4^{2-})$ ($\Delta^{17}O_{obs}$). **(c)** Temporal evolution of observed O_3 and calculated H_2O_2. The error bar of $\Delta^{17}O_{obs}$ in (b) is ±1σ of replicate measurements (n = 2–4) of each sample. The light yellow shaded area indicates polluted days (PD, $PM_{2.5} \geq 75$ μg m^{-3}). Data used here are 12h-averaged values, corresponding with filter samples.



566

567 **Figure 2.** Ternary diagram of possible fractional contribution of different pathways to total sulfate production directly
568 estimated from $\Delta^{17}O_{obs}$. The colored lines are contour lines of $\Delta^{17}O_{obs}$, representing possible fractional contribution of sulfate
569 formation via O_3 ($f_{S(IV)+O3}$) and H_2O_2 ($f_{S(IV)+H2O2}$) oxidation or zero-$\Delta^{17}O$ processes ($f_{zero-\Delta17O}$) such as primary sulfate, secondary
570 sulfate formed via OH oxidation, NO_2 oxidation and O_2 oxidation.

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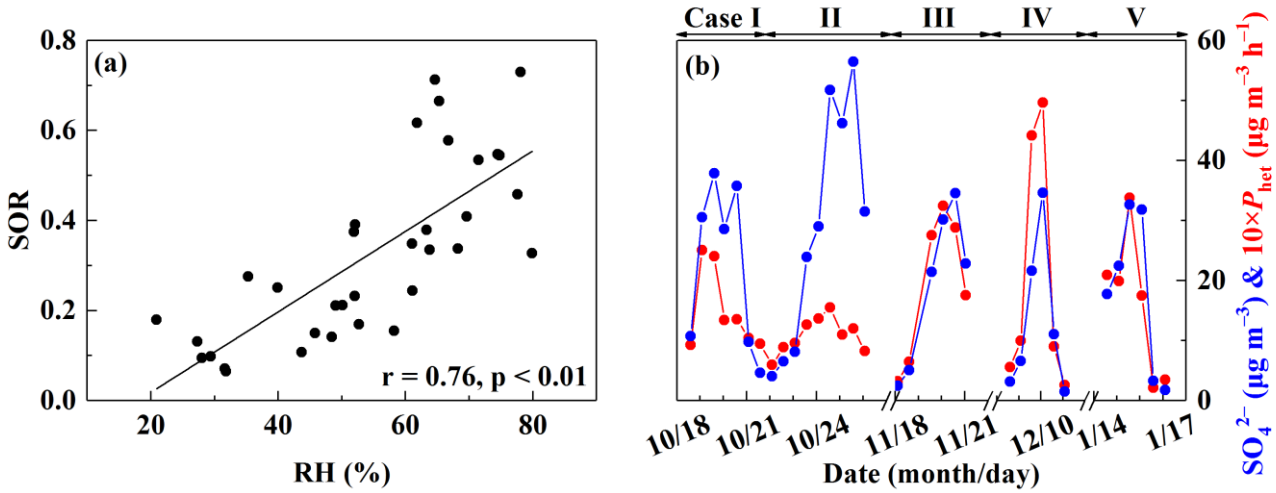


572

573 **Figure 3.** The relationship between RH and SOR **(a)** and time series of overall heterogeneous sulfate production (P_{het}) along
574 with SO_4^{2-} concentrations **(b)**. The black line in (a) is linear least-squares fitting line.

