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Nitrate chemistry in the northeast US – Part 1: Nitrogen isotope seasonality tracks nitrate formation chemistry

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Abstract. Despite significant precursor emission reductions in the US over recent decades, atmospheric nitrate deposition remains an important terrestrial stressor. Here, we utilized statistical air mass back trajectory analysis and nitrogen stable isotope deltas ($\delta(^{15}N)$) to investigate atmospheric nitrate spatiotemporal trends in the northeastern US from samples collected at three US EPA Clean Air Status and Trends Network (CASTNET) sites from December 2016–2018. For the considered sites, similar seasonal patterns in nitric acid (HNO_3) and particulate nitrate (pNO_3) concentrations were observed with spatial differences attributed to nitrogen oxide (NO_x) emission densities in source contributing regions that were typically $\leq 1000\,\text{km}$. Significant spatiotemporal $\delta(^{15}N)$ variabilities in HNO_3 and pNO_3 were observed with higher values during winter relative to summer, like previous reports from CASTNET samples collected in the early 2000s for our study region. In the early 2000s, $\delta(^{15}N)$ of atmospheric nitrate in the northeast US had been suggested to be driven by NO_x emissions; however, we did not find significant spatiotemporal changes in the modeled NO_x emissions by sector and fuel type or $\delta(^{15}N, NO_x)$ for the source regions of the CASTNET sites. Instead, the seasonal and spatial differences in the observed $\delta(^{15}N)$ of atmospheric nitrate were driven by nitrate formation pathways (i.e., homogeneous reactions of NO_2 oxidation via hydroxyl radical or heterogeneous reactions of dinitrogen pentoxide on wetted aerosol surfaces) and their associated $\delta(^{15}N)$ fractionation. Under the field conditions of low NO_x relative to O_3 concentrations and when $\delta(^{15}N, NO_x)$ emission sources do not have significant variability, we demonstrate that $\delta(^{15}N)$ of atmospheric nitrate can be a robust tracer for diagnosing nitrate formation.

1 Introduction

Nitrogen oxides ($NO_x = NO + NO_2$) are a significant source of air pollution derived from electricity generation, industrial processes, vehicle emissions, biomass burning, lightning, and microbial activity in soils (Jaeglé et al., 2018, 2005; Delmas et al., 1997). NO_x emissions have an important impact on climate and human and ecosystem health due to their influence on atmospheric oxidation chemistry and produc-tion of total atmospheric nitrate ($tNO_3 =$ nitric acid (HNO_3) + particulate nitrate (pNO_3)) (Galloway et al., 2004; Zhang et al., 2003; Frost et al., 2006; Pinder et al., 2012). NO_x chemistry facilitates the production of atmospheric oxidants, including ozone (O_3) and hydrogen oxide radicals ($HO_x = OH + HO_2$), which defines the tropospheric oxidation capacity (Bloss et al., 2005; Prinn, 2003). These oxidants play an important role in the removal of trace gases and formation of particulate matter, with important consequences for human

health and climate (Bauer et al., 2007; Ehn et al., 2014; Pye et al., 2010). Particulate nitrate contributes to poor air quality and represents a significant portion of ambient fine particulate matter ($PM_{2.5}$), negatively affecting the human respiratory and cardiovascular systems (Xing et al., 2016). Wet and dry deposition of tNO_3 contributes bioavailable nitrogen to often sensitive ecosystems (Galloway et al., 2004; Greaver et al., 2016; Pinder et al., 2012; Walker et al., 2019). In the US, NO_x emissions from power plants and vehicles have dramatically declined over the last several decades due to effective regulations (Hand et al., 2014). Yet, atmospheric nitrogen deposition remains a major terrestrial stressor, which has important implications for land and water quality and interacting effects with climate (Greaver et al., 2016).

Previous studies have suggested that stable nitrogen isotope deltas $\delta(^{15}N) = [R_{sample}(^{15}N/^{14}N)/R_{air-N_2}(^{15}N/^{14}N) - 1]$ may be a powerful observational constraint to enhance our understanding of atmospheric nitrate sources and/or chemical processing (Elliott et al., 2009, 2007; Beyn et al., 2014, 2015; Freyer, 1991; Savard et al., 2017; Savarino et al., 2013; Vicars et al., 2013; Chang et al., 2019; Li et al., 2019; Zong et al., 2017; Hastings et al., 2009; Geng et al., 2014). Precursor NO_x emission sources tend to have distinct $\delta(^{15}N)$ values (or "fingerprints") dependent on formation mechanisms (Miller et al., 2017, 2018; Felix et al., 2012; Walters et al., 2015a, b; Li and Wang, 2008; Yu and Elliott, 2017). For example, biogenic soil emissions tend to have low $\delta(^{15}N, NO_x)$ values of typically less than $-25‰$ (Miller et al., 2018; Yu and Elliott, 2017), stationary liquid fuel combustion has been measured to range between $-19.7‰$ to $-13.9‰$ (Walters et al., 2015a), on-road vehicle plumes have been measured to have a range of $-9‰$ to $-2‰$ (Miller et al., 2017), and coal combustion tends to have elevated values with a range of $9.8‰$ to $19.8‰$ (Felix et al., 2012). If these $\delta(^{15}N)$ emission source signatures are proportionally transferred into atmospheric nitrate, it can be a useful observational constraint for tracking precursor NO_x emission sources to spatiotemporal deposition patterns (Hastings et al., 2013). However, chemical and physical processing associated with NO_x cycling and formation of atmospheric nitrate can also induce significant isotope fractionation, such that $\delta(^{15}N)$ may not be conserved from emission to deposition (Freyer, 1991; Freyer et al., 1993; Walters et al., 2016; Walters and Michalski, 2015a; Li et al., 2020; Walters and Michalski, 2016a; Vicars et al., 2013). These $\delta(^{15}N)$ fractionations are associated with equilibrium isotope effects (EIEs), unidirectional kinetic isotope effects (KIEs), and photo-induced fractionation isotope effects (PHIEs) (Freyer, 1991; Freyer et al., 1993; Walters et al., 2016; Walters and Michalski, 2015a; Li et al., 2020; Walters and Michalski, 2016a; Fang et al., 2021). Accounting for these isotope effects is important for $\delta(^{15}N)$ to be used as a quantitative tracker of precursor emission sources (Li et al., 2020; Vicars et al., 2013; Fang et al., 2021; Walters et al., 2018; Savarino et al., 2013; Chang et al., 2018, 2019; Feng et al., 2020).

The northeastern US remains important to monitor due to its high population density, transport patterns, historically degraded air quality, and elevated acid deposition influenced by NO_x emissions and transformations (Sickles and Shadwick, 2015). Previous landmark $\delta(^{15}N)$ studies of atmospheric nitrate in this region have reported significant correlations between concentration and $\delta(^{15}N)$ of atmospheric nitrate in wet (National Atmospheric Deposition Program; NADP) and dry deposition (Clean Air Status and Trends Network; CASTNET) samples with regional stationary NO_x emission sources from power plant and industrial sectors in the mid-2000s (Elliott et al., 2007, 2009). Considering dramatic NO_x emission changes over the past decades, it is critical to update our understanding of atmospheric tNO_3 deposition's precursor sources and drivers in polluted regions such as the northeastern US. Furthermore, our understanding of $\delta(^{15}N, NO_x)$ emission signatures and $\delta(^{15}N)$ isotope fractionation patterns has significantly improved in recent years. In this study, we have measured the $\delta(^{15}N)$ compositions of HNO_3 and pNO_3 from CASTNET samples collected in the northeastern US from December 2016 to 2018. Our study contributes to an update on the spatiotemporal $\delta(^{15}N)$ compositions and interpretation of atmospheric tNO_3 in the northeastern US and our understanding of the concentration and $\delta(^{15}N)$ drivers of atmospheric tNO_3 after a period of aggressive NO_x emission reductions.

2   Materials and methods

2.1   CASTNET filter samples

Filter samples from December 2016 to 2018 were obtained from the US EPA CASTNET program for several sites in the northeastern US, including (from west to east) Connecticut Hill, NY (CTH110; 42.40° N, −76.65° W; Elevation = 511 m); Abington, CT (ABT147; 41.84° N, −72.01° W; Elevation = 202 m); and Woodstock, NH (WST109; 43.94° N, −71.70° W; Elevation = 255 m) (Fig. 1). The CASTNET sites were characterized by their primary land use as forest for CTH110, urban/agricultural for ABT147, and forest for WST109, respectively (CASTNET Site Locations, 2023). CASTNET is a national monitoring program sponsored by the US EPA to assess spatiotemporal trends in pollutant concentrations and atmospheric deposition. The CASTNET monitoring locations have been sited to avoid the influence of major cities, highways, local activities, and point source pollution and are expected to be regionally representative (Clarke et al., 1997).

The CASTNET sampling protocols have been previously described (Baumgardner et al., 2002). The atmospheric samples consist of week-long integrated collections using a three-stage filter pack. The filter pack contains three types of filters in sequence: (1) a Teflon filter (Whatman membrane filter, 47 mm diameter, 1.0 μm pore size) for particulate collection, including pNO_3; (2) a nylon filter (before January
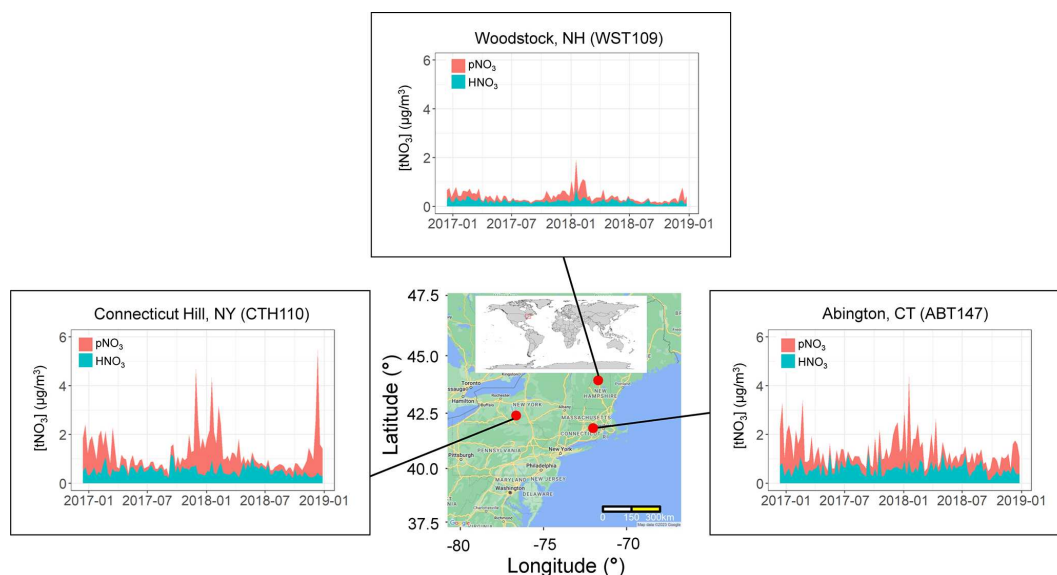
Figure 1. Location and nitrate concentrations (nitric acid (HNO_3), particulate nitrate (pNO_3), and total nitrate ($tNO_3 = HNO_3 + pNO_3$)) from December 2016–2018 of the three northeastern CASTNET monitoring sites included in the study. The map was created using Google Maps (Map data © 2022 Google).

2018: Pall Corporation Nylasorb, 47 mm diameter, 1.0 µm pore size; after January 2018: One Measurement Technology Laboratories, 47 mm diameter, 1.0 µm pore size) for acidic gas collections, including HNO_3; and (3) two potassium carbonate (K_2CO_3) impregnated cellulose filters (Whatman 41 Ashless Circle filter) for SO_2 collection. The filter pack sampling system is characterized as "open faced", because a size-selective inlet is not used. The filter packs are prepared and shipped to the field weekly. The filter packs are exchanged at the sampling sites every Tuesday and shipped to the analytical chemistry laboratory for analysis. Blank filter packs are prepared quarterly to evaluate contamination. The filter pack samples are collected at 10 m, and the filter pack flow rate is maintained at 1.50 L min^{-1} at standard conditions. The filters were extracted and analyzed for concentrations following standardized protocols at the Wood Gainesville, FL, US laboratory. Briefly, the filters were extracted using 25 mL of ultra-high purity water ($> 18.2 \, \text{M}\Omega$), and the Teflon and nylon filter extracts were measured using a micro membrane-suppressed ion chromatography to determine NO_3^-(aq) concentrations, which were utilized to calculate the concentration of pNO_3 and HNO_3 in the air (µg m^{-3}) based on the volume of collected air. Following this analysis, the samples were stored in a laboratory at room temperature for up to 2 years until shipment to Brown University.

To determine the stability of the sample extracts during storage and shipment, the filter extracts were re-measured for the total concentrations of nitrate (NO_3^-(aq)) and nitrite (NO_2^-(aq)) utilizing standard colorimetric methods (i.e., US EPA Method 353.2) on an automated discrete UV-Vis Analyzer (SmartChem Westco Scientific Instruments, Inc.) once

at Brown University. The detection limit was 0.1 and 0.3 µM for NO_2^-(aq) and NO_3^-(aq), respectively, and the pooled relative standard deviation of replicate quality control standards was better than 3 %. The nitrate concentrations reported by CASTNET were compared to our measured concentrations and gave a near 1 : 1 relationship for all sites and both filter types (nylon filter: $y = (-0.08 \pm 0.03) + (0.99 \pm 0.01)x$; $r = 0.994$; $p < 0.01$; Teflon filter: $y = (0.09 \pm 0.03) + (1.04 \pm 0.09)x$; $r = 0.997$; $p < 0.01$) indicating excellent NO_3^-(aq) stability in the filter extracts (Fig. 2). Additionally, the mean absolute difference and the mean percent difference between the re-measured and reported NO_3^-(aq) concentrations were $(0.31 \pm 0.36 \, \mu\text{M}; \ \overline{x} \pm \sigma)$ and $(10.4 \pm 13.3 \, \%)$, respectively ($n = 632$). Equal volumes of 4-weekly collected filter extracts were combined into approximately monthly aggregates to provide sub-seasonal resolution of nitrogen isotope analysis for HNO_3 and pNO_3. Samples were combined into month aggregates to meet the typical mass requirements for isotope analysis, requiring 20 nmol for $\delta(^{15}N)$ and $\delta(^{18}O)$ and 50 nmol for $\Delta(^{17}O)$ quantification. For samples where $[NO_2^-] > 0.1 \, \mu\text{M}$, NO_2^-(aq) was removed using a sulfamic acid treatment (Granger and Sigman, 2009), as it will cause interference when measuring the nitrogen and oxygen isotope ratios of the nitrate (see below). The samples were then frozen until subsequent isotopic analysis.

2.2 Isotopic analysis

Nitrogen stable isotopic analysis was conducted for HNO_3 and pNO_3 from the monthly aggregated filter extracts using the well-established bacterial denitrifier method (Sig-
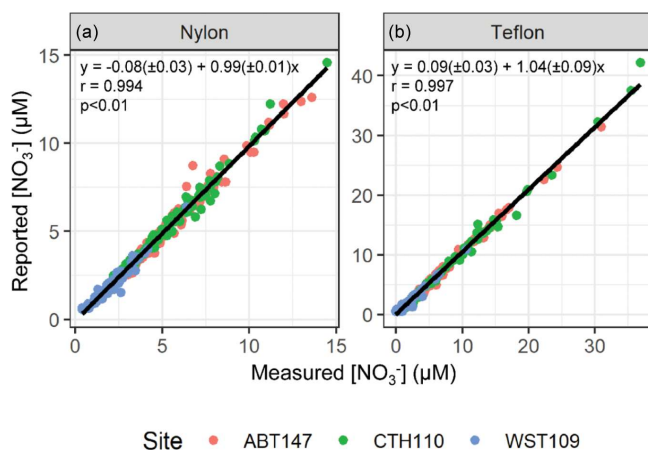
Figure 2. Comparison between the nitrate (NO_3^-) concentrations reported by CASTNET with those measured at Brown University for the nylon filter **(a)** and Teflon filter **(b)** extracts.

man et al., 2001; Casciotti et al., 2002). Briefly, samples were injected into vials containing *Pseudomonas aureofaciens*, which lacks the N_2O reductase enzyme, such that NO_3^- (and NO_2^-) are quantitatively converted to nitrous oxide (N_2O). The generated N_2O was concentrated and purified using an automatic purge and trap system and introduced to a continuous flow isotope ratio mass spectrometer (CF-IRMS; Thermo Scientific Delta V) with a modified gas bench interface at Brown University. Measurement of N_2O was conducted at m/z of 44, 45, and 46 to determine $\delta(^{15}N)$, and unknowns were corrected relative to internationally recognized nitrate salt reference materials that included USGS34 ($\delta(^{15}N) = -1.8‰$), USGS35 ($\delta(^{15}N) = 2.7‰$), and IAEA-N3 ($\delta(^{15}N) = 4.7‰$) (Böhlke et al., 1993, 2003). We acknowledge that the $\delta(^{15}N)$ range of the nitrate reference material is relatively narrow; however, the range of our calibrated unknowns was quite near these values (calibrated unknowns ranged from $-10.6‰$ to $5.8‰$ and averaged $-1.7 \pm 3.7‰$; $n = 158$). Thus, while some of the unknowns will have a calibrated $\delta(^{15}N)$ extrapolated from the reference materials, we do not anticipate this to impact our measurement accuracy and precision or the interpretation of the results. Isobaric influences from ^{17}O contributions were corrected based on a separate analysis, in which N_2O was thermally decomposed to O_2 by passing through a gold tube heated to $770\,°C$. The generated O_2 was introduced to a CF-IRMS (Thermo Scientific Delta V) and measured at m/z 32, 33, and 34 for $\Delta(^{17}O)$ (defined as $\Delta(^{17}O) = \delta(^{17}O) - 0.52 \times \delta(^{18}O)$) determination (Kaiser et al., 2007). This correction resulted in a $\delta(^{15}N)$ decrease typically near $1.5‰$. All isotopic reference materials were diluted to similar concentrations as samples and run intermittently in each batch analysis. The overall standard deviations of isotopic reference materials were $\sigma(\delta(^{15}N)) = 0.2‰$ ($n = 13$), $0.4‰$ ($n = 13$),

and $0.2‰$ ($n = 15$) for USGS34, USGS35, and IAEA-N3, respectively.

