Changes in the Isotopic Signature of Atmospheric Nitrous Oxide and Its Global Average Source During the Last Three Millennia

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Abstract Nitrous oxide (N2O) is a strong greenhouse gas whose mole fraction in the atmosphere has increased over the industrial period. We present a new set of isotope measurements of N2O in air extracted from ice cores covering the last 3,000 years. For the preindustrial (PI) atmosphere, we find an average N2O mole fraction of (267 ± 1) nmol/mol and average tropospheric N2O isotopic values of δ15N = (9.5 ± 0.1)%o, δ18O = (47.1 ± 0.2)%o, δ15N = (17.8 ± 0.4)%o, and δ18O = (1.2 ± 0.4)%o. From PI to modern times all isotope signatures decreased with a total change of δ15N = (−2.7 ± 0.2)%o, δ18O = (−2.5 ± 0.4)%o, δ15N = (−2.0 ± 0.7)%o, and δ18O = (−3.5 ± 0.7)%o. Interestingly, the temporal evolution is not the same for δ15N and δ18O. δ15N trends are relatively larger during the early part, and δ18O trends are larger during the late part of the industrial period, implying a decoupling of sources over the industrial period. Using a mass balance model, we determined the isotopic composition of the total average N2O source. Assuming that the total present source is the sum of a constant natural source and an increasing anthropogenic source, this anthropogenic source has an isotopic signature of δ15N = (−15.0 ± 2.6)%o, δ18O = (30.0 ± 2.6)%o, δ15N = (−4.5 ± 1.7)%o, and δ18O = (−24.0 ± 8.4)%o. The 15N site preference of the source has increased since PI times, which is indicative of a relative shift from denitrification to nitrification sources, consistent with agricultural emissions playing a major role in the N2O increase.

1. Introduction

Nitrous oxide (N2O) is an important long-lived greenhouse gas that contributes significantly to the increased radiative forcing of the climate system (Forster et al., 2007; Stocker et al., 2013). Ice core and firn data of N2O mole fraction have been reported extending back 800,000 years before present and show pronounced glacial-interglacial variability with values as low as 200 nmol/mol during glacial periods and up to 280 nmol/mol during interglacial periods (Bernard et al., 2006; Flückiger et al., 2002; Ishijima et al., 2007; MacFarling Meure et al., 2006; Röckmann, Kaiser, & Brenninkmeijer, 2003; Schilt, Baumgartner, Blunier, et al., 2010; Schilt, Baumgartner, Schwander, et al., 2010; Sowers et al., 2003, 2002). Since 1750 the mole fraction of N2O in the atmosphere has steadily increased and is currently about (330 ± 1) nmol/mol, a value that is unprecedented in the ice core record.

Global N2O production is largely attributed to microbial sources. Bacteria and archaea produce N2O through nitrification and denitrification. Nitrification is the main source of N2O under aerobic conditions, while denitrification dominates under anoxic conditions (Denk et al., 2017; Ostrom & Ostrom, 2011; Toyoda et al., 2015). The main sink of N2O is destruction in the stratosphere, through UV photolysis (~90%) and reactions with excited oxygen atoms (~10%; Minschwaner et al., 1993).

Microbial sources can be both natural and anthropogenic. Natural sources represent processes in uncultivated soils, oceans, and other aquatic systems (EPA, 2010). Anthropogenic microbial emissions are associated with agricultural emissions and are strongly affected by the use of synthetic fertilizers (Kroeze et al., 1999). Other anthropogenic sources are fossil fuel combustion, especially from automobiles, industrial processes (nylon production), and biomass burning (Syakila & Kroeze, 2011).
The N₂O budget is difficult to constrain mainly due to the long N₂O residence time in the atmosphere (123 \( \pm \) 29 year, SPARC, 2013), resulting in small temporal and spatial gradients, and because N₂O production varies strongly spatially and temporally, which complicates scaling up from local measurements.

Global estimates of N₂O emissions are based on bottom-up (summing individual source estimates) and top-down (using atmospheric measurements to constrain sources) approaches, which mainly rely on atmospheric mole fraction measurements. The preindustrial (henceforth PI) N₂O flux derived by both methods is \( \approx (11.0 \pm 1.7) \) Tg N/year (Stocker et al., 2013). Current estimates suggest that during PI times 63% of the natural sources originated from microbial production in soils and 37% from oceans (Stocker et al., 2013). Currently, the total annual flux of N₂O is estimated to be 16 to 20 Tg N/year (Denman et al., 2007; Syakila & Kroeze, 2011; Thompson et al., 2014). Bottom-up model calculations suggest that of the anthropogenic emissions 1 Tg N/year is due to nitrogen deposition to oceans from anthropogenic processes (Duