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Source forensics of inorganic and organic nitrogen using δ^{15}N for tropospheric aerosols over Mt. Tai

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Nitrogen-containing species are major components in atmospheric aerosols. However, little is known about the sources of N-containing aerosols over high mountainous regions, especially for organic nitrogen (ON). This study aims to reveal the emission sources of both inorganic and organic nitrogen in tropospheric aerosols atop Mt. Tai, China, and to improve our understanding of the N cycle imbalance in the North China Plain (NCP). Total suspended particle (TSP) samples were collected on a daytime/nighttime basis in spring 2017 and were investigated for the concentrations and stable N isotopic compositions of total nitrogen, NH_{4}^{+}, NO_{3}^{-}, and ON. Our results show that the concentrations of N-containing compounds were higher in daytime than nighttime, mainly resulting from mountain–valley breezes and the changes of planetary boundary layer height. However, no significant day/nighttime changes were found for their corresponding δ^{15}N values, indicating similar contributions from different N sources between day and night. The MixSIAR Bayesian stable isotope mixing model results suggest that the most important emission source of NH_{3} for aerosol NH_{4}^{+} was agriculture, followed by fossil fuel-related sources, human waste and biomass burning. Aerosol NO_{3}^{-} was mainly formed from combustion and mobile emitted NO_{x}. Interestingly, the isotopes of ON suggest that ON were very likely firstly of primary origin. Our study reveals the characteristics of reactive N emission sources and helps understand the regional transport of tropospheric N-containing aerosols in the NCP.

ARTICLE

INTRODUCTION

Nitrogen (N) is a key element of life on Earth and its circulation in nature has received great attention. In recent years, global reactive N (Nr) emissions have increased significantly due to population growth and increased industrial and agricultural activities. This has caused the N cycle to become unbalanced and impact the earth’s environment. In the atmosphere, excess N can undergo a series of chemical reactions. Surplus N can convert to nitrogenous substances, which are important components of atmospheric aerosols, making air pollution even more serious. In addition, N-containing aerosols can affect climate change and human health, widely participate in the N cycle and play an important role in the process of atmospheric N budget imbalance. Source apportionment is a prerequisite for taking accurate measures to reduce the concentrations of N-containing aerosols in the atmosphere.

Using stable isotope techniques to identify the source and conversion process of N-containing aerosols has shown significant advantages and been a focus of recent research. Due to the simplicity of the test, stable N isotope analysis focused first on the measurement of total nitrogen (TN). However, the sources and components of aerosol N are very complex, with both primary emissions and secondary formation. Stable isotope analysis of TN is too broad to accurately indicate the source of N-containing aerosols. Increasing numbers of studies have focused on a single N-containing component to obtain more detailed information. In terms of inorganic nitrogen (IN), the stable N isotope was used to analyze the source of aerosol ammonium (NH_{4}^{+}), while N and oxygen (O) isotopes were used to analyze the source and formation process of aerosol nitrate (NO_{3}^{-}). In addition to IN, organic nitrogen (ON) is also an important component of atmospheric aerosols, but its source apportionment has received little attention. Limited studies have focused on simultaneous analyses and source identification of multiple N-containing components although they are necessary for a comprehensive understanding of N-containing aerosols in the atmosphere.

Due to dense populations and severe air pollution, most research on stable isotope analyses of aerosol NH_{4}^{+} or NO_{3}^{-} has focused on urban areas. However, the N cycle imbalance in nature affects not only urban ecosystems, but the whole earth surface and broader ecosystems, including rural, forest and mountain areas. The regional transport and deposition of atmospheric N-containing aerosols have a non-negligible impact on the ecological environment in these regions. For high mountain regions, air pollutants in the troposphere could be transported from the foothill area, or over a long distance at a regional scale. The mountain–valley breeze circulation would also transport air pollutants between the top and bottom of the mountain. Stable isotopes provide useful information of the sources of multiple N-containing components in tropospheric aerosols, and a better understanding of their distribution patterns is essential for understanding the effects of pollutants on the environment and climate.
The regional pollutants in the NCP25, we hypothesize that stable isotope analyses of N-containing aerosols there could indicate Nr emission sources of the whole NCP. After a large amount of N-containing substances being released into the environment, they affect the ecological environment on a larger scale through atmospheric circulation and threaten regional atmospheric N budget balance. Mt. Tai is an ideal place to study aerosols in the free troposphere and their interaction with the planetary boundary layer (PBL).24 Pollutants investigated from the summit of Mt. Tai could accurately represent the characteristics of the regional pollutants in the NCP.26,27 We hypothesize that stable isotope analyses of N-containing aerosols there could indicate N emission sources of the whole NCP.