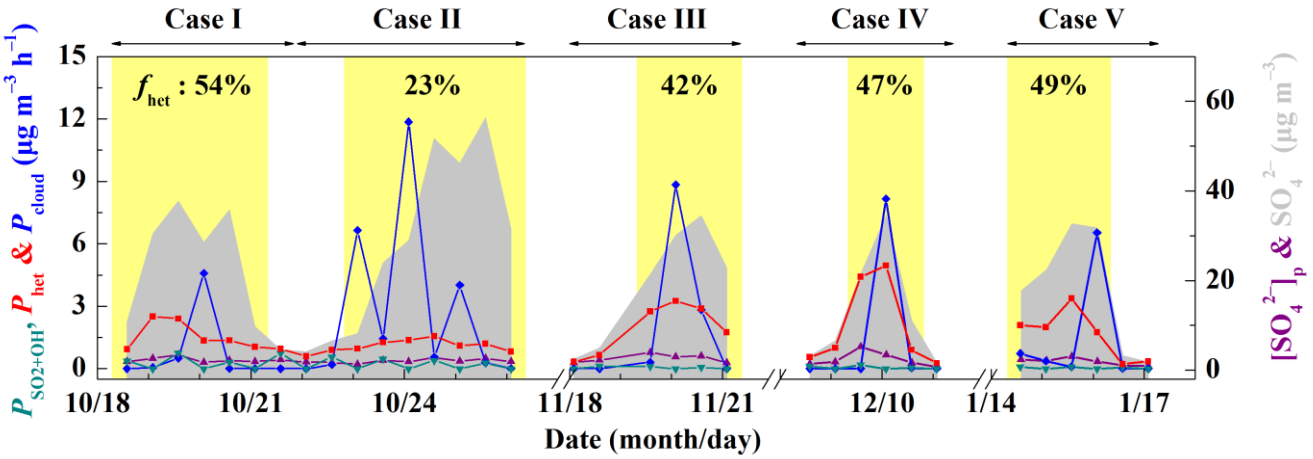


Figure 4. Estimate of different sulfate production pathways. Time series of estimated sulfate production rate via OH oxidation in the gas-phase (P_{SO2+OH}), overall heterogeneous reactions on aerosols (P_{het}) and in-cloud reactions (P_{cloud}) and concentrations of primary sulfate ([SO_4^{2-}]$_p$) and observed sulfate. f_{het} represents the fraction of overall heterogeneous sulfate production to total sulfate production during PD of each Case. The light yellow shaded area indicates polluted days (PD, $PM_{2.5} \geq 75$ μg m^{-3}). Data used here are 12h-averaged values, corresponding with filter samples.

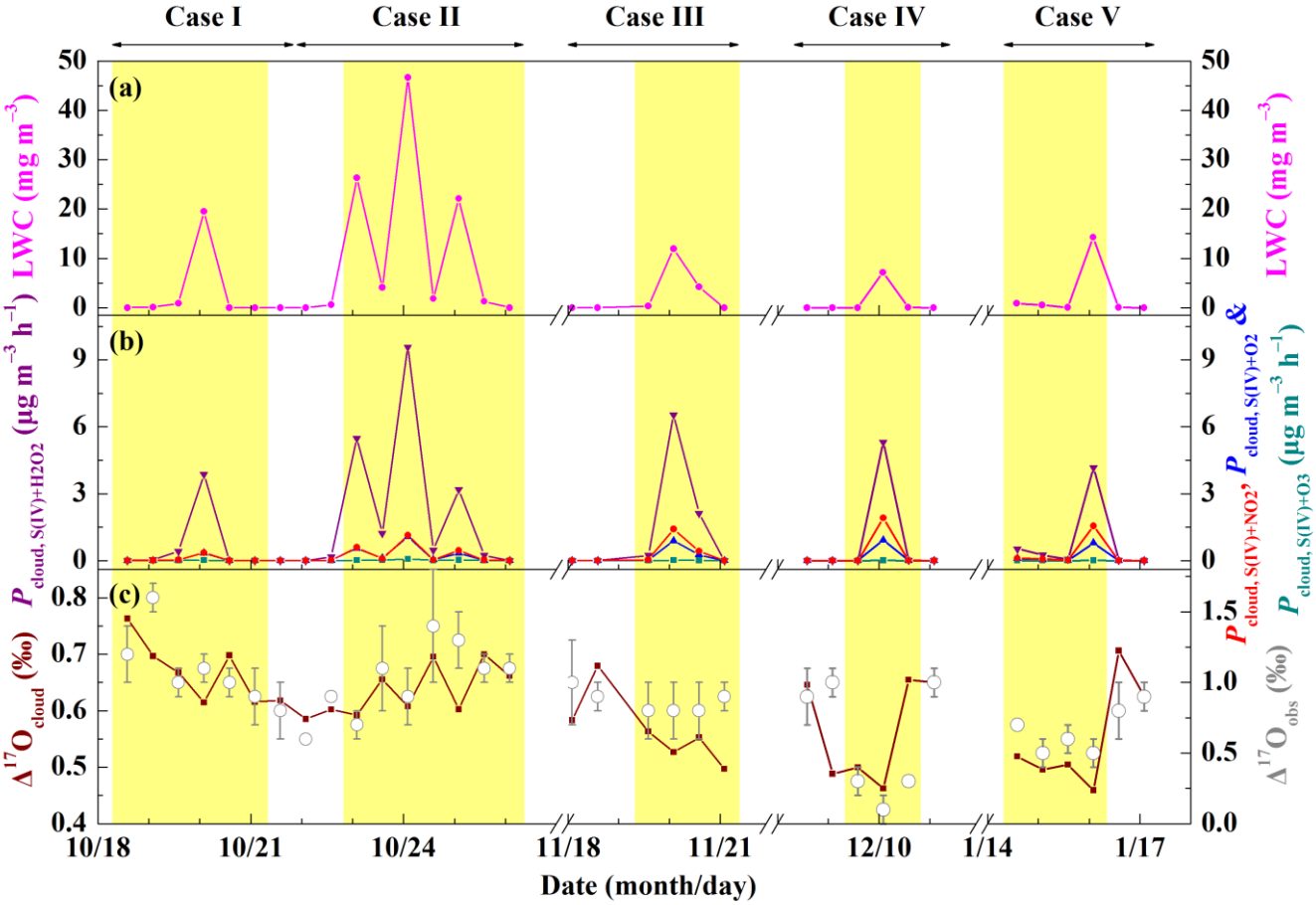
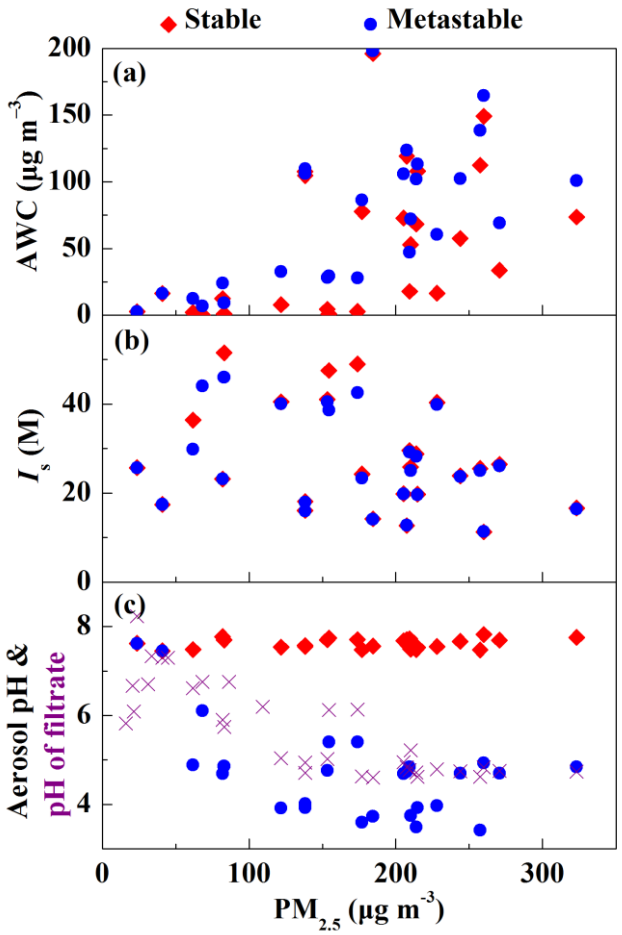


Figure 5. Temporal evolution of cloud liquid water content (LWC, **a**), in-cloud sulfate production rate via S(IV) oxidation by H_2O_2, O_3, NO_2 and O_2 initiated by TMIs (denoted as $P_{cloud, S(IV)+H2O2}$, $P_{cloud, S(IV)+O3}$, $P_{cloud, S(IV)+NO2}$ and $P_{cloud, S(IV)+O2}$, respectively,

584 **b**) and estimated $\Delta^{17}O$ of sulfate produced in clouds ($\Delta^{17}O_{cloud}$, **c**). The light yellow shaded area indicates polluted days (PD,

585 $PM_{2.5} \geq 75$ μg m^{-3}). Data used here are 12h-averaged values, corresponding with filter samples.