2.3 HYSPLIT modeling and "openair" package

Air mass back trajectories were computed using the HYSPLIT model and the North American Regional Reanalysis (NARR) 12 km dataset (Stein et al., 2015). The 72 h back trajectories were calculated at 50 m above ground level every other day for each site (CTH110, ABT147 and WST109) across the sample collection period from December 2016 to 2018. The trajectory data were collated with the reported CASTNET concentration data (pNO_3, HNO_3, and tNO_3) at a weekly resolution to link concentration trends to the source regions for nitrate. Using the "openair" program package in R (Carslaw and Ropkins, 2012), geospatial statistical analysis that included back-trajectory clustering and the concentrated weighted trajectory (CWT) algorithm was conducted to determine patterns of transport and major contributing source regions for atmospheric nitrate. The CWT model is a statistical tool that utilizes the air mass residence time analysis to identify emission source regions (Hsu et al., 2003; Salamalikis et al., 2015; Cheng et al., 2013; Dimitriou et al., 2015). For each grid cell, CWT calculates the concentration of a pollutant as the following (Eq. 1):

$$\overline{c_{ij}} = \frac{1}{\sum_{k=1}^{N} \tau_{ijk}} \sum_{k=1}^{N} c_k \tau_{ijk}, \quad (1)$$

where i and j are the indices of grid, k is the index of trajectory, N is the total number of trajectories used in the analysis, c_k is the pollutant concentration measured upon arrival of trajectory k, and t_{ijk} is the residence time of trajectory k in grid cell (i, j). A high value of $\bar{c}_{ij}$ means that air parcels that pass over the cell (i, j) would, on average, cause a high concentration at the receptor site (Carslaw and Ropkins, 2012).

2.4 NO_x emissions database and $\delta^{15}N(NO_x)$ estimation

Monthly anthropogenic NO_x emission density estimates were extracted from a recent sector and fuel-based emission inventory to understand how precursor NO_x emissions contribute to nitrate concentration and isotope trends (McDuffie et al., 2020). The monthly NO_x emissions data were reported in gridded $0.5° \times 0.5°$ units divided into 11 anthropogenic sectors: agriculture, energy production, industry, on-road transportation, non-road transportation, combustion-residential, combustion-commercial, combustion-other, shipping, solvents, and waste (note that solvents are not a source of NO_x emissions). The combustion sector emissions were further broken down into fuel types (coal, solid biofuel, and liquid fuel), while non-combustion emissions were assigned to a single "process" fuel type. Monthly NO_x emission density estimates by sector and fuel-type data were extracted

from the nitrate source regions determined from the CWT analysis. The regions were defined using spatial polygons in "R", which sets latitude and longitude coordinates to retrieve spatially encoded data. Monthly $\delta(^{15}N, NO_x)$ was modeled based on isotope mass balance using the fraction of NO_x emissions by sector and fuel type and previously reported $\delta(^{15}N, NO_x)$ emission signatures following a previously described method (Eq. 2) (Walters et al., 2015a):

$$\delta(^{15}N, NO_x) = \sum_{i=1}^{n} f_i \delta_i(^{15}N, NO_x), \qquad (2)$$

where δ_i is the emission signature of source and f_i is the fraction contributing to the NO_x emissions. The considered $\delta(^{15}N, NO_x)$ emission signatures included grouped agriculture and waste (Miller et al., 2018), on-road transportation (Miller et al., 2017), non-road transportation (Walters et al., 2015a), and shipping (Walters et al., 2015a). Energy production, industry, and combustion were grouped by fuel type as either combustion – coal & solid biofuel (Felix et al., 2012) or combustion – liquid fuel & process (Walters et al., 2015a). The emission inventory only considers anthropogenic NO_x emissions such that natural emissions such as lightning and wildfires were not considered. Table 1 summarizes the $\delta(^{15}N, NO_x)$ emission signatures (Walters et al., 2015a; Miller et al., 2018, 2017; Felix et al., 2012).

2.5 GEOS-Chem simulations

The GEOS-Chem global model of atmospheric chemistry (http://www.geos-chem.org, last access: 22 September 2022) was utilized to predict NO_x and O_3 concentrations in the regions of the various CASTNET sites (Bey et al., 2001; Walker et al., 2012, 2019). The model was utilized to account for $\delta(^{15}N)$ isotope fractionation that occurs during chemical reactions. We use version 13.2.1 (http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_13.2.1, last access: 22 September 2022) of the model driven by GEOS5-FP assimilated meteorology from the NASA Global Modeling and Assimilation Office (GMAO). A nested grid (0.25° latitude × 0.3125° longitude horizontal resolution; 25 km) simulation was conducted over the northeastern United States (97–60° W; 35–60° N) in 2017 and 2018. Boundary conditions were from global simulations performed at 4° latitude × 5° longitude horizontal resolution for the same years after a one-year initialization. Gas- and aerosol-phase chemistry was simulated using the default "fullchem" mechanism (Bates and Jacob, 2019; Wang et al., 2021). Inorganic gas and aerosol partitioning were conducted using version 2.2 of the ISORROPIA II thermodynamic equilibrium model (Fountoukis and Nenes, 2007). All default anthropogenic emissions were applied, which is primarily version 2.0 of the Community Emissions Data System (Hoesly et al., 2018) as previously implemented (McDuffie et al., 2020). Natural emissions respond to local meteorology and

include biogenic volatile organic compounds from terrestrial plants and the ocean (Millet et al., 2010; Guenther et al., 2012; Hu et al., 2015; Breider et al., 2017), NO_x from lightning and soil microbial activity (Murray et al., 2012; Hudman et al., 2012), mineral dust (Ridley et al., 2012), and sea salt (Jaeglé et al., 2011; Huang and Jaeglé, 2017). Biomass burning emissions were monthly means from version 4.1s of the Global Fire Emissions Database (GFED4.1s; van der Werf et al., 2017). Wet deposition for water-soluble aerosols is described by Liu et al. (2001) and by Amos et al. (2012) for gases. Dry deposition is based on the resistance-in-series scheme of Wesely and Lesht (1989).

3 Results and discussion

3.1 Atmospheric nitrate spatiotemporal concentrations

The atmospheric nitrate concentrations (U.S. Environmental Protection Agency Clean Air Markets Division Clean Air Status and Trends Network, 2022) are shown in Fig. 1 and summarized in Table 2. The speciation of tNO_3 concentration is important to evaluate due to HNO_3 and pNO_3 different atmospheric lifetime driven by deposition rates (Benedict et al., 2013). Due to a higher dry deposition rate, HNO_3 has a shorter atmospheric lifetime of a few days (i.e., 1–3 d) relative to pNO_3, which has a lifetime of several days (i.e., 5 to 15 d). Overall, the mean concentrations of the three examined northeastern US CASTNET sites were significantly different but showed similar seasonal trends. Lower nitrate concentrations at the Woodstock, NH, site compared to the other sites likely reflect the different amounts of NO_x emissions and, thus, the amount of nitrate impacting the study sites. For example, the Woodstock, NH, site is relatively remote compared to the urban/agricultural characterization of Abington, CT, and Connecticut Hill, NY, which is directly downwind of the highly industrialized Ohio River valley and other midwestern cities. Across the sites, the annual concentrations of HNO_3, pNO_3, and tNO_3 were significantly higher at Abington, CT, and Connecticut Hill, NY, than at Woodstock, NH ($p < 0.01$). The concentrations were binned by season including winter (DJF), spring (MAM), summer (JJA), and autumn (SON), which indicated seasonal statistical differences at the considered CASTNET sites. The HNO_3 concentrations were significantly greater during the winter for Woodstock, NH, than in other seasons ($p < 0.01$). Additionally, HNO_3 at Abington, CT, was significantly higher during summer than in autumn ($p < 0.01$). There was no significant seasonal difference in HNO_3 concentrations at Connecticut Hill, NY. At all three sites, the concentrations of pNO_3 were greatest during the winter and lowest during the summer. These findings were consistent with previous reports of CASTNET samples in the northeastern and midwestern US collected from 2004 to 2005, in which pNO_3 concentrations were highest in the winter and lowest in the summer and with little seasonal variation in HNO_3 (Elliott et al., 2009). Thus, even as NO_x emis-

Table 1. Summary of $\delta(^{15}N, NO_x)$ emission source values.