In this study, we collected daytime and nighttime total suspended particle (TSP) samples at the summit of Mt. Tai in spring 2017. Stable isotope analyses and a Bayesian stable isotope analysis mixing model MixSIAR were used to analyze the sources of NH₄⁺, NO₃⁻, and ON in TSP samples. The objectives are to quantify the main emission sources of multiple N-containing aerosols atop Mt. Tai, and reveal the characteristics of N, emission sources of the whole NCP. Our study shows that mountain–valley breeze affects the levels but not the source attributions of N-containing aerosols over Mt. Tai, and the emission sources of tropospheric N-containing aerosols (especially NH₄⁺ and ON) are somewhat different with urban aerosols in the NCP.

### RESULTS

#### Concentrations of aerosol TN and IN

Figure 1 shows the concentrations of N-containing components in daytime and nighttime samples. The average concentrations of daytime and nighttime TN were 9.73 ± 5.27 and 7.14 ± 4.35 μg m⁻³, respectively (Table 1). NH₄⁺ was the largest distributor among the three N-containing compounds, followed by NO₃⁻ and ON. Air mass backward trajectories (Supplementary Fig. 4) show that air masses were mainly from the northwest when TN was extremely low, but air masses were mainly from the east (local Shandong) when TN was extremely high. There was a significant positive correlation between the concentrations of NO₃⁻ and NH₄⁺ with an intercept of ~0 (Supplementary Fig. 5). The lowest concentrations of NO₃⁻ and NH₄⁺ were close to the detection limits, indicating a low level of atmospheric particulate matter pollution over Mt. Tai under favorable dispersion conditions. The concentrations of TN, NO₃⁻, and NH₄⁺ were higher in the daytime than the nighttime (Student’s t-test, for TN or NH₄⁺, p < 0.05; for NO₃⁻, p < 0.1). This phenomenon was firstly attributed to the mountain–valley breezes. In the daytime, the valley breeze brings air masses containing particles from the foot area of Mt. Tai with intense human activities to the top, while at night, the mountain breeze reverses this transmission process. The wind rose in Supplementary Figure 3 supports this argument. Our sampling site is located at the top of the mountain, which is surrounded by terrains consisting of primarily plains with very low altitude. Therefore, the valley breeze can blow from all directions and mountain breeze can blow to all directions. Besides, the summit of Mt. Tai is within the PBL in the daytime of spring.

### Table 1. Statistics (average ± standard deviation) of the concentrations of daytime and nighttime total nitrogen (TN), inorganic nitrogen (IN: NH₄⁺, NO₃⁻) and organic nitrogen (ON), and corresponding isotopic compositions in total suspended particles over Mt. Tai in spring 2017.

| Item          | Daytime         | Nighttime        |
|---------------|-----------------|------------------|
| TN (μg m⁻³)   | 9.73 ± 5.27     | 7.14 ± 4.35      |
| NH₄⁺ (μg m⁻³) | 5.56 ± 3.13     | 4.09 ± 2.31      |
| NO₃⁻ (μg m⁻³) | 3.31 ± 2.04     | 2.62 ± 1.65      |
| ON (μg m⁻³)   | 0.86 ± 0.69     | 0.43 ± 1.00      |
| δ¹⁵N-TN (%)   | 4.0 ± 3.1       | 3.4 ± 3.6        |
| δ¹⁵N-NH₄⁺ (%) | 6.7 ± 7.0       | 5.8 ± 6.7        |
| δ¹⁵N-NO₃⁻ (%) | 1.8 ± 2.4       | 1.4 ± 3.6        |
| δ¹⁸O-NO₃⁻ (%) | 78.5 ± 4.5      | 81.1 ± 4.1       |
| δ¹⁵N-IN (%)   | 4.9             | 4.1              |
| δ¹⁵N-ON (%)   | −5.0            | −7.2             |
season, while air mass over the summit of Mt. Tai is probably representative of the lower free troposphere at night due to the decrease of PBL height.