586

587 **Figure 6.** Aerosol parameters during Beijing haze. The aerosol water content (AWC, **a**), ionic strength (I_s, **b**) and aerosol pH

588 (**c**) was predicted by ISORROPIA II assuming stable aerosol state and metastable aerosol state. The pH of filtrate was

589 measured by an ion activity meter.

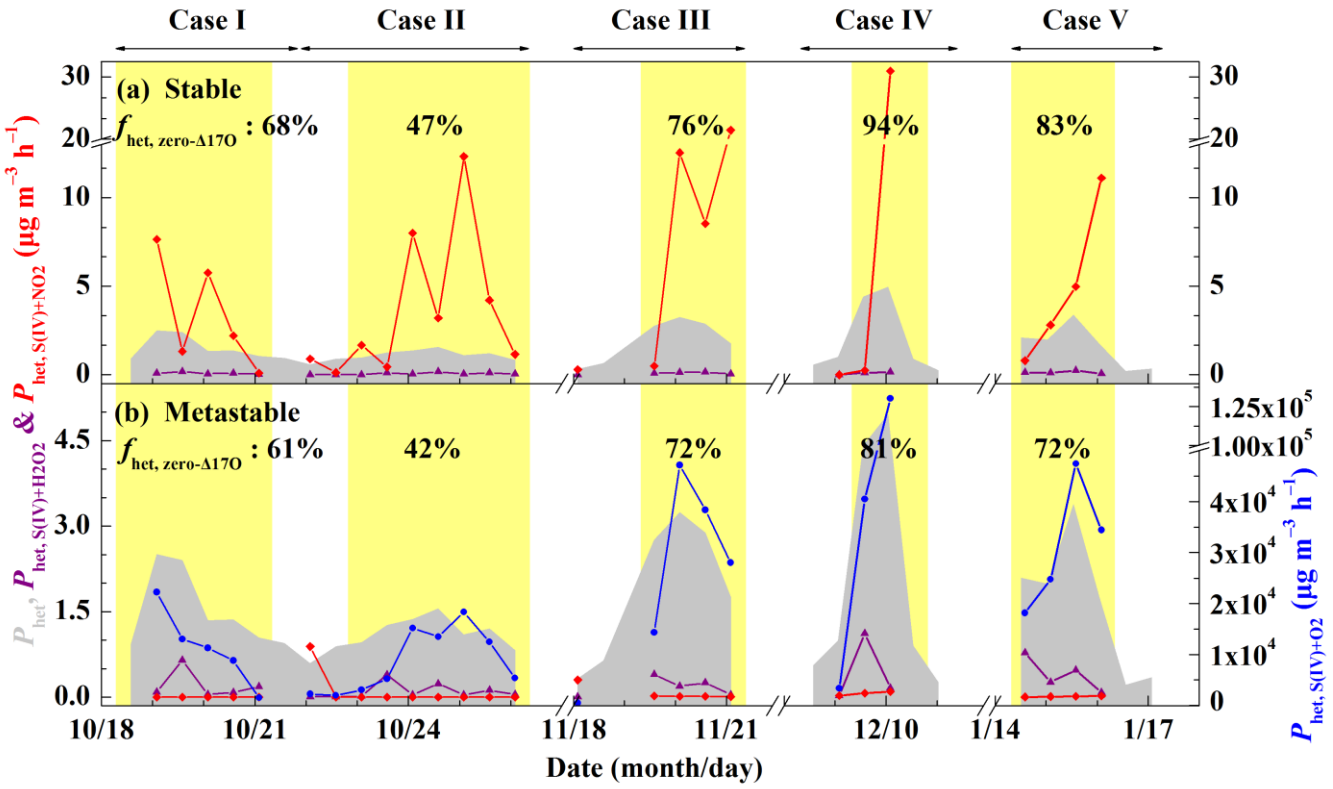


Figure 7. Estimate of heterogeneous sulfate production pathways. Time series of overall heterogeneous sulfate production rate (P_{het}), heterogeneous sulfate production rate in aerosol water via H_2O_2 ($P_{het, S(IV)+H2O2}$) and NO_2 ($P_{het, S(IV)+NO2}$) under stable **(a)** and metastable **(b)** aerosol assumption. $P_{het, S(IV)+O2}$ in (b) represents heterogeneous sulfate production rate via SO_2 oxidation by O_2 via a radical chain mechanism on acidic microdroplets. $f_{het, zero-\Delta17O}$ represents the fraction of heterogeneous reactions that result in sulfate with zero-$\Delta^{17}O$, such as S(IV) oxidation by NO_2 and O_2, to the overall heterogeneous sulfate production during PD of each case with the constraint of $\Delta^{17}O(SO_4^{2-})$ (see the main text for details). In