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Quantifying SO_2 oxidation pathways to atmospheric sulfate using stable sulfur and oxygen isotopes: laboratory simulation and field observation

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Abstract. The formation of secondary sulfate in the atmosphere remains controversial, and it is an urgent need to seek a new method to quantify different sulfate formation pathways. Thus, SO_2 and $PM_{2.5}$ samples were collected from 4 to 22 December 2019 in the Nanjing region. Sulfur and oxygen isotopic compositions were synchronously measured to study the contribution of SO_2 homogeneous and heterogeneous oxidation to sulfate. Meanwhile, the correlation of $\delta^{18}O$ values between H_2O and sulfate from SO_2 oxidation by H_2O_2 and Fe^{3+} / O_2 was simulatively investigated in the laboratory. Based on isotope mass equilibrium equations, the ratios of different SO_2 oxidation pathways were quantified. The results showed that secondary sulfate constituted higher than 80 % of total sulfate in $PM_{2.5}$ during the sampling period. Laboratory simulation experiments indicated that the $\delta^{18}O$ value of sulfate was linearly dependent on the $\delta^{18}O$ value of water, and the slopes of linear curves for SO_2 oxidation by H_2O_2 and Fe^{3+} / O_2 were 0.43 and 0.65, respectively. The secondary sulfate in $PM_{2.5}$ was mainly ascribed to SO_2 homogeneous oxidation by OH radicals and heterogeneous oxidation by H_2O_2 and Fe^{3+} / O_2. SO_2 heterogeneous oxidation was generally dominant during sulfate formation, and SO_2 oxidation by H_2O_2 predominated in SO_2 heterogeneous oxidation reactions, with an average ratio around 54.6 %. This study provided an insight into precisely evaluating sulfate formation by combining stable sulfur and oxygen isotopes.

1 Introduction

Sulfate is one of the prevalent components of $PM_{2.5}$ (Brüggemann et al., 2021; Huang et al., 2014; Yang et al., 2023). Sulfate makes up approximately 25 % of $PM_{2.5}$ mass in Shanghai, 23 % in Guangzhou, and 10 %–33 % in Beijing (Xue et al., 2016). The rapid sulfate formation is a crucial factor determining the explosive growth of fine particles and the frequent occurrence of severe haze events in China (Lin et al., 2022; Y. Y. Liu et al., 2020; Meng et al., 2023; Wang et al., 2021; Zhang et al., 2018). Sulfate plays an important role in the chemical and physical processes in the troposphere and lower stratosphere, and it significantly affects global climate change by scattering solar radiation and acting as cloud condensation nuclei (Gao et al., 2022; Ramanathan et al., 2001). Meanwhile, sulfate exerts a significant influence on air quality and public health (Abbatt et al., 2006).

In the past decades, numerous attempts have been made to evaluate SO_2 oxidation pathways that are involved in homogeneous and heterogeneous reactions. Traditionally, sulfate formation mechanisms mainly include SO_2 homogeneous oxidation by OH radicals and heterogeneous oxidation by

H_2O_2, O_3, and O_2 catalysed by transition metal ions (TMIs) in cloud/fog water droplets. The relative importance of different sulfate formation pathways is strongly dependent on oxidant concentrations, the occurrence of fog/cloud events, and the pH of the aqueous phase (Kuang et al., 2022; Oh et al., 2023). Generally, SO_2 homogeneous oxidation by OH radicals and heterogeneous oxidation by H_2O_2 are considered the most important pathways for sulfate production on the global scale (Seinfeld and Pandis, 1998). The photochemical reactivity during the winter in Beijing has been found to be relatively high, which favours the formation of reactive species such as OH radicals and H_2O_2, thereby facilitating SO_2 oxidation (Zhang et al., 2020). Xue et al. (2014) suggested that SO_2 oxidation by O_3 and H_2O_2 in the aqueous phase contributed to the majority of total sulfate production. T. Liu et al. (2020) proposed that S(IV) oxidation by H_2O_2 in aerosol water could be an important pathway that considers the ionic strength effect. He et al. (2018) found that the contribution of SO_2 oxidation by H_2O_2 could reach 88 % during the haze period in Beijing. Ye et al. (2018) observed that the SO_2 oxidation rate by H_2O_2 was 2–5 times faster than the summed rate of the other three oxidation pathways. As a result, the actual contribution of SO_2 oxidation by H_2O_2 during the winter might be underestimated in the previous studies.

In addition, the presence of NO_2 is obviously favourable for SO_2 oxidation under the conditions of high relative humidity (RH) and NH_3. NH_3 can promote the hydrolysis of NO_2 dimers to HONO and result in more sulfate formation on the particle surface in humid conditions (He et al., 2021). However, this conclusion was doubted by Liu et al. (2017), who believed that the reaction on actual fine particles with the pH at 4.2 was too slow to account for sulfate formation. Li et al. (2020) deemed that SO_2 oxidation by NO_2 might not be a major oxidation pathway in China. Furthermore, a GEOS-Chem modelling study suggested that NO_2 oxidation contributed less than 2 % of total sulfate production. It is found that the TMI pathway was very important in highly polluted regions, and the contribution of metal-catalysed SO_2 oxidation to sulfate was as high as 49 ± 10 % in haze. Wang et al. (2021) also argued that SO_2 oxidation via TMIs on the aerosol surface could be the dominant sulfate formation pathway. They found that manganese-catalysed oxidation of SO_2 contributed 69.2 ± 5.0 % of sulfate production. Overall, the mechanisms for sulfate rapid growth remain unclear and controversial. Therefore, sulfate formation pathways need to be further explored, and it is urgent that a new method to quantify different sulfate formation processes is developed.

Generally, sulfur isotopes allow for investigating SO_2 oxidation processes in the atmosphere because of distinctive isotope fractionation associated with different oxidation reactions (Harris et al., 2013). Harris et al. (2012) presented the respective sulfur isotope fractionation factors of SO_2 oxidation by OH radicals, O_3 / H_2O_2, and iron catalysis. In addition, the observed sulfur isotope fractionation of SO_2 oxidation by H_2O_2 and O_3 appeared to have no significant difference. Therefore, the results were particularly useful to determine the importance of transition metal-catalysed oxidation pathway compared to other oxidation pathways. However, other main SO_2 oxidation pathways could not be distinguished only based on stable sulfur isotope determination.

The oxygen isotope ratio ($\delta^{18}O$) can be used to deduce sulfate formation processes due to those SO_2 oxidation pathways affecting oxygen isotopes of the sulfate product differently. In particular, mass-independent fractionation signals of oxygen isotopes (nonzero $\Delta^{17}O$, where $\Delta^{17}O = \delta^{18}O - 0.52 \times \delta^{17}O$) in sulfate are usually adopted to investigate the contribution of different SO_2 oxidation pathways. This method can identify the contribution of SO_2+O_3 pathway when a high $\Delta^{17}O$ value (> 3 ‰) is measured in sulfate. However, there is obvious uncertainty when interpreting the sulfate with a low $\Delta^{17}O$ value (< 1 ‰). Unfortunately, most sulfate samples in the atmosphere present $\Delta^{17}O < 1$ ‰, suggesting a limited contribution of the SO_2+O_3 pathway during sulfate formation. It is noteworthy that the contribution of SO_2+ H_2O_2 and TMI pathway is unclear if solely using $\Delta^{17}O$ (Li et al., 2020). Holt and Kumar (1984) found that the use of oxygen isotopes was a valuable and complementary method to determine probable mechanisms of SO_2 oxidation to sulfate in the atmosphere. This provides us an insight into precisely evaluating sulfate formation pathways by combining oxygen and sulfur isotopes.

In this contribution, $PM_{2.5}$ and SO_2 were sampled from 4 to 22 December 2019 in Nanjing. Sulfur and oxygen isotopic compositions were measured to study the contribution of SO_2 homogeneous and heterogeneous oxidation during sulfate formation. In addition, the linear relationships of $\delta^{18}O$ values between H_2O and sulfate from SO_2 oxidation by H_2O_2 and Fe^{3+} / O_2 were synchronously investigated in the laboratory. Based on sulfur and oxygen isotope mass equilibrium equations, the ratios of different SO_2 oxidation pathways during the sampling period were calculated. The study aims to seek a novel method to quantify different SO_2 oxidation processes with sulfur and oxygen isotopes.

2 Materials and methods

2.1 Sampling location

$PM_{2.5}$ and SO_2 in the atmosphere were sampled from 4 to 22 December 2019 in Nanjing, China. The sampling site was located on the roof of the library of Nanjing University of Information Science and Technology (NUIST; 32.1° N, 118.5° E), which is depicted in Fig. 1. The sampling location is on the side of Ningliu Road and close to Nanjing chemical industry park. There are some large-scale chemical enterprises present such as Nanjing steel plant, Nanjing thermal power plants, and Nanjing petrochemical company, which inevitably release lots of SO_2 and iron metal into the atmosphere.

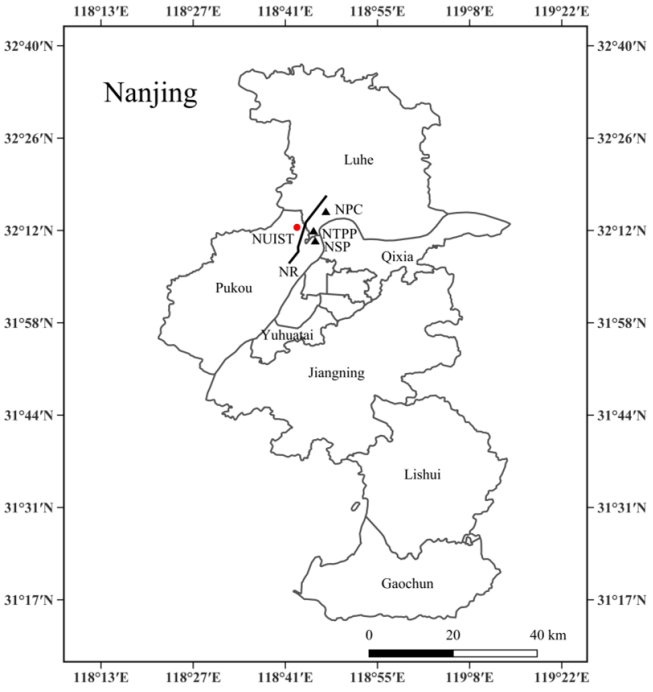

Figure 1. Sampling site of NUIST in Nanjing, China. NSP: Nanjing steel plant. NTPP: Nanjing thermal power plants. NPC: Nanjing petrochemical company. NR: Ningliu Road.

2.2 $PM_{2.5}$ and SO_2 samples collection

$PM_{2.5}$ and SO_2 were sampled using a modified JCH-1000 sampler (Juchuang Co., Qingdao) with a flow rate of 1.05 m^3 min^{-1} from 08:00 to 20:00 from 4 to 22 December 2019. $PM_{2.5}$ and SO_2 were collected with a quartz filter (203 × 254 mm, Munktell, Sweden) and a glass fibre filter (203 × 254 mm, Tisch Environment INC, USA), respectively. The filters were incinerated in a muffle furnace at 450 °C for 2 h and then preserved in the desiccators at room temperature. The glass fibre filters were firstly soaked in 2 % K_2CO_3 and 2 % glycerol solution for 2 h and dried in a DGG-9070A electric oven. SO_2 can be changed into sulfite immediately during the sampling.

2.3 Extractions of water-soluble sulfate

$PM_{2.5}$ sample filters were shredded and soaked in 400 mL of Milli-Q (18 MΩ) water for extractions of water-soluble sulfate. Filters were then isolated from solutions by centrifugation, and sulfate was precipitated as $BaSO_4$ by adding 1 mol L^{-1} $BaCl_2$. After the filtration with 0.22 µm acetate membrane, $BaSO_4$ precipitate was rinsed with Milli-Q water to remove Cl^-. Finally, $BaSO_4$ powers were calcined at 800 °C for 2 h to obtain high-purity $BaSO_4$. In addition, a small amount of H_2O_2 solution was added to oxidize sulfite to sulfate.

2.4 Laboratory simulation of SO_2 oxidation by H_2O_2 and Fe^{3+} / O_2

For SO_2 oxidation by H_2O_2, 30 mL min^{-1} Ar was firstly introduced into three kinds of different water for about 30 min to drive out air. Sulfate was produced by adding 10 mL H_2O_2 dilute solution (0.1 mL 30 % H_2O_2 in 50 mL water) to SO_2 in the reaction chamber at 10 °C. H_2O_2 solution was agitated vigorously for 1 min before admission of air. For SO_2 oxidation by Fe^{3+} / O_2, 2 mL min^{-1} SO_2 and 2 mL min^{-1} O_2 were simultaneously put into the Fe^{3+} dilute solution at 10 °C. Then, 10 mL 1 mL min^{-1} $BaCl_2$ was added to prepare $BaSO_4$. Oxygen isotopic compositions of product sulfate and three kinds of water were measured to study their linear relationships.

2.5 Sulfur and oxygen isotope determination

Sulfur isotopic compositions in sulfate were analysed using an elemental analyser (EA; Flash 2000, Thermo) and isotope mass spectrometer (IRMS; Delta V Plus, Finningan). High-purity $BaSO_4$ was converted into SO_2 in EA in the presence of Cu_2O. SO_2 from EA was ionized, and the $\delta^{34}S$ value was measured using the IRMS. For the determination of $\delta^{18}O$, $BaSO_4$ pyrolysis was conducted in a graphite furnace at 1450 °C, and the $\delta^{18}O$ value was obtained in CO produced from the pyrolysis at continuous-flow mode. The results of $\delta^{34}S$ and $\delta^{18}O$ were with respect to the international standards V-CDT and V-SMOW, and the accuracy was better than ± 0.2 ‰ and ± 0.3 ‰, respectively.

3 Results and discussion

3.1 Concentrations of $PM_{2.5}$, sulfate and SO_2

As described in Fig. 2, the mass concentrations of $PM_{2.5}$, SO_4^{2-}, and SO_2 during the period from 4 to 22 December 2019 in NUIST changed from 28.1 to 67.0 µg m^{-3}, 8.3 to 17.8 µg m^{-3}, and 6.2 to 20.9 µg m^{-3}, with an average and standard deviation at 45.7 ± 12.1, 12.7± 3.3 and 10.2 ± 4.4 µg m^{-3}, respectively. It can be observed that $PM_{2.5}$ average concentration was about 1.3 times the First Grade National Ambient Air Quality Standard (35 µg m^{-3}) and beyond the safety standard of the World Health Organization (10 µg m^{-3}). The photochemical reactivity during the winter in Beijing has been found to be relatively high (Zhang et al., 2020), which facilitates the formation of some photooxidants. The relatively clean days during the sampling period indicate the importance of photoinduced oxidation of SO_2.

Meanwhile, the change trends of $PM_{2.5}$, SO_4^{2-}, and SO_2 concentrations were found to be basically the same during the sampling period, indicating that sulfate was mainly from SO_2 oxidation. In particular, $PM_{2.5}$, SO_4^{2-}, and SO_2 concentrations increased to the maximum values on 10 December. It is noted that NO_2 and CO concentrations were 85 and

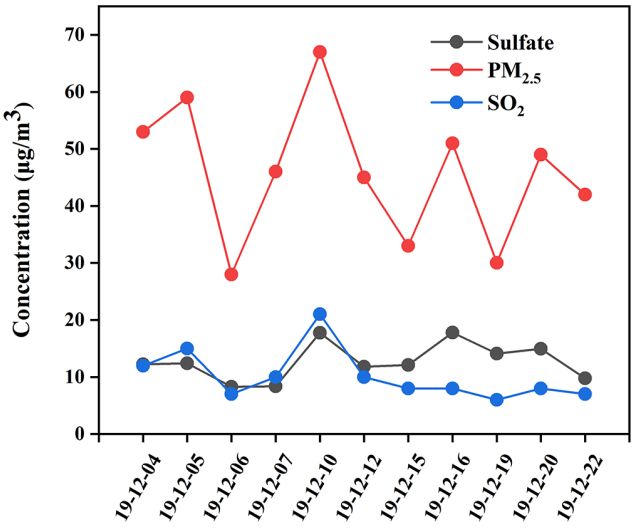

Figure 2. Variations in concentrations of $PM_{2.5}$, SO_4^{2-}, and SO_2.

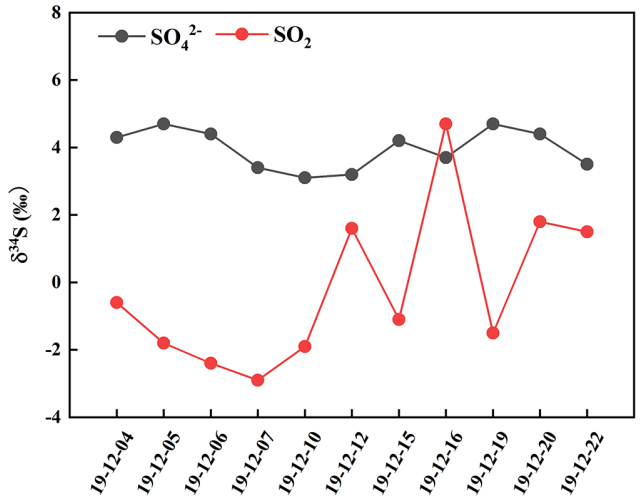

Figure 3. Variations in sulfur isotopic compositions in sulfate and SO_2.