Stable isotopes of aerosol TN and IN
Stable N isotopic compositions of aerosol TN, NH$_4^+$, and NO$_3^-$, as well as stable O isotopic compositions of aerosol NO$_3^-$ are presented in Fig. 2. Since NH$_4^+$-N comprises the majority of TN, the trends of $\delta^{15}$N-TN and $\delta^{15}$N-NH$_4^+$ are similar to each other. On the contrary, there is an obvious difference between $\delta^{15}$N-TN and $\delta^{15}$N-NO$_3^-$. Therefore, $\delta^{15}$N-TN is not a good indicator for the source and formation process of atmospheric N. Although the concentrations of N-containing compounds were evidently higher in daytime than nighttime, no significant diurnal change was found for their isotopic compositions (Table 1, Fig. 2). Student’s t-test, for $\delta^{15}$N-NH$_4^+$ or $\delta^{15}$N-NO$_3^-$, $p > 0.1$; for $\delta^{15}$N-TN, $p > 0.05$), suggesting little day/night difference in the source contribution of aerosol N-containing compounds.

Aerosol NH$_4^+$ was mainly formed from the reaction of ammonia (NH$_3$) and acids, and NO$_3^-$ was mainly formed from the secondary conversion of nitrogen oxides (NO$_x$) in the atmosphere. There is a significant negative correlation between $\delta^{15}$N-NH$_4^+$ and the concentrations of NH$_4^+$-N, but no obvious correlation between $\delta^{15}$N-TN and TN, or $\delta^{15}$N-NO$_3^-$ and NO$_3^-$-N (Supplementary Fig. S), suggesting that the $\delta^{15}$N value of NH$_3$ emissions was more variable than for NO$_3$. The MixSIAR source apportionment results of aerosol NH$_4^+$, NO$_3^-$ and ON are presented below.

**Source apportionment of aerosol NH$_4^+$**
There is an obvious $^{15}$N fractionation factor ($\Delta^{15}$N = $\delta^{15}$N-NH$_4^+$ – $\delta^{15}$N-NH$_3$) during the gas-to-particle partitioning of NH$_3$ along with acids to form particulate NH$_4^+$. Since the environment is an open system, a previous research studied the $\Delta\delta^{15}$N in a dynamic chamber and found $\Delta\delta^{15}$N was 31.6 ± 2.0‰ and 24.1 ± 2.8‰ for NH$_3$ turnover rate of 0.9 per day (low turnover rate) and 6.8 per day (high turnover rate), respectively. Fig. 3a, b presents the source apportionment results of aerosol NH$_4^+$ under two assumptions, i.e. $\Delta\delta^{15}$N = 31.6 ± 2.0‰ and $\Delta\delta^{15}$N = 24.1 ± 2.8‰. The contribution of livestock breeding was 42.1–48.3% and 35.8–49.0% for daytime and nighttime aerosol NH$_4^+$, respectively. For N-fertilizer application, it was 11.6–13.8% and 8.1–11.0%, for daytime and nighttime respectively. Thus, the total contribution of agricultural sources was 55.9–59.9% and 43.9–60.0% for daytime and nighttime aerosol NH$_4^+$, respectively. According to statistics, the output of livestock products in Shandong Province was the highest of all provinces in China and reached 8.66 million tonnes in 2017. This supports the high contribution of livestock breeding to aerosol NH$_4^+$. Although the use of chemical fertilizer in Shandong Province was the second highest in China (1.39 million tonnes N fertilizer and 2.17 million tonnes compound fertilizer in Shandong in 2017), the fertilizing amount and related NH$_3$ emissions were high during certain periods (e.g. summer) throughout the year. The sampling period in this study was not within the main period of fertilization in the NCP, so the contribution of N-fertilizer application in this study was not high.
The contribution of fossil fuel-related sources (fossil fuel sources and NH3 slip) was 21.9–26.7% and 22.5–31.3% for daytime and nighttime aerosol NH4+, respectively, and was highly variable (Fig. 3a, b). We infer that the contribution of fossil fuel-related sources was very small compared to agricultural sources, which is consistent with a previous research29. The contribution of human waste was only 9.7–10.7% and 9.7–9.9% for daytime and nighttime aerosol NH4+, respectively. This source contribution atop Mt. Tai was much smaller than urban Beijing30, which can be attributed to the lower population density around Mt. Tai. The contribution of biomass burning was also small, being 6.7–8.6% and 7.6–15.2% for daytime and nighttime aerosol NH4+, respectively.