calculating $P_{het, S(IV)+H2O2}$, the influence of I_s was considered. In calculating $P_{het, S(IV)+NO2}$, and $P_{het, S(IV)+O2}$ the influence of I_s was not considered due to the lack of experimental data about the influence of I_s. $P_{het, S(IV)+O2}$ was calculated using the aqueous-phase rate constant for pH ≤ 3 due to the lack of rate constant information at pH > 3. The light yellow shaded area indicates polluted days (PD, $PM_{2.5} \geq 75$ μg m^{-3}). Data used here are 12h-averaged values, corresponding with filter samples.

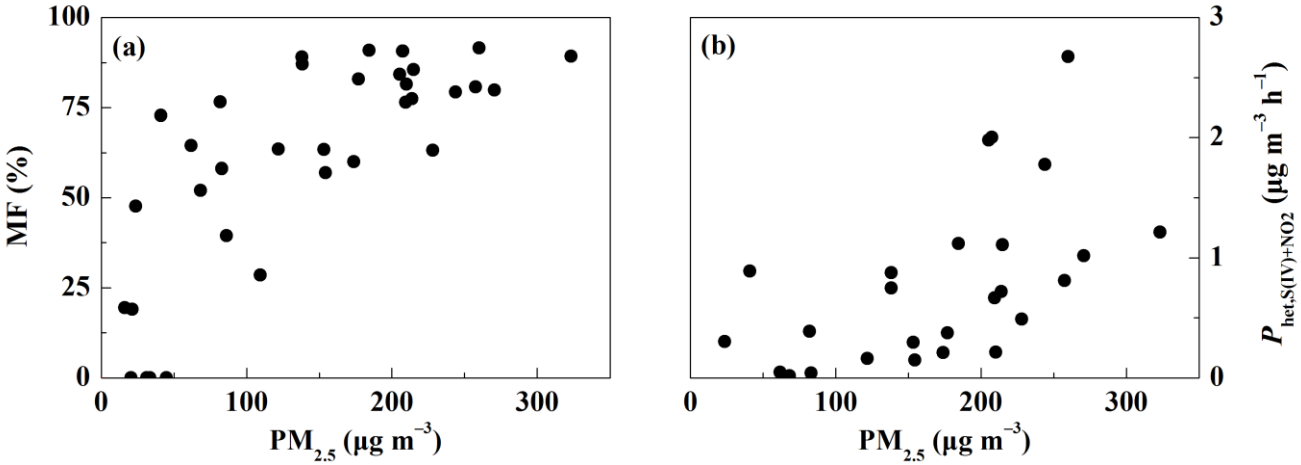


Figure 8. The estimated fraction of metastable aerosol to total aerosol (MF, **a**) using Eq. (9) and heterogeneous sulfate production rate from S(IV) oxidation by NO_2 assuming a combination of metastable and stable state ($P_{het,\ S(IV)+NO2}$, **b**) as $P_{het,\ S(IV)+NO2} = MF \times P_{het,\ S(IV)+NO2,\ metastable} + (100\ \%\text{–}MF) \times P_{het,\ S(IV)+NO2,\ stable}$.

Table 1. Sulfate isotope assumptions.

Sulfate formation pathways	$\Delta^{17}O(SO_4^{2-})$ (‰)
SO_2 + OH	0
S(IV) + H_2O_2	0.7
S(IV) + O_3	6.5
S(IV) + NO_2	0
S(IV) + O_2	0
Primary sulfate	0