1.60 μg m^{-3} on 10 December, which were also the maximum values during the sampling period. Based on the wind speed being lower than 3 m s^{-1} and there being static weather during the sampling period, we believe that high CO concentration was mainly from local emissions. However, O_3 concentration on 10 December had a minimum value at 24 μg m^{-3}, which preliminarily indicated that SO_2 oxidation by NO_2 might be a major pathway in sulfate formation. Previous studies showed that SO_2 oxidation by NO_2 in aerosol water dominated heterogeneous sulfate formation during wintertime at neutral aerosol pH (Wang et al., 2016; Cheng et al., 2016). However, subsequent studies showed that the calculated aerosol pH was in the range of 4.2–4.7, and the reactions between SO_2 and NO_2 during this pH range were too slow to produce sulfate. Considering low aerosol pH in the Nanjing region, we suggested that SO_2 oxidation by NO_2 was not a dominant pathway for sulfate formation during the sampling period.

In contrast, $PM_{2.5}$, SO_4^{2-}, and SO_2 concentrations were observed to be at minimum values on 6 December. Similarly, NO_2 and CO concentrations were also at minimum values of 36 and 0.6 mg m^{-3}, respectively. However, O_3 concentration on 6 December had a maximum value at 50 μg m^{-3}. In addition, the rate of SO_2 oxidation with O_3 becomes fast only when pH > 5, and the reaction rate of SO_2 with O_3 is one-hundredth of that with H_2O_2 or TMIs when pH < 5. Therefore, pH values of actual fine particles at 4–5 in the Nanjing region could markedly restrain SO_2 oxidation by O_3. The lowest SO_4^{2-} concentration on 6 December further demonstrated that SO_2 oxidation by O_3 played an insignificant role in sulfate formation.

Generally, aqueous-phase oxidation is deemed to be a main process of sulfate formation in atmospheric environment. Shao et al. (2018) believed that heterogeneous sulfate production on aerosols occurred when RH was higher than 50 %. The RH values of the atmosphere ranging from 50.7 % to 88.9 % during the sampling period indicated that sulfate formation was closely related to SO_2 heterogeneous oxidation.

3.2 Sulfur isotopic compositions in sulfate and SO_2

It can be observed from Fig. 3 that the values of δ^{34}S-SO_4^{2-} were generally higher compared to those of δ^{34}S-SO_2 during the sampling period except on 16 December. The δ^{34}S-SO_4^{2-} values ranged from 3.1 ‰ to 4.7 ‰, with an average and standard deviation at 4.0 ± 0.6 ‰, while δ^{34}S-SO_2 values changed from −2.9 ‰ to 4.7 ‰, with an average and standard deviation at −0.2 ± 2.3 ‰. The discrepancy between the values of δ^{34}S-SO_4^{2-} and δ^{34}S-SO_2 was mainly related to the sulfur isotope fractionation effect during SO_2 oxidation to secondary sulfate.

It is noteworthy that δ^{34}S-SO_4^{2-} values were similar to those in $PM_{2.5}$, with an average at 4.2 ‰ during the Youth Olympic Games in August 2014 in Nanjing (Guo et al., 2016). However, the average value of δ^{34}S-SO_4^{2-} during the sampling period was lower than 5.6 ‰ in Nanjing during a typical haze event from 21 December 2015 to 1 January 2016 (Guo et al., 2019). The higher δ^{34}S values of sulfate in haze were possibly ascribed to SO_2 heterogeneous oxidation, which typically enriched heavy sulfur isotope in sulfate. In this study, the average concentrations of $PM_{2.5}$ were 45.7 μg m^{-3}, indicating a time interval that is not heavily polluted. In addition, the relatively high temperature during the sampling period was favourable for photochemical reactions and OH radicals' formation. As a result, the contribution of SO_2 homogenous oxidation increased during sulfate formation, which enriched light sulfur isotope compared to that in haze. Han et al. (2017) determined δ^{34}S values in Beijing

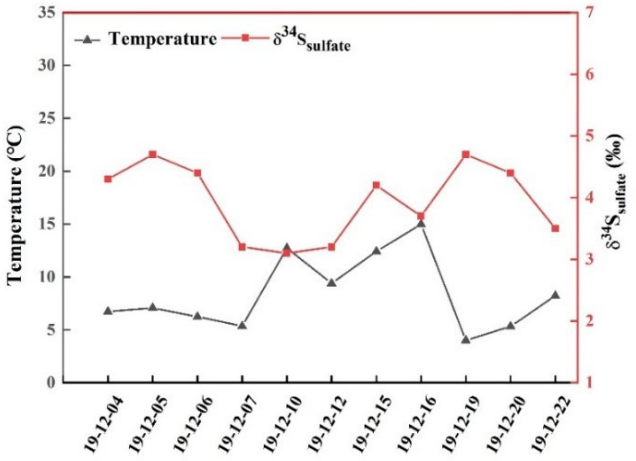

Figure 4. The correlation between δ^{34}S-SO_4^{2-} values and atmospheric temperature.

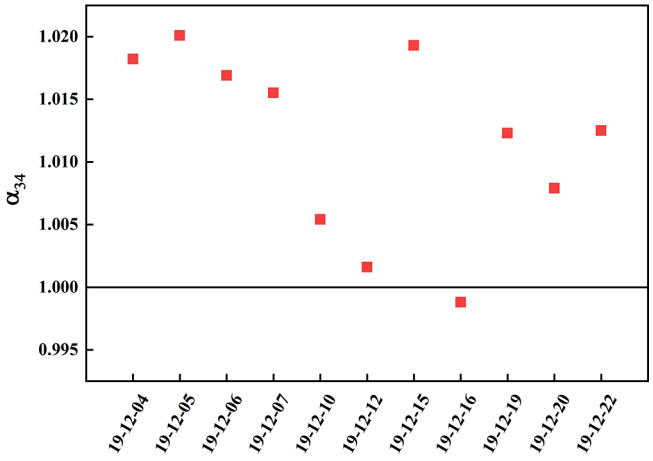

Figure 5. Sulfur isotope fractionation coefficients during SO_2 oxidation.

$PM_{2.5}$, with an average at 6.0 ‰. It is observed that there was a regional difference in δ^{34}S-SO_4^{2-} values. The δ^{34}S-SO_4^{2-} value in Nanjing was generally lower than that in Beijing. The discrepancy of δ^{34}S-SO_4^{2-} value illustrated different sulfur sources and SO_2 oxidation pathways in these regions. In addition, δ^{34}S-SO_4^{2-} values presented a seasonal change. δ^{34}S values in Beijing aerosol sulfate varied from 3.4 ‰ to 7.0 ‰, with an average of 5.0 ‰ in summer, and from 7.1 ‰ to 11.3 ‰, with an average of 8.6 ‰ in winter. Generally, SO_2 homogeneous oxidation dominated in summer compared to that in winter due to strong solar irradiation (Han et al., 2016). SO_2 oxidation might lead to sulfur isotope fractionation, which was mainly attributed to equilibrium or kinetic discrimination between SO_2 and sulfate. The influence of different oxidants on sulfur isotope fractionation needed to be further investigated.

Figure 4 presents the relationship between the δ^{34}S-SO_4^{2-} value and atmospheric temperature during the sampling period. It can be observed that there was an obviously negative correlation. The higher temperature generally corresponded to the lower δ^{34}S-SO_4^{2-} value. This is mainly ascribed to the kinetic effect of sulfur isotope fractionation during SO_2 oxidation. At high temperature, more OH radicals were produced, and the contribution of SO_2 homogeneous oxidation increased. It is reported that sulfur isotope fractionation about SO_2 was −9 ‰ for homogeneous oxidation process (Tanaka et al., 1994). Therefore, a low δ^{34}S value in sulfate at high temperature was chiefly due to the elevated SO_2 homogeneous oxidation.

3.3 Sulfur isotope fractionation during SO_2 oxidation

The secondary sulfate was generally from SO_2 homogeneous and heterogeneous oxidation (Seinfeld and Pandis, 1998). The homogeneous and heterogeneous oxidation of SO_2 might lead to sulfur isotope fractionation, which is described using the fractionation coefficient: (α)

$$\alpha = \frac{\frac{\delta^{34}S_{SO_4^{2-}}}{10^3} + 1}{\frac{\delta^{34}S_{SO_2}}{10^3} + 1}. \quad (1)$$

Sulfate enriched heavy sulfur isotope ($\alpha > 1$) during SO_2 heterogeneous oxidation for the presence of isotope equilibrium fractionation and kinetic fractionation. However, the light sulfur isotope enriched by sulfate ($\alpha < 1$) during SO_2 homogeneous oxidation due to this process was only related to kinetic fractionation. As described in Fig. 5, α values ranged from 0.9988 to 1.0201, indicating there was SO_2 homogeneous and heterogeneous oxidation during the sampling period. The α value was at a minimum of 0.9988 on 16 December, which showed SO_2 homogeneous oxidation played a crucial role.

It is reported that the sulfur isotope fractionation during SO_2 heterogeneous and homogeneous oxidation to sulfate was 16.5 ‰ and −9 ‰, respectively (Tanaka et al., 1994). Consequently, the contribution of SO_2 heterogeneous and homogeneous oxidation to sulfate could be calculated by sulfur isotope mass equilibrium in Eqs. (2) and (3).

$$\delta^{34}S_{SO_2} + 16.5x - 9y = \delta^{34}S_{SO_4^{2-}} \quad (2)$$

$$x + y = 1, \quad (3)$$

where x and y represent the contribution of SO_2 heterogeneous and homogeneous oxidation, respectively.

It is observed from Fig. 6 that most of the days (7 out of 11) had more than 50 % contributions from SO_2 heterogeneous oxidation, which indicated that SO_2 heterogeneous

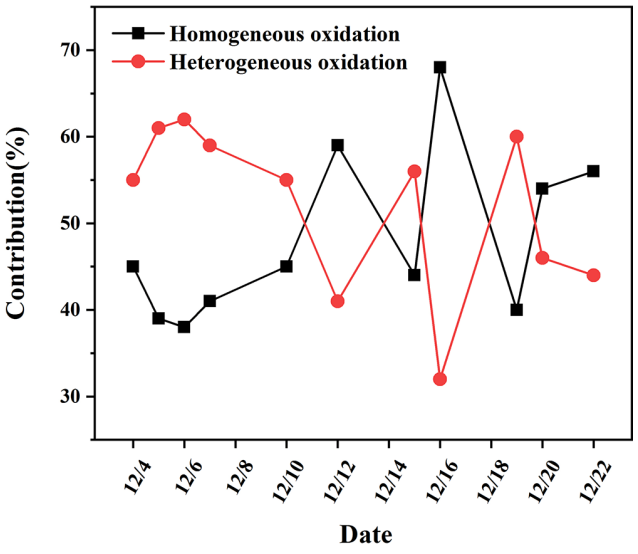

Figure 6. The contributions of SO_2 heterogeneous and homogeneous oxidation to sulfate.

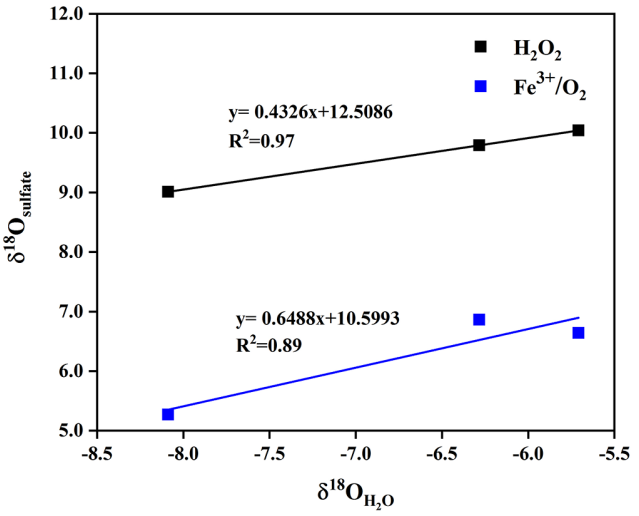

Figure 7. The correlation of $\delta^{18}O$ values between H_2O and sulfate from SO_2 oxidation by H_2O_2 and Fe^{3+} / O_2, respectively.

oxidation was generally dominant during sulfate formation. He et al. (2018) presented the observations of oxygen-17 excess of $PM_{2.5}$ sulfate collected in Beijing haze from October 2014 to January 2015 and found the contribution of heterogeneous sulfate production was about 41 %–54 % with a mean of 48 ± 5 %. The contribution of SO_2 heterogeneous oxidation reached a high level during 5–7 December and on 19 December, which was closely related to the temperature of the atmosphere. The low temperature of about 5 °C during these days was favourable for SO_2 dissolution in water and further oxidized to sulfate. On 16 December, the contribution of SO_2 heterogeneous oxidation was at a minimum of 31.4 %. The highest temperature of 15 °C on 16 December restrained SO_2 solubility in the aqueous solution and facilitated production of lots of gaseous oxidants such as OH radicals to promote SO_2 homogeneous oxidation.

Overall, the temperature was an important factor in controlling SO_2 oxidation pathways. High temperature facilitated kinetic fractionation of sulfur isotope during SO_2 oxidation to sulfate, thereby decreasing the $\delta^{34}S$ value in sulfate. In addition, there was a lack of positive correlation between the contribution of SO_2 heterogeneous oxidation and O_3 or NO_2 concentration. This further demonstrated that SO_2 oxidation by O_3 and NO_2 was not an important pathway during the sampling period. Consequently, we mainly focused on SO_2 heterogeneous oxidation by H_2O_2 and Fe^{3+} / O_2 in the following study.

3.4 The correlation of $\delta^{18}O$ values between H_2O and SO_4^{2-} from SO_2 oxidation by H_2O_2 and Fe^{3+} / O_2

It is known that SO_2 rapidly equilibrates with ambient water for very high molar ratios of H_2O to SO_2 in the atmosphere. As a result, the $\delta^{18}O$ value of SO_2 is dynamically controlled by the $\delta^{18}O$ value of water, and the $\delta^{18}O$ value of SO_2 has no obvious effect on the $\delta^{18}O$ value of sulfate produced from different oxidation pathways. Meanwhile, sulfate is very stable with respect to O atom exchange with ambient water. Consequently, $\delta^{18}O$ can be adopted to distinguish SO_2 oxidation processes due to the $\delta^{18}O$ value of product sulfate reflecting the distinctive signals of different oxidants.

We simulatively studied SO_2 heterogeneous oxidation by H_2O_2 and Fe^{3+} / O_2 in the laboratory, which aims to clarify the relationship of $\delta^{18}O$ values between product sulfate and three kinds of water at 10 °C. It can be observed from Fig. 7 that the $\delta^{18}O$ value of sulfate was linearly dependent on the $\delta^{18}O$ value of water, and the slope of linear curve for H_2O_2 oxidation approximates a ratio of 0.43, indicating that the isotopy of about two of four oxygen atoms in sulfate was controlled by the $\delta^{18}O$ value of water. The other two oxygen atoms were from H_2O_2 molecules, whose O–O bond remained intact during SO_2 oxidation. In addition, we noted from Fig. 7 that the slope of the linear curve for Fe^{3+} / O_2 oxidation was about 0.65, which represented that the isotopy of about three of four oxygen atoms in sulfate was related to the $\delta^{18}O$ value of water. A 3/4 control of sulfate oxygens by water is also characteristic of heterogeneous oxidation mechanisms in which HSO_3^- isotopically equilibrated with water prior to significant oxidation to SO_4^{2-}. The other one oxygen atom in sulfate was from O_2. The higher slope suggested a higher dependence of the $\delta^{18}O$ value of sulfate on the $\delta^{18}O$ value of water during SO_2 heterogeneous oxidation by Fe^{3+} / O_2. The discrepancy of the slopes for different SO_2 heterogeneous oxidation processes provides us with a potential method to distinguish SO_2 oxidation pathways.

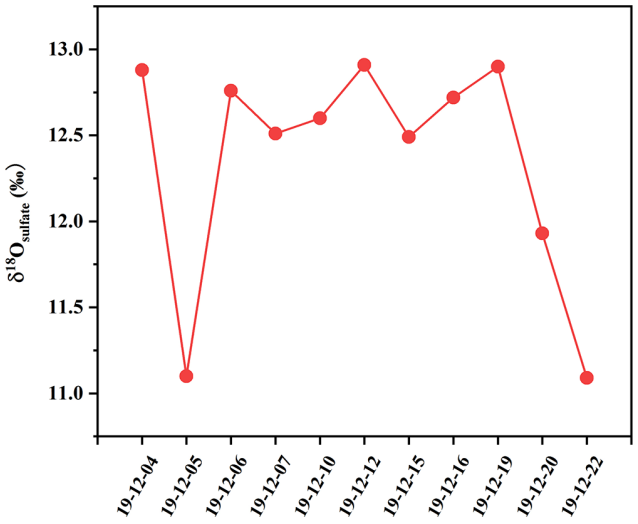

Figure 8. $\delta^{18}O$ values of sulfate in $PM_{2.5}$ during the sampling period.

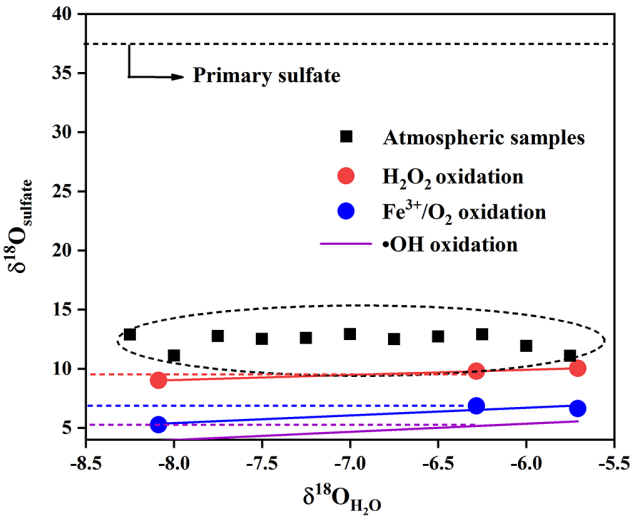

Figure 9. The correlation between $\delta^{18}O$ values in water and sulfate in $PM_{2.5}$.

3.5 $\delta^{18}O$-SO_4^{2-} values in $PM_{2.5}$ and SO_2 main oxidation pathways

As depicted in Fig. 8, $\delta^{18}O$ values of sulfate in $PM_{2.5}$ ranged from 11.09 ‰ to 12.93 ‰, with an average and standard deviation of 12.35 ± 0.68 ‰. $\delta^{18}O$ values of sulfate focused on a narrow scope, except those on 5 and 22 December. It should be pointed out that the $\delta^{18}O$ value of secondary sulfate was a comprehensive result from different SO_2 oxidation processes. Sulfate in $PM_{2.5}$ usually consisted of primary sulfate and secondary sulfate. The $\delta^{18}O$ value of primary sulfate is about 38 ‰ (Holt and Kumar, 1984), which is significantly higher than the values of secondary sulfate. The contribution of primary and secondary sulfate in the atmosphere can be calculated by the oxygen isotope mass equilibrium in Eq. (4) (Ben et al., 1982):

$$\delta^{18}O_{PM_{2.5}} = \delta^{18}O_{PS} \times (1 - f_{SS}) + \delta^{18}O_{SS} \times f_{SS}, \quad (4)$$

where $\delta^{18}O_{PM_{2.5}}$, $\delta^{18}O_{PS}$, and $\delta^{18}O_{SS}$ mean $\delta^{18}O$ values of $PM_{2.5}$, primary sulfate, and secondary sulfate, respectively, and f_{SS} is the contribution of secondary sulfate in $PM_{2.5}$.

It is noteworthy from Fig. 9 that there is a linear relationship between $\delta^{18}O$ values in water and secondary sulfate from different SO_2 oxidation pathways, and this can be described by Eqs. (5)–(7), where the value of $\delta^{18}O_{water}$ is about −6.2 ‰ in the Nanjing region. As discussed above, secondary sulfate was mainly ascribed to SO_2 homogeneous oxidation by OH radicals and heterogeneous oxidation by H_2O_2 and Fe^{3+} / O_2. Therefore, the $\delta^{18}O_{SS}$ value in Eq. (4) can be obtained based on Eqs. (5)–(7), respectively. As a result, the average contribution of primary and secondary sulfate in $PM_{2.5}$ is presented in Table 1. It can be observed that the majority of sulfate in $PM_{2.5}$ was secondary sulfate, which appears to constitute from 79.9 % to 86.2 % of total sulfate during the sampling period. It is admirable to quantitatively describe these formation pathways of secondary sulfate in $PM_{2.5}$.

Table 1. The average contribution of primary sulfate and secondary sulfate in $PM_{2.5}$.

Sampling time	Primary sulfate (%)	Secondary sulfate (%)
4 December	19.7	80.3
5 December	13.9	86.1
6 December	19.3	80.7
7 December	18.4	81.6
10 December	18.7	81.3
12 December	20.0	80.0
15 December	18.4	81.6
16 December	20.1	79.9
19 December	19.7	80.3
20 December	16.7	83.3
22 December	13.8	86.2

$$\delta^{18}O_{SS} = 0.69 \times \delta^{18}O_{water} + 9.5‰ \text{ (OH)} \quad \text{(Holt and Kumar, 1984)} \quad (5)$$

$$\delta^{18}O_{SS} = 0.65 \times \delta^{18}O_{water} + 10.6‰ \ (Fe^{3+}/O_2) \quad \text{(this study)} \quad (6)$$

$$\delta^{18}O_{SS} = 0.43 \times \delta^{18}O_{water} + 12.5‰ \ (H_2O_2) \quad \text{(this study)} \quad (7)$$

According to the percentages of SO_2 heterogeneous and homogeneous oxidation to sulfate in Fig. 6 and the average contributions of primary sulfate and secondary sulfate in

Table 2. The ratios of SO_2 different oxidation pathways to sulfate.

Time	f_{SS-OH}	$f_{SS-H_2O_2}$	f_{SS-Fe_3+/O_2}	$f_{SS-H_2O_2}/(f_{SS-H_2O_2}+f_{SS-Fe_3+/O_2}$ (%)
4 December	0.45	0.27	0.28	49.1
5 December	0.39	0.24	0.37	39.3
6 December	0.38	0.24	0.38	38.7
7 December	0.41	0.25	0.34	42.3
10 December	0.45	0.27	0.28	49.1
12 December	0.59	0.30	0.11	73.2
15 December	0.44	0.26	0.30	46.5
16 December	0.68	0.26	0.06	81.2
19 December	0.40	0.25	0.35	41.6
20 December	0.54	0.31	0.15	67.4
22 December	0.56	0.32	0.12	72.7

$PM_{2.5}$ in Table 1, we can further calculate the ratios of different SO_2 oxidation pathways at 10 °C via the oxygen isotope mass equilibrium in Eqs. (8)–(10), and the corresponding results are depicted in Table 2.

$$\delta^{18}O_{PM_{2.5}} = \delta^{18}O_{PS} \times f_{PS} + \left(\delta^{18}O_{SS-OH} \times f_{SS-OH} + \delta^{18}O_{SS-Fe_3+/O_2} \times f_{SS-Fe_3+/O_2} + \delta^{18}O_{SS-H_2O_2} \times f_{SS-H_2O_2}\right) \times f_{SS} \quad (8)$$

$$f_{PS} + f_{SS} = 1 \quad (9)$$

$$f_{SS-OH} + f_{SS-Fe_3+/O_2} + f_{SS-H_2O_2} = 1, \quad (10)$$

where $\delta^{18}O_{PM_{2.5}}$ and $\delta^{18}O_{PS}$ are $\delta^{18}O$ values of total sulfate and primary sulfate in $PM_{2.5}$; $\delta^{18}O_{SS-OH}$, $\delta^{18}O_{SS-Fe_3+/O_2}$ and $\delta^{18}O_{SS-H_2O_2}$ are $\delta^{18}O$ values of secondary sulfate from SO_2 oxidation by OH radicals, Fe^{3+} / O_2, and H_2O_2, respectively; f_{PS} and f_{SS} are the contribution of primary and secondary sulfate; and f_{SS-OH}, f_{SS-Fe_3+/O_2}, and $f_{SS-H_2O_2}$ are the ratios of secondary sulfate from SO_2 oxidation by OH radicals, Fe^{3+} / O_2, and H_2O_2, respectively.

Unlike heavily polluted days with reduced solar irradiation, the photochemical reactivity can remain high in clean days during the observation period because of relatively intense solar irradiation. As a result, some photochemical reactive species such as OH radicals and H_2O_2 are deemed to be the major oxidants for sulfate formation. Generally, H_2O_2 production in the relatively clean atmosphere is ascribed to self-reaction of HO_2 radicals that mainly comes from the reactions of OH radicals with CO and volatile organic compounds. It is observed from Table 2 that the ratios of SO_2 oxidation by OH radicals ranged from 38 % to 68 %, with an average and standard deviation at 48 ± 9.7 %. The ratio reached the maximum of 68 % on 16 December, which is mainly ascribed to the highest temperature of 15 °C during the sampling period. The photochemical reactions are favourable for producing more OH radicals. In contrast, the ratio of SO_2 oxidation by OH radicals decreased to the minimum of 38 % on 6 December due to the low temperature.

It is known that SO_2 oxidation by H_2O_2 and Fe^{3+} / O_2 is the most important pathway during SO_2 heterogeneous oxidation. It can be observed from Table 2 that the percentage of sulfate from SO_2 oxidation by H_2O_2 in secondary sulfate from SO_2 heterogeneous oxidation changed from 38.7 % to 81.2 %, with an average and standard deviation at 54.6 ± 15.7 %, indicating that SO_2 oxidation by H_2O_2 predominated during SO_2 heterogeneous oxidation. In addition, there was an obviously positive correlation between the ratios of SO_2 oxidation by H_2O_2 and OH radicals, which was chiefly attributed to the photochemical reactions. The relatively strong solar irradiation on 16 December resulted in the maximum ratio of 81.2 % for H_2O_2 oxidation in SO_2 heterogeneous reactions. The sampling site is close to Nanjing steel plant. As companion emitters, Fe^{3+} is present in much higher concentrations than that in other areas. It is believed that SO_2 oxidation by O_2 in the presence of Fe^{3+} was not negligent in the areas where the concentrations of SO_2 and Fe^{3+} were high. This inevitably resulted in the high SO_2 oxidation ratio by Fe^{3+} / O_2 in SO_2 heterogeneous oxidation processes.

4 Conclusions

There was no serious $PM_{2.5}$ pollution during the sampling period. The secondary sulfate constitutes from 79.9 % to 86.2 % of total sulfate in $PM_{2.5}$. SO_2 oxidation by O_3 and NO_2 played an insignificant role in sulfate formation. The secondary sulfate was mainly ascribed to SO_2 homogeneous oxidation by OH radicals and heterogeneous oxidation by H_2O_2 and Fe^{3+} / O_2. Compared to homogeneous oxidation, SO_2 heterogeneous oxidation was generally dominant, with an average contribution of 51.6 %. SO_2 oxidation by H_2O_2

predominated in SO_2 heterogeneous oxidation reactions, the average ratio of which reached 54.6 %. Consequently, sulfur and oxygen isotopes can be used to gain an insight into sulfate formation. The determination of sulfur isotopic compositions in SO_2 and sulfate is advantageous in quantifying the contribution of SO_2 homogeneous and heterogeneous oxidation. Combining field observations of oxygen isotope in the atmosphere with the linear relationships of $\delta^{18}O$ values between H_2O and sulfate from different SO_2 oxidation processes can obtain an increased understanding of specific sulfate formation pathways. This study is favourable for deeply investigating the sulfur cycle in the atmosphere.

Data availability. Data supporting this paper are available upon request from the corresponding author (guocumt@nuist.edu.cn).

Author contributions. ZiG carried out the experiment and wrote the original draft. KL designed the methodology and administrated the project. PQ and MX performed the data collection. ZhG instructed the experiment and revised the paper.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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