**Source apportionment of aerosol NO3⁻**

The average aerosol δ¹⁸O-NO3⁻ during the entire sampling period was 78.5 ± 4.5‰ and 81.1 ± 4.1‰ for daytime and nighttime samples, respectively. Based on these values and related computational methods (Supplementary Methods)9, the average contribution of the two pathways NOₓ+·OH and N₂O₅+H₂O were calculated to be 48% and 52% for daytime samples, and 43% and 57% for nighttime samples, respectively. Overall, the contributions of the two pathways were comparable. Since the production of aerosol NO₃⁻ was mainly from the NOₓ+·OH pathway in the daytime, and N₂O₅+H₂O at night31, it is concluded that the aerosol NO₃⁻ in the high mountain aerosol samples was not only formed in-situ (within a few hours)32, but also transported from elsewhere. This explains why the average contribution ratio of NOₓ+·OH was comparable to N₂O₅+H₂O for both daytime and nighttime samples.

Similar to the formation of aerosol NH₄⁺, there is also a ¹⁵N fractionation factor during the conversion of initial NOₓ to aerosol NO₃⁻ (p), the average was calculated to be 5.4 ± 8.1‰ and 6.3 ± 8.8‰ for the daytime and nighttime samples, respectively, based on observed data and reported computational formulas (Supplementary Methods)9. Thus, the initial ¹⁵N-NOₓ for daytime and nighttime aerosol NO₃⁻ was –3.6 ± 8.4‰ and –5.0 ± 9.5‰, respectively, there is no clear difference between these values (Student’s t-test, p > 0.1). In the daytime, the contribution ratio of mobile emissions, combustion sources and microbial processes was 40.3 ± 14.2%, 42.8 ± 11.0% and 16.9 ± 7.4%, respectively. At night, the contribution of the three emission sources was 40.3 ± 15.8%, 40.5 ± 13.3% and 19.2 ± 8.3%, respectively (Fig. 3c). In the past decade, the NOₓ emissions in Shandong Province decreased significantly33. Previous studies pointed out that NOₓ emissions from power plants and industry were the most important about 10 years before 201734. They suggested that the decrease in NOₓ emissions in the NCP was mainly due to the decrease in emissions from power plants and industry, and mobile emissions have become one of the most important NOₓ source. In addition, natural microbial processes might be a relatively unimportant NOₓ emission source in this study, which might be due to the large population and intensive human activities in the NCP.

**Stable isotopes and source apportionment of aerosol ON**

As shown in Fig. 1 and Table 1, the average concentrations of ON were calculated based on the Eq. 1 to be 0.86 ± 0.69 and 0.43 ± 1.00 µg m⁻³ for the daytime and nighttime samples, respectively. Similar to TN and IN, due to mountain–valley breezes, the concentrations of ON in the daytime was evidently higher than...
those at night. It is worth pointing out that the ON content for some samples was too low to be calculated as a result of uncertainties during the calculation process, and the detection of ON using other advanced methods such as mass spectrometry is necessary. The average $\delta^{15}$N-ON in daytime and nighttime TSP samples was calculated to be $-5\%$ and $-7.2\%$, respectively (Table 1), based on the Eq. 2. Correspondingly, the average $\delta^{15}$N-IN was 4.9$\%$ and 4.1$\%$ for the daytime and nighttime samples, respectively. Assuming there was no significant difference between $\delta^{15}$N in ON and corresponding IN from secondary formation, we suggest that secondary formation was not likely the dominant source of aerosol ON.

Based on MixSIAR model, the contribution ratios of plant debris, soil dust, combustion source, agricultural activity, organic nitrate and organic amine to aerosol ON were 30.3 ± 21.2%, 10.3 ± 8.0%, 10.6 ± 12.4%, 15.4 ± 13.6%, 15.9 ± 12.8% and 17.5 ± 17.6%, respectively, in the daytime; and they were 23.8 ± 20.4%, 13.3 ± 11.6%, 9.9 ± 10.3%, 20.0 ± 18.1%, 15.8 ± 17.2% and 17.2 ± 14.7% at night (Fig. 3d).

**DISCUSSION**

We believe the significant difference of the prevailing wind directions between day and night (Supplementary Fig. 3) was a result of mountain–valley breeze. Due to mountain breeze and the decrease of PBL height, the levels of N-containing compounds in nighttime aerosols atop Mt. Tai were lower than those in daytime. Air pollutants over spring Mt. Tai possibly come from regional transport, especially at night. Air mass backward trajectories (Supplementary Fig. 4) show that air pollutants over spring Mt. Tai possibly come from the whole NCP. Since Mt. Tai is a relatively clean area with less local pollutant emissions, the concentration of N-containing aerosols over Mt. Tai was significantly lower than that in urban areas, such as Beijing, a megacity located in the north of NCP. Stable isotope analyses suggested there was very small difference between the sources of daytime and nighttime N-containing aerosols. Atmospheric particulates and therein N-containing compounds could be transported between the top and the foot of Mt. Tai. A conceptual scheme of the sources and transport processes of daytime and nighttime N-containing aerosols over spring Mt. Tai is presented in Fig. 4.

Usually, $\delta^{15}$N-NH$_3$ values in agricultural emission sources were lower than non-agricultural (e.g. fossil fuel-related) sources. In Beijing, since the contribution ratio of non-agricultural NH$_3$ emission increased with the increase of NH$_4^+$-N concentrations, $\delta^{15}$N-NH$_4^+$ values increased with increasing NH$_4^+$-N concentrations; however, $\delta^{15}$N-NH$_4^+$ values decreased with increasing NH$_3$-N concentrations in this study. It is concluded that there is no significant variation in the contributions from non-agricultural NH$_3$ sources to NH$_4^+$ when particulate matter level is higher. This might be caused by that the contribution of non-agricultural NH$_3$ sources was small whether during non-haze or haze days atop Mt. Tai. The increase in the NH$_4^+$-N concentration was partly due to the increased fraction of initial NH$_3$ converted to aerosol NH$_4^+$, so $\Delta\delta^{15}$N and $\delta^{15}$N-NH$_4^+$ decreased.

Based on MixSIAR model, the contributions of different NH$_3$ emission sources to aerosol NH$_4^+$, different NO$_x$ emission sources to aerosol NO$_3^-$, and different sources to aerosol ON, were well calculated. For the source apportionment results of aerosol NH$_4^+$, or NO$_3^-$, there is an uncertainty (standard deviation) of about or less than 15% for each source (Fig. 3a–c), but the uncertainty could reach up to 20% for aerosol ON (Fig. 3d); this mainly depends on the $\delta^{15}$N difference among possible sources. However, we could still identify the major emission source(s) of each N-containing compound in aerosol samples, suggesting that the model is available in such studies, no matter assuming more emission sources (e.g., 6 sources) or less sources (e.g., 3 sources).

As for NH$_3$ emission sources to aerosol NH$_4^+$ over Mt. Tai, agricultural sources (livestock breeding and N-fertilizer application) were the dominant ones with livestock breeding as the most important source. Although the important or even dominant contribution of non-agricultural sources were reported in Beijing and other urban cities of the NCP, our results suggest that...
agricultural sources of NH3 emissions still play a major role in the whole NCP. Therefore, we conclude NH3 emission inventories might be different in urban and the entire areas of NCP. Biomass burning is not an important source of NH3 emission in the NCP, no matter in an urban area or in a mountainous area surrounded by plains and countryside (this study). Overall, the source apportionment results under the assumption of $\delta^{15}N = 31.6 \pm 2.0$‰ were closer to the emission inventory29,40 than $\delta^{15}N = 24.1 \pm 2.8$‰. This indicates that 31.6 ± 2.0‰ is probably closer to the actual $^{15}N$ fractionation factor during the conversion of NH3 to NH4+ for aerosols atop Mt. Tai, and the turnover rate of NH3 in our study area is closer to 0.9 per day, which is considered as a low turnover rate. Thus, we conclude only a little fresh gaseous NH3 might be added to the observed air masses during the transport of aerosol NH4+.

Combustion sources (coal and biomass burning) and mobile emissions were the main emission sources of NOx that formed aerosol NO2 atop Mt. Tai. Their contribution ratios were very close. Since NOx emissions are a major contributor to secondary inorganic aerosols over East Asia41, this needs to be considered when making NOx reduction policies. Previous study showed that microbial processes contributed only a little to NOx in spring Beijing42. Similar results between Beijing and Mt. Tai suggest that, anthropogenic activity, rather than microbial processes, was the dominant NOx emission source in the NCP. Although aerosol NO2− over Mt. Tai has a lower concentration than urban regions39, its source apportionment results partly reveal the main NO2− emission sources of the whole NCP.

Compared with previous reports, our results show that the concentrations of aerosol NO over Mt. Tai were lower than those in urban regions39, but much higher than forest43 or marine areas46. ON accounted for 6–9% of the TN on average, which is consistent with the situation in Beijing46. Since Mt. Tai is covered with thick vegetation and dust storm weather often occurs in NCP in spring with blooming flowers47, plant debris (for example, pollen) and dust particles are important primary emission sources of ON. They accounted for more than one third of the total ON. Due to intensive human activities in the NCP, the contributions of agricultural activity and combustion sources (fossil fuel and biomass burning) to aerosol NOx are also non-negligible. Primary emission was possibly the largest contribution to aerosol NOx over Mt. Tai in spring. Around one third of ON originated from secondary formation, it was lower than the results obtained from high-resolution aerosol mass spectrometer combined with positive matrix factorization in urban Beijing (56–65%)46. This was probably because of relatively less precursors of N-containing secondary organic aerosols, for example, volatile organic compounds, NOx, NH3 and soot48 over Mt. Tai than in urban Beijing. It should be noted that high uncertainties exist in the source apportionment of ON, which warrants in-depth research in the future.

METHODS

Aerosol sampling

A total of 34 daytime and nighttime TSP samples were collected at the summit of Mt. Tai (36°26′ N, 117°10′ E, 1534 m a.s.l.), Shandong Province, China, from the 22nd of March to the 8th of April 2017 (Supplementary Methods)39.

Chemical and isotopic analyses

$^\delta^{15}N$ of NH4+, $^\delta^{15}N$ and $^\delta^{16}O$ of NO3 in the aerosol samples were analyzed using a commercially available purge and cryogenic trap system coupled to an isotope ratio mass spectrometer (PT-IRMS, IsoPrime100, IsoPrime Ltd., UK). For $^\delta^{15}N$NH4+ analyses, NH4+ was oxidized to NOx by alkaline hypobromite, and then reduced to N2O by hydroxylamine50,42. $^\delta^{15}N$ and $\delta^{16}O$ analyses of NO3− were conducted using the combination of denitrifying bacteria51,52 and thermal decomposition of N2O methods53,54,55.

The concentrations of NH4+ and NO3− were analyzed using a Smart Chem 200 Discrete Chemistry Analyzer (AMS, Italy).

The concentration of TN and $^\delta^{15}N$-TN were determined using a MAT 253 Isotope Ratio Mass Spectrometer (Thermo Fisher) coupled with a FLASH 2000 HT Elemental Analyzer (Thermo Fisher). The concentration of ON was obtained using TN minus IN, and $^\delta^{15}N$-ON was calculated from the concentration of TN and $^\delta^{15}N$ values of TN and IN. Nitrite was overlooked because of its significant lower contribution to IN and possible conversion to NO3− during analyses. Thus, the formulas are as follows:

$$[\text{TN}] = [\text{ON}] + [\text{NH}_4^+] - N + [\text{NO}_3^- - N]$$

(1)

$$[\text{TN}] \times \delta^{15}N = [\text{ON}] \times \delta^{15}N \times [\text{ON}] + [\text{NH}_4^+] \times \delta^{15}N - [\text{NO}_3^- - N]$$

(2)

Stable N and O isotope ratios were expressed in $\delta$ notation as the deviation from standards in parts per thousand (‰). $\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$‰, where R represents the $^{15}N$/$^{14}N$ or $^{18}O$/$^{16}O$ values in the sample ($R_{\text{sample}}$) and in the standards (Rstandard). Atmospheric nitrogen for $^{15}N$-VIenna Standard Mean Ocean Water for $\delta^{18}O$.

$^\delta^{15}N$-N, NO3−-N and ON source forensics

The MixSIAR model, a Bayesian stable isotope analysis mixing model in R (MixSIAR), was used to determine the contributions of different emission sources to aerosol N-containing compounds (Supplementary Methods).

As stated above, $^\delta^{15}N$ fractionation factor ($\Delta^{15}N$) during the gas-to-particle partitioning of NH3 to form particulate NH4+ was 31.6 ± 2.0‰ and 24.1 ± 2.8‰ for NH3 turnover rates of 0.9 per day and 6.8 per day, respectively27. Both $\Delta^{15}N$ values were used when carrying out source apportionment of aerosol NH4+. We assumed that NH3 was emitted from six major sources: volatilized livestock breeding, N-fertilizer application, human waste (including solid waste, waste water and human excreta), fossil fuel sources emitted from coal combustion and vehicle exhaust, NH3 slip from industrial/power plants and diesel engines equipped with selective catalytic reduction techniques, and biomass burning, with mean $^{15}N$ values of −32.3 ± 10.3‰, −44.8 ± 7.4‰, −37.8 ± 3.7‰, −3.0 ± 3.3‰, −13.0 ± 1.7‰ and 12.0‰, respectively34,43,45.

The total $^\delta^{15}N$ fractionation factor ($\Delta^{15}N$ = $^\delta^{15}N$-NO3− (p) − $^\delta^{15}N$-NO3− was calculated during the conversion process of initial NOx (generally including NO and NO2) to particulate NO3−. It was assumed that NOx was oxidized to HNO3 (g) by two major pathways: NOx + HO − H2O and NOx + O3 + H2O, there are different $^1N$ fractionation factors during these two conversion processes. Contribution of the two pathways could be calculated and N isotope equilibrium fractionation of the oxidation process could be estimated, based on O isotopes. The oxidation of NOx to NO3− was shown to have a kinetic $^1N$ fractionation of about −3.0‰57, and the conversion from HNO3 (g) to NO3− (p) can have a $^1N$ equilibrium fractionation of about 21.0‰57. We assumed that NOx was emitted from three major sources: mobile emissions, combustion sources (coal combustion and biomass burning) and microbial processes, with mean $^\delta^{15}N$ values of −7.2 ± 7.8‰, 8.0 ± 7.9‰ and −35.4 ± 10.7‰, respectively52,53,55,56.

Aerosol ON could originate from primary emission of ON or secondary formation of IN46. In this study, we assumed that primary ON was from four major sources: soil dust, plant debris, combustion source and agricultural activity, with average $^\delta^{15}N$-ON values of 2.0 ± 1.5‰, −5.7 ± 0.8‰, 12.0 ± 5.0‰ and −2.4 ± 2.1‰, respectively53,54; and the $^{15}N$ fractionation between emission source and aerosol samples was ignored. Besides, we assumed that there were two categories of aerosol secondary ON: organic amine and organic nitrates, whose formation process is related to NH3, NH4+ or gaseous amine, and NO3 or NO2−, respectively. Due to the lack of related research and data, we supposed no difference between $^\delta^{15}N$ values in aerosol NO3− and organic nitrate, or $^\delta^{15}N$ in NH4+ and organic amine, in this study.

DATA AVAILABILITY

The data needed for the air mass backward trajectories was downloaded from the website of Air Resources Laboratory (https://www.arl.noaa.gov/). Other data used in this study are available from the corresponding author upon reasonable request.

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P.F. and L.W. conceived the study. P.F., R.M.H. and Y.F. supported the study. S.Y., H.R., J.C., L.R. and W.L. conducted the field work. L.W. and S.Y. conducted experiments and analyses. L.W. wrote the paper with contribution and review from all coauthors.

COMPETING INTERESTS
The authors declare no competing interest.

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