NO_x emission source	$\delta(^{15}N, NO_x)$ (‰) (mean $\pm \sigma$)	Reference
Agriculture/waste[a]	-33.0 ± 12.3	Miller et al. (2018)
On-road transport	-4.7 ± 1.7	Miller et al. (2017)
Non-road transport	-16.8 ± 5	Walters et al. (2015a)
Shipping	-16.8 ± 5	Walters et al. (2015a)
Combustion – coal & solid biofuel[b]	13.6 ± 3.9	Felix et al. (2012)
Combustion – liquid fuel & process[b]	-16.5 ± 1.7	Walters et al. (2015a)

[a] Waste NO_x emissions represented < 1 % of total monthly NO_x emissions within each identified nitrate source region and were lumped with agricultural NO_x emissions. [b] Combustion-residential, combustion-commercial, and combustion-other were combined (Combustion) and separated by fuel type (i.e., Combustion – coal & Solid Biofuel & Combustion – liquid fuel & process). The "process" combustion emissions were assumed to have a similar $\delta(^{15}N, NO_x)$ value as liquid fuel.

sions have dramatically decreased in the US by 38 % from 2005–2014 as evidenced from top-down global surface NO_x observations (Miyazaki et al., 2017), the HNO_3 and pNO_3 seasonal trends in the northeast US have been retained.

Clustered air mass back trajectories were calculated for the CASTNET sites (Fig. 3). The annual clustered trajectories indicate that most air masses were associated with westerlies with prevailing winds from the continental US and Canada for all the considered CASTNET sites. The clustered trajectories also indicate the influence of marine/coastal air masses and winds from the northeast. The CWT analysis of tNO_3 concentrations indicated that contributing source regions tended to be within approximately 1000 km of the CASTNET sites (Fig. 3). Like the cluster trajectory results, the CWT analysis indicated that the tNO_3 source contributing regions tended to extend towards the west and northwest of the CASTNET sites with minimal contributions east of the sites. Similar source regions were identified for the various CASTNET sites, but there were slight spatial differences due to the location of the sites, which likely impacted the nitrate concentration trends observed at the sites. For example, the source regions contributing to CTH110 tended to extend further from the Midwest compared to the other sites, and a higher relative contribution from southeast Canada was identified for the WST109 site.

3.2 Atmospheric nitrate spatiotemporal $\delta(^{15}N)$ compositions

The measured atmospheric nitrate $\delta(^{15}N)$ data are shown in Fig. 4 and summarized in Table 2. The $\delta(^{15}N)$ data indicated significant spatial differences but with consistent seasonal patterns for $\delta(^{15}N, HNO_3)$, $\delta(^{15}N, pNO_3)$, and $\delta(^{15}N, tNO_3)$. The $\delta(^{15}N)$ values were highest for Abington, CT, second highest for Connecticut Hill, NY, and lowest for Woodstock, NH. Across the sites, there was a consistent offset between $\delta(^{15}N, HNO_3)$ and $\delta(^{15}N, pNO_3)$, in which $\delta(^{15}N, pNO_3)$ tends to have higher values relative to $\delta(^{15}N, HNO_3)$ that

averaged a (3.9 ± 1.8)‰ ($n = 79$) difference for simultaneously collected samples. This value was in close agreement with the theoretical isotope effect associated with N isotopic equilibrium between NO_3^- and HNO_3, which has been calculated to be 3.2‰ at 298 K, favoring the preferential partitioning of ^{15}N into NO_3^- (Walters and Michalski, 2015a).

Across all sites, $\delta(^{15}N, HNO_3)$, $\delta(^{15}N, pNO_3)$, and $\delta(^{15}N, tNO_3)$ indicated consistent temporal patterns, with the highest values observed during the winter and lowest values during the summer (Fig. 4). These findings were similar to previous $\delta(^{15}N)$ measurements from HNO_3, pNO_3, and precipitation NO_3^- samples collected in the early 2000s in the midwestern and northeastern US, which also reported a significant spatiotemporal variation (Elliott et al., 2009, 2007). The CTH110 site was previously analyzed for its $\delta(^{15}N)$ deltas in the early 2000s (Elliott et al., 2009). Overall, the range of measured $\delta(^{15}N)$ at CTH110 was lower in 2017–2018 ($\delta(^{15}N, HNO_3) = -11.1$‰ to -0.1‰; $\delta(^{15}N, pNO_3) = -6.8$‰ to 4.4‰), compared to measurements conducted for 2004–2005 ($\delta(^{15}N, HNO_3) = -5$‰ to 10‰; $\delta(^{15}N, pNO_3) = -1.0$‰ to 12‰) (Elliott et al., 2009). This trend is consistent with an expected decrease in $\delta(^{15}N)$ of atmospheric nitrate after implementing NO_x reduction technologies on electricity generation units and their subsequent relative decrease in NO_x emissions (Felix et al., 2012).

3.3 NO_x emission modeling

Previous spatiotemporal $\delta(^{15}N)$ differences in atmospheric nitrate in the midwestern and northeastern US had been concluded to reflect the importance of precursor emission sources (Elliott et al., 2009, 2007). Specifically, stationary source NO_x emissions associated with coal combustion with a high $\delta(^{15}N, NO_x)$ emission signature were suggested to drive higher $\delta(^{15}N)$ values during winter and a longitudinal gradient across the midwestern and northeastern US (Elliott et al., 2009). To test this hypothesis on the current dataset, the monthly predicted NO_x emission densities speciated by

Table 2. Statistical summary including minimum (Min), maximum (Max), mean (Mean), standard deviation (SD), and number of counts (N) for concentration and $\delta(^{15}N)$ of HNO_3, pNO_3, and tNO_3 at the CASTNET sites.

Descriptive statistic	HNO_3		pNO_3		tNO_3	
	Concentration ($\mu g\,m^{-3}$)	$\delta(^{15}N)$ (‰)	Concentration ($\mu g\,m^{-3}$)	$\delta(^{15}N)$ (‰)	Concentration ($\mu g\,m^{-3}$)	$\delta(^{15}N)$ (‰)
Connecticut Hill, NY						
Min	0.219	−11.1	0.091	−6.8	0.320	−9.8
Max	1.203	−0.1	5.033	4.4	5.474	3.0
Mean (SD)	0.526 ± 0.200	−4.7 ± 3.2	0.735 ± 0.813	−0.6 ± 3.2	1.261 ± 0.832	−2.7 ± 4.1
N	105	26	105	26	105	26
Abington, CT						
Min	0.138	−9.5	0.142	−4.3	0.488	−7.5
Max	1.326	4.3	3.466	5.8	4.375	5.1
Mean (SD)	0.600 ± 0.255	−2.1 ± 4.4	0.723 ± 0.582	0.6 ± 2.8	1.323 ± 0.662	−0.9 ± 3.9
N	107	27	107	27	107	27
Woodstock, NH						
Min	0.061	−11.7	0.058	−6.9	0.148	−10.6
Max	0.721	−3.4	1.213	2.3	1.934	−0.4
Mean (SD)	0.218 ± 0.094	−6.7 ± 2.4	0.199 ± 0.183	−1.8 ± 2.7	0.417 ± 0.252	−4.8 ± 3.0
N	105	26	105	26	105	26

sector and fuel-specific sources based on the Community Emissions Data System (McDuffie et al., 2020) were extracted for spatial polygons that approximately corresponded to the identified tNO_3 source contributing regions from the CWT analysis (Fig. 3). Across all sites, the predicted NO_x emission densities ($kg\,m^{-2}\,s^{-1}$) indicated similar seasonal variability, with a maximum observed during winter from higher residential, commercial, and other combustion emissions due to a significant heating demand (Fig. 5). A local maximum in NO_x emission densities ($kg\,m^{-2}\,s^{-1}$) was also observed during summer due to increased emissions related to electricity generation for cooling (Fig. 5). The absolute NO_x emission densities were higher for CTH110 and ABT147 compared to WST109, which may explain the observed nitrate concentration trends with the lowest concentrations observed at WST109 (Fig. 1). Across the sites, the Community Emissions Data System predicts that there were similar annual contributing NO_x emission sectors for the identified source regions contributing tNO_3 to the study sites (CTH110, ABT147, WST109) that included energy (21.9 %, 22.5 %, 23.5 %), industry (14.4 %, 14.6 %, 14.1 %), non-road transport (17.3 %, 16.2 %, 15.0 %), combustion-residential, commercial, other (12.8 %, 14.2 %, 14.3 %), road (23.9 %, 23.2 %, 23.3 %), shipping (7.5 %, 7.5 %, 8.5 %), and agricultural/waste (2.1 %, 1.7 %, 1.5 %) (Fig. 5). Additionally, there was similar annual NO_x emission density contributing fuel types across sites, including biofuel (2.6 %, 2.7 %, 2.7 %), coal (5.8 %, 5.2 %, 4.8 %), liquid-

fuel (76.4 %, 75.0 %, 73.9 %), and process-based emissions (15.3 %, 17.2 %, 18.7 %) for the identified source regions contributing to tNO_3 at CTH110, ABT147, and WST109, respectively (Fig. 5).

The monthly $\delta(^{15}N, NO_x)$ was calculated using the NO_x emission estimates, assumed emission source values, and isotope mass balance (Fig. 6). Overall, this calculation indicated limited spatial variability with an annual $\delta(^{15}N, NO_x)$ average of $(−11.7 ± 0.1)$ ‰, $(−11.6 ± 0.1)$ ‰, and $(−11.8 ± 0.8)$ ‰ for ABT147, CTH110, and WST109, respectively. We note that while there were significant differences in modeled NO_x emission densities and observed nitrate concentrations at the study site, the relative contributions of NO_x emissions contributing to the study sites were nearly identical, leading to similar modeled $\delta(^{15}N, NO_x)$ values. Thus, NO_x emissions were not the main contributor to the observed spatial differences in $\delta(^{15}N, HNO_3, pNO_3, tNO_3)$. We note that for each of the monthly $\delta(^{15}N, NO_x)$ estimations, the propagated uncertainty based on the $\delta(^{15}N, NO_x)$ emission signature reported uncertainty was approximately ±3.4 ‰ and was not seasonally variable. There was limited seasonality in the modeled $\delta(^{15}N, NO_x)$ across all sites that was different by no more than 0.3 ‰ in the monthly mean values. The highest modeled mean $\delta(^{15}N, NO_x)$ values occurred during the summer due to increased emissions from the energy production sector, namely, an increase in coal and solid biofuel combustion, which has an elevated $\delta(^{15}N, NO_x)$ signature (Table 1) (Felix et al., 2012).
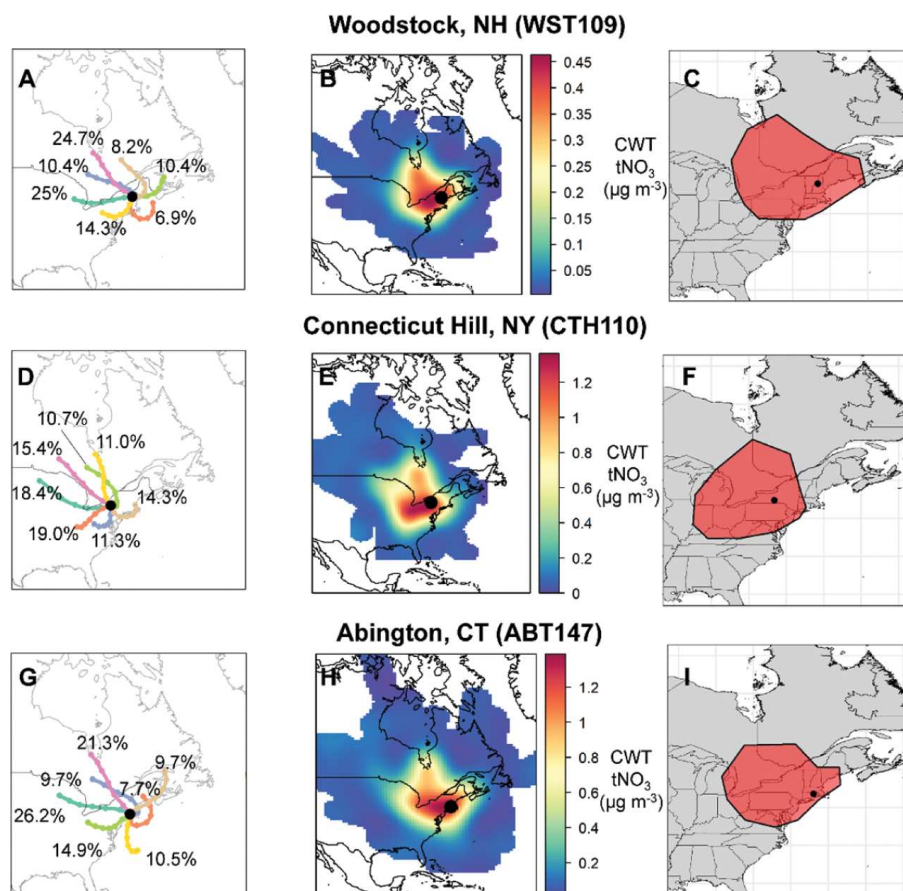
Figure 3. Clustered air mass back trajectories (**a, d, g**), total nitrate (tNO$_3$ = HNO$_3$ + pNO$_3$) concentration weighted trajectories (**b, e, h**), and geospatial polygons (shown in red) representing the tNO$_3$ source contribution regions (**c, f, i**) at the CASTNET sites from December 2016 to 2018. The percentage contribution of each cluster to the total is also indicated.

The modeled $\delta(^{15}N, NO_x)$ was compared with the measured monthly $\delta(^{15}N, tNO_3)$ to remove the potential $\delta(^{15}N)$ phase fractionation between HNO$_3$ and pNO$_3$. Overall, the modeled $\delta(^{15}N, NO_x)$ was lower than the observed $\delta(^{15}N, tNO_3)$ values, and the lack of spatiotemporal variability in the modeled $\delta(^{15}N, NO_x)$ was in direct contrast to the $\delta(^{15}N, tNO_3)$ values (Fig. 6). This finding suggests that seasonal changes in NO$_x$ emission sectors by fuel type did not drive significant seasonal variability in $\delta(^{15}N, NO_x)$ or $\delta(^{15}N, tNO_3)$ across the considered CASTNET sites. Previous studies of atmospheric nitrate in the northeastern/midwestern US during the early 2000s found that stationary source NO$_x$ emissions, including power plants and industrial processes, were strongly positively correlated with $\delta(^{15}N, NO_3^-)$ (Elliott et al., 2009, 2007), which is inconsistent with our results from a similar region from samples collected 10 years later. This inconsistency may suggest that the dramatic decrease in stationary combustion emissions, particularly from coal combustion, has led to decoupling between NO$_x$ emissions and $\delta(^{15}N)$ of atmospheric nitrate.

The mismatch between the modeled $\delta(^{15}N, NO_x)$ and the observed $\delta(^{15}N, tNO_3)$ did not suggest that there were significant inaccuracies in the NO$_x$ emission inventories, such as under-constrained soil emissions and/or not accounting for natural sources of NO$_x$ such as lightning. Soil NO$_x$ emissions have a characteristic low $\delta(^{15}N, NO_x)$ emission signature (Miller et al., 2018; Yu and Elliott, 2017), such that underestimation of soil emissions could not explain the observed mismatch as the modeled $\delta(^{15}N, NO_x)$ was already lower than the observed $\delta(^{15}N, tNO_3)$. Lightning-generated NO$_x$ was also unlikely to explain the model mismatch with observations. Lightning NO$_x$ has a reported $\delta(^{15}N)$ signature near 0‰ (Hoering, 1957), such that to match the modeled $\delta(^{15}N, NO_x)$ with the observed $\delta(^{15}N, tNO_3)$ would require a substantial amount of lightning-produced NO$_x$. However, lightning NO$_x$ emissions are expected to be several times smaller than NO$_x$ emissions from anthropogenic sources (Murray, 2016). Thus, we next considered if the spatiotemporal $\delta(^{15}N, tNO_3)$ variability observed at the CASTNET sites during 2016–2018 can be explained by $\delta(^{15}N)$ isotope fractionation associated with NO$_x$ oxidation.
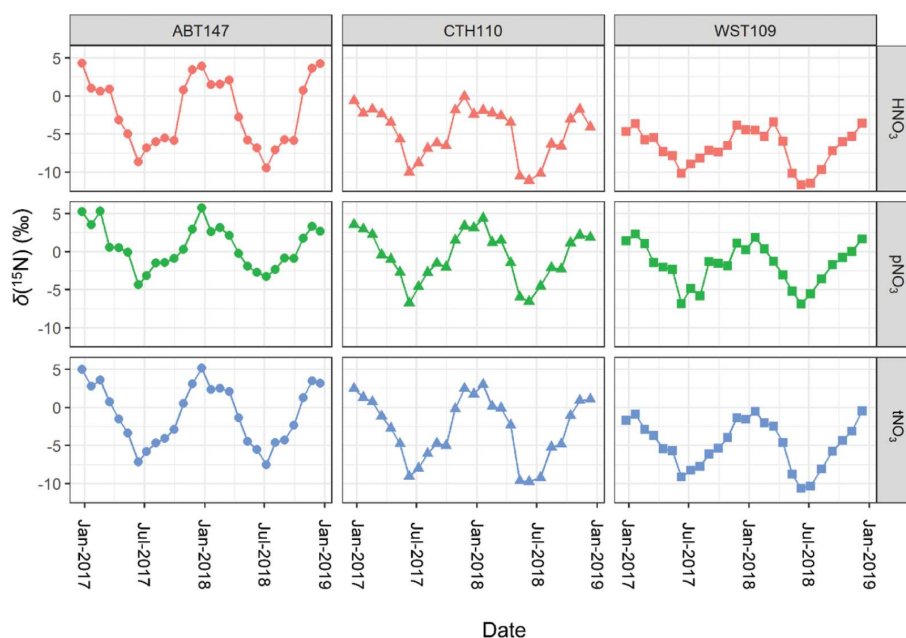
Figure 4. Stable nitrogen isotope ($\delta(^{15}N)$) composition data of nitric acid (HNO_3), particulate nitrate (pNO_3), and total nitrate ($tNO_3 = HNO_3 + pNO_3$) at the three CASTNET sites (Connecticut Hill, NY (CTH110); Abington, CT (ABT147); and Woodstock, NH (WST109)) from December 2016 to December 2018.
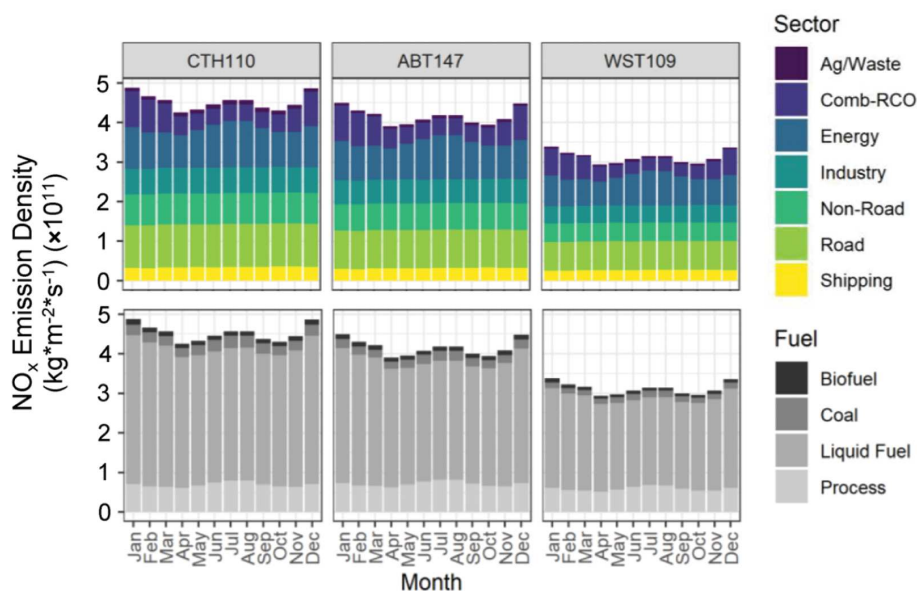

Figure 5. Estimated NO_x emission density by sector and fuel type for source regions contributing to the considered CASTNET sites, including Connecticut Hill, NY (CTH110); Abington, CT (ABT147); and Woodstock, NH (WST109).

3.4 NO_x cycle isotope fractionation

NO_x oxidation to atmospheric nitrate has been suggested to induce significant $\delta(^{15}N)$ fractionation associated with NO_x cycling and the reaction pathways leading to nitrate formation (Walters and Michalski, 2015; Freyer, 1991; Freyer et al., 1993; Walters et al., 2016; Walters and Michalski, 2016b;

Fang et al., 2021; Li et al., 2020). We calculated the influence of $\delta(^{15}N)$ fractionation associated with NO_x cycling on $\delta(^{15}N, NO_2)$ derived from previous studies as the following (Eq. 3):

$$\delta(^{15}N, NO_2) \approx \delta(^{15}N, NO_x)$$
$$+ {}^{15}\varepsilon(NO_2/NO) \times (1 - f(NO_2)), \qquad (3)$$

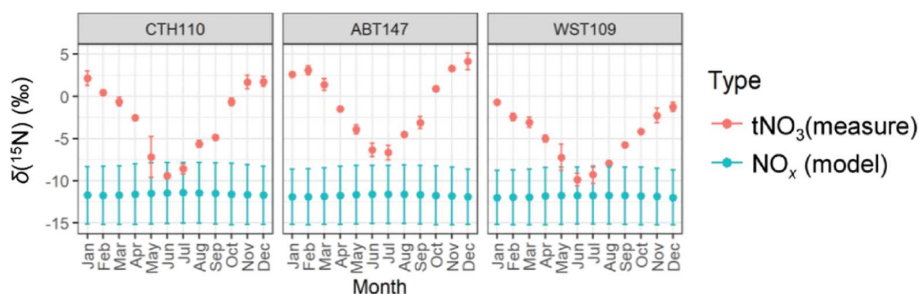**Figure 6.** The monthly predicted $\delta(^{15}N, NO_x)$ from the emission estimates and the observed monthly average $\delta(^{15}N, tNO_3)$. The data points correspond to the mean, and the error bars correspond to the uncertainty, representing the propagated uncertainty for the modeled $\delta(^{15}N, NO_x)$ and the standard deviation for the $\delta(^{15}N, tNO_3)$ measurements.

where $\delta(^{15}N, NO_x)$ represents the modeled emissions (Fig. 6), $^{15}\varepsilon(NO_2 / NO)$ is the isotope effect associated with NO conversion to NO_2, and $f(NO_2)$ represents the amount fraction of NO_2 in NO_x (i.e., $f(NO_2) = [NO_2] / [NO_x]$). The $^{15}\varepsilon(NO_2 / NO)$ value represents a combination of the NO_x equilibrium isotope effect (EIE) and the Leighton cycle isotope effect (LCIE) (Freyer et al., 1993; Walters et al., 2016; Li et al., 2020). Briefly, the EIE between NO and NO_2 has been shown to have an isotope effect of $(28.9 \pm 1.9)‰$ from an experimental investigation under ambient NO_x conditions (Li et al., 2020). The effect favors higher $\delta(^{15}N)$ values in NO_2, which dominates $\delta(^{15}N, NO_x)$ fractionation during conditions of high NO_x concentrations (Freyer et al., 1993; Walters et al., 2016; Li et al., 2020). The LCIE represents a combination of the kinetic isotope effect associated with NO oxidation, primarily driven by reaction with O_3, and the isotope effect associated with NO_2 photolysis (Walters et al., 2016; Li et al., 2020). The dominant factor in LCIE is likely the NO + O_3 fractionation, as the NO_2 photolysis isotope effect has been suggested to have a near-negligible fractionation (Fang et al., 2021). Indeed, laboratory investigation of the LCIE suggests an enrichment value of $(-10 \pm 5)‰$, which is in close agreement with the KIE from ab initio calculations of NO + O_3 of $-6.7‰$ at 298 K (Walters and Michalski, 2016a). In contrast to the EIE, the LCIE dominates NO_x $\delta(^{15}N)$ fractionation during conditions of higher O_3 concentrations relative to NO_x concentrations (Li et al., 2020).

We have estimated the relative role of EIE and LCIE based on the following (Eq. 4):

$$^{15}\varepsilon(NO_2/NO) = f_{EIE}\left(^{15}\varepsilon_{EIE}\right) + (1 - f_{EIE})\left(^{15}\varepsilon_{LCIE}\right). \quad (4)$$

The f_{EIE} represents the relative rate of NO_x EIE to NO oxidation and is calculated as the following (Eq. 5):

$$f_{EIE} = \frac{k(NO_x - EIE)[NO_2]}{k(NO + O_3)[O_3] + k(NO_x - EIE)[NO_2]}, \quad (5)$$

where $k(NO_x\text{-EIE})$ is the reaction rate of NO_x EIE with a reported value of $8.14 \times 10^{-14}\,cm^3\,s^{-1}$ (Sharma et al.,

1970), and $k(NO+O_3)$ is the NO + O_3 reaction rate of $1.73 \times 10^{-14}\,cm^3\,s^{-1}$ (Atkinson et al., 2004).

The value of f_{EIE} was calculated using modeled NO, NO_2, and O_3 concentrations from GEOS-Chem integrated over the source regions that contributed tNO_3 to the CASTNET sites. The modeled O_3 and NO_x concentrations indicated opposite seasonal trends for all considered source regions: O_3 reached a maximum during summer due to increased photochemical activity, while NO_x reached a maximum during winter due to lower photolysis frequencies and relatively higher NO_x emissions, as expected (Fig. 7). The modeled $f(NO_2)$ closely followed the O_3 seasonal profile (Fig. 7). The calculated f_{EIE} also followed the NO_x seasonal profile with peaks during the winter and ranged from 0.124 to 0.513 across the CAST-NET sites (Fig. 7), which is the expected trend as the influence of EIE on $\delta(^{15}N)$ fractionation is highest during conditions of higher NO_x concentrations relative to O_3 (Freyer et al., 1993; Walters et al., 2016; Li et al., 2020). The f_{EIE} averaged 0.255 ± 0.108, 0.271 ± 0.115, and 0.218 ± 0.093 for ABT147, CTH110, and WST109, indicating that $\delta(^{15}N)$ fractionation was largely driven by the NO + O_3 oxidation rather than by NO_x EIE due to the low modeled NO_x concentration relative to O_3. The calculated $^{15}\varepsilon(NO_2 / NO)$ had a similar seasonal profile as f_{EIE}, with peaks during the winter compared with summer, and ranged from $-5.2‰$ to $10.0‰$ across the CASTNET sites with an average of $(0.5 \pm 4.5)‰$, $(-0.1 \pm 4.2)‰$, and $(-1.5 \pm 3.6)‰$ for CTH110, ABT147, and WST109, respectively (Fig. 7).

The $\delta(^{15}N, NO_2)$ was then calculated using the monthly calculated $^{15}\varepsilon(NO_2 / NO)$, modeled $f(NO_2)$, and modeled $\delta(^{15}N, NO_x)$. Overall, the $\delta(^{15}N, NO_2)$ ranged from $-12.4‰$ to $-10.3‰$ across the CASTNET sites and averaged $(-11.5 \pm 0.5)‰$, $(-11.7 \pm 0.5)‰$, and $(-12.0 \pm 0.4)‰$ for CTH110, ABT147, and WST109, respectively (Fig. 7). These annual averages were nearly identical to the modeled $\delta(^{15}N, NO_x)$ values. There was slight seasonal variability in the calculated $\delta(^{15}N, NO_2)$, with slightly higher values during winter than in summer. However, neither the magnitude of the seasonal variability, which was no more than $1.6‰$, nor the absolute value of the calculated
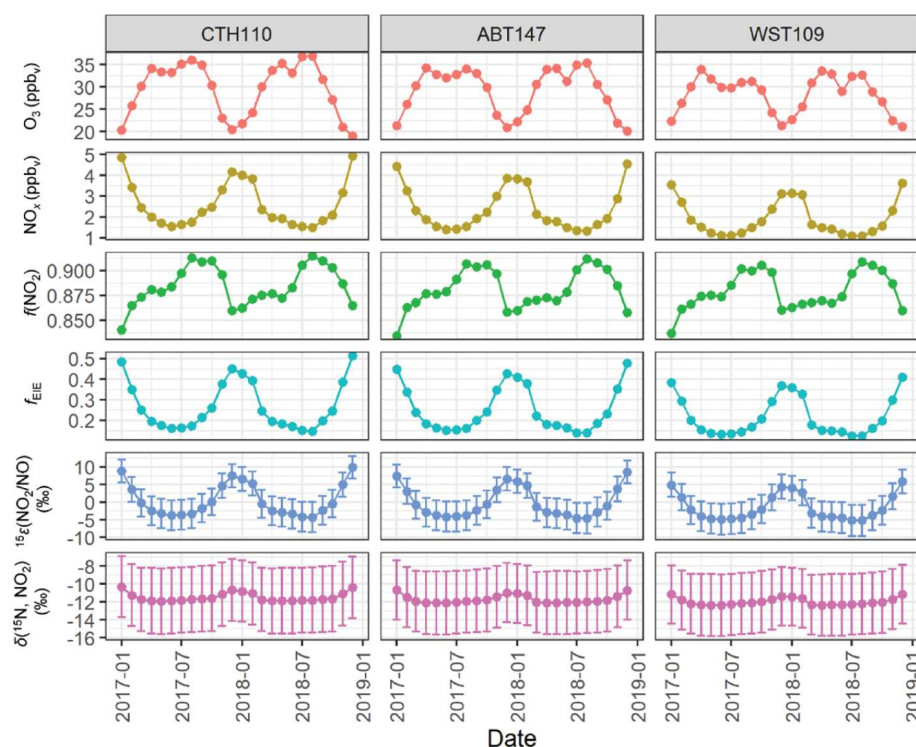
Figure 7. GEOS-Chem output of O_3, NO_x, and $f(NO_2)$ data and the calculated fraction of NO_x at isotope equilibrium (f_{EIE}), the NO_2 / NO enrichment factor $^{15}\varepsilon(NO_2 / NO)$, and $\delta(^{15}N, NO_2)$ at the considered CASTNET sites. The error bars in $^{15}\varepsilon(NO_2 / NO)$ and $\delta(^{15}N, NO_2)$ correspond to the propagated uncertainty.

$\delta(^{15}N, NO_2)$ agreed with the measured $\delta(^{15}N, tNO_3)$. Overall, this indicates that $\delta(^{15}N)$ fractionation associated with NO_x cycling played an insignificant role in explaining the spatiotemporal variabilities observed for $\delta(^{15}N, tNO_3)$ at the CASTNET sites.

3.5　Nitrate formation isotope fractionation

Nitrogen isotope fractionation has also been suggested to occur during reactions leading to HNO_3 and/or pNO_3 formation (Walters and Michalski, 2015, 2016b; Fang et al., 2021). Assuming atmospheric nitrate formation represents an irreversible reaction in an open system with a constant supply of NO_x emissions, we model the $\delta(^{15}N, tNO_3)$ as the following (Eq. 6):

$$\delta(^{15}N, tNO_3) = \delta(^{15}N, NO_2) + {}^{15}\varepsilon(tNO_3/NO_2). \quad (6)$$

The $^{15}\varepsilon(tNO_3 / NO_2)$ corresponds to the enrichment factor associated with converting NO_2 to tNO_3. We acknowledge there could be potential differences in the formation pathway for the speciated phases of atmospheric nitrate (i.e., HNO_3 and pNO_3). However, we evaluated nitrate formation from the mass-weighted $\delta(^{15}N, tNO_3)$ to remove the potential $\delta(^{15}N)$ phase fractionation between HNO_3 and pNO_3, which complicates evaluating the potential phase-dependent formation pathway. We calculated

the $^{15}\varepsilon(tNO_3 / NO_2)$ as the difference between the measured $\delta(^{15}N, tNO_3)$ and the calculated $\delta(^{15}N, NO_2)$ (Fig. 8). Across all sites, $^{15}\varepsilon_{calc}(tNO_3 / NO_2)$ ranged from 1.6‰ to 16.1‰, with an average of (8.7 ± 3.8)‰, (10.9 ± 3.5)‰, and (6.9 ± 2.9)‰, for CTH110, ABT147, and WST109. Additionally, the $^{15}\varepsilon_{calc}(tNO_3 / NO_2)$ indicated strong seasonality with higher values during the winter compared to the summer. The shift in the seasonal $^{15}\varepsilon_{calc}(tNO_3 / NO_2)$ was likely attributed to a change in the dominant nitrate formation pathway from NO_2 oxidation via hydroxyl radical during the summer to increased N_2O_5 hydrolysis during the winter, as previously suggested (Li et al., 2021) and in our companion study (Kim et al., 2023).

The two dominant polluted mid-latitude nitrate formation pathways include NO_2 oxidation via hydroxyl radical (Reaction R1) and N_2O_5 hydrolysis (Reaction R2):

$$NO_2 + OH + M \longrightarrow HNO_3 + M \quad (R1)$$
$$N_2O_5 + H_2O(surface) \longrightarrow 2HNO_3. \quad (R2)$$
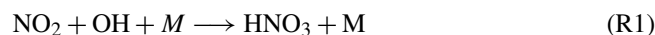
These reactions have an isotope effect of -3‰ based on the reduced masses of the transition complex (Freyer, 1991) and 25.5‰ at 300 K based on EIE between NO_2 and N_2O_5 (Walters and Michalski, 2016b) for Reactions (R1) and (R2), respectively, indicating that the range of the $^{15}\varepsilon_{calc}(tNO_3 / NO_2)$ is between these end-member values. We estimated the relative role of Reactions (R1) and
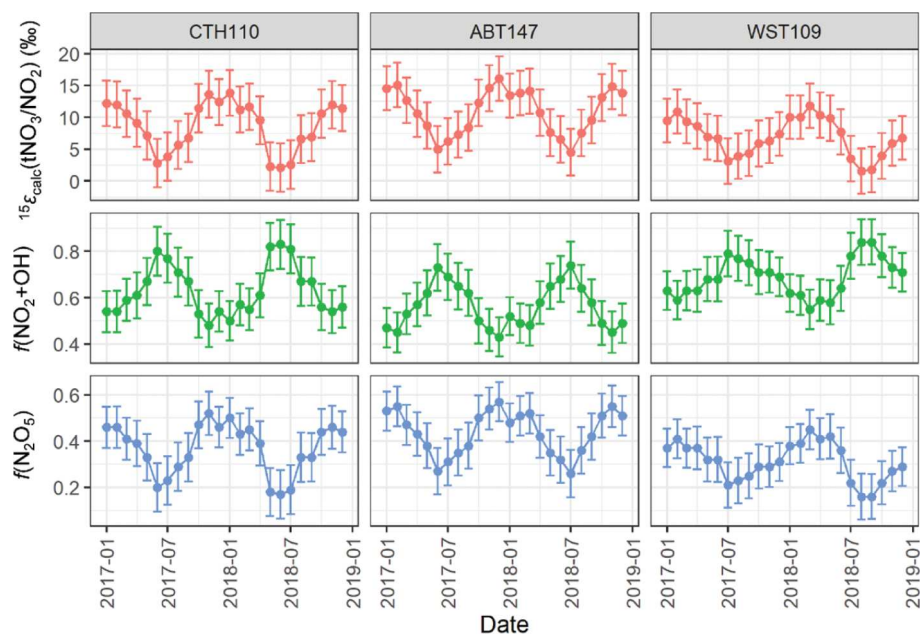
Figure 8. The calculated nitrogen enrichment factor associated with nitrate formation $^{15}\varepsilon(\text{tNO}_3\,/\,\text{NO}_2)$ and the estimated relative fraction of total atmosphere nitrate (tNO$_3$) formation via the N$_2$O$_5$ hydrolysis (Reaction R1) and NO$_2$+ OH (Reaction R2) pathways at the considered CASTNET sites. The error bars represent propagated uncertainty.

(R2) contributing to nitrate formation across the considered CASTNET sites based on the following (Eq. 7):

$$^{15}\varepsilon_{\text{calc}}(\text{tNO}_3/\text{NO}_2) = f(\text{NO}_2 + \text{OH}) \times (^{15}\varepsilon(\text{NO}_2 + \text{OH})$$
$$+ (1 - f(\text{NO}_2 + \text{OH})) \times (^{15}\varepsilon(\text{N}_2\text{O}_5, T)), \quad (7)$$

assuming that Reactions (R1) and (R2) dominate the observed tNO$_3$ formation, as expected for the polluted midlatitudes (Alexander et al., 2020) (8):

$$f(\text{NO}_2 + \text{OH}) + f(\text{N}_2\text{O}_5) = 1, \quad (8)$$

where $^{15}\varepsilon_{\text{calc}}(\text{tNO}_3\,/\,\text{NO}_2)$ is our calculated results (Fig. 8); $f(\text{NO}_2+\text{OH})$ and $f(\text{N}_2\text{O}_5)$ correspond to the fractional contribution of Reactions (R1) and (R2), respectively; $^{15}\varepsilon(\text{NO}_2+\text{OH}) = -3\,‰$ (Freyer, 1991a); and $^{15}\varepsilon(\text{N}_2\text{O}_5, T)/‰ = -0.163 \cdot T/\text{K} + 74.08$ for a temperature range of 250 to 305 K (Walters and Michalski, 2016b). We utilized the temperature derived over the source regions contributing to the CASTNET sites from the GEOS-Chem simulations in our calculations, which indicated a range in the monthly temperature of 262.4 to 294.8 K, corresponding to a range in $^{15}\varepsilon(\text{N}_2\text{O}_5, T)$:‰ of 26.4‰ to 31.3‰. Overall, we estimated $f(\text{NO}_2+\text{OH})$: $f(\text{N}_2\text{O}_5)$ contributed $0.63 \pm 0.11 : 0.37 \pm 0.11$, $0.56 \pm 0.09 : 0.44 \pm 0.09$, and $0.69 \pm 0.8 : 0.31 \pm 0.08$ to CTH110, ABT147, and WST109, respectively (Fig. 8). This calculation suggests that the observed spatial $\delta(^{15}\text{N})$ differences at the considered sites were driven by slight differences in nitrate formation and oxidation chemistry. For each of the considered sites, the temporal trends in the oxidation chemistry were similar.

The calculated $f(\text{NO}_2+\text{OH})$ peaked during the summer, and $f(\text{N}_2\text{O}_5)$ peaked during the winter, consistent with expected seasonal atmospheric nitrate formation and model results (Alexander et al., 2020). This seasonality in atmospheric nitrate formation is driven by photochemistry and temperature. The OH is formed via photolysis, so its abundance is greater during the summer, leading to a relative increase in the proportion of atmospheric nitrate formed via NO$_2$+ OH homogeneous reactions. During the nighttime, higher order nitrogen oxides form and new pathways of atmospheric nitrate production become important. Under these conditions, NO$_2$ is oxidized by O$_3$ forming the nitrate (NO$_3$) radical, which exists at thermal equilibrium with NO$_2$ and N$_2$O$_5$, which can subsequently hydrolyze on wetted aerosol surfaces leading to atmospheric nitrate production. N$_2$O$_5$ is photolabile and thermally unstable, so N$_2$O$_5$ heterogeneous reactions on aerosol surfaces are typically most prevalent during the winter (Alexander et al., 2020).

We acknowledge that are uncertainties in our model regarding potential contributions from other nitrate formation pathways and the considered enrichment factors that have not been experimentally determined. Nevertheless, our results highlight that seasonal $\delta(^{15}\text{N}, \text{tNO}_3)$ values were driven by nitrate formation based on our current understanding of fractionation patterns.

4 Conclusions

Significant spatiotemporal differences in concentrations and $\delta(^{15}N)$ were observed for atmospheric nitrate in the northeastern US from December 2016 to 2018 from CASTNET locations. These findings were consistent with a previous study of atmospheric nitrate from CASTNET sites collected in the early 2000s, indicating that even after dramatic reductions in NO_x emissions in the US over the past decade (e.g., a decrease of 38 % from 2005–2014; Miyazaki et al., 2017), atmospheric nitrate spatiotemporal trends have been retained. We focused on evaluating the drivers of the spatiotemporal trends of $\delta(^{15}N)$ observed at the CASTNET sites. Back trajectory and geospatial statistical analyses indicated that atmospheric nitrate source regions tended to be within 1000 km and tended to extend towards the west/northwest of the CASTNET sites. Utilizing NO_x emission data for the identified source regions, we modeled $\delta(^{15}N, NO_x)$ for each of the CASTNET sites, indicating no significant spatiotemporal differences. This finding suggested that NO_x emissions were not a key driver of the observed spatiotemporal $\delta(^{15}N)$ variability as previously reported for CASTNET sites in the early 2000s. Instead, we found that $\delta(^{15}N)$ fractionation primarily associated with nitrate formation was the key driver of the observed spatiotemporal $\delta(^{15}N)$ variabilities.

Our results highlight that $\delta(^{15}N)$ of atmospheric nitrate fractionation could lead to new insights via tracking nitrate formation mechanisms. The $\delta(^{15}N)$ fractionation associated with NO_x conversion to atmospheric nitrate reflected the nitrate formation pathways. Thus, the $\delta(^{15}N)$ of atmospheric nitrate could be a useful way to track the reactions contributing to nitrate formation, similarly to $\Delta(^{17}O)$ (Alexander et al., 2020; Michalski et al., 2003). Tracking the formation pathways of nitrate is important for evaluating atmospheric chemistry model representation of oxidation chemistry. For example, uncertainties in the rate of NO_x oxidation to nitrate have been shown to represent a significant source of uncertainty for the formation of major tropospheric oxidants (i.e., ozone (O_3) and the hydroxyl radical (OH)) that has important implications for our understanding of atmospheric lifetimes of many trace gases, including greenhouse gases. However, $\delta(^{15}N)$ would arguably be more sensitive to nitrate formation pathways because most of the $\Delta(^{17}O)$ of nitrate reflects NO_x photochemical cycling ($NO + O_3$ vs. $NO + RO_2 / HO_2$) rather than the reactions contributing to nitrate formation. Thus, $\delta(^{15}N)$ and $\Delta(^{17}O)$ could be useful complementary tools to improve our ability to track NO_x oxidation and nitrate formation and compare with model expectations. Future studies are needed to verify the assumed $\delta(^{15}N)$ fractionation values associated with nitrate formation, enabling $\delta(^{15}N)$ to be a useful tool for tracking oxidation chemistry pathways.

Author contributions. CB, WWW, and MGH designed the varying aspects of the study. CB and WWW carried out the laboratory measurements. CB conducted the statistical analysis, back-trajectory calculations, and emissions modeling. LTM contributed GEOS-Chem simulations. CB and WWW prepared the article with contributions from all co-authors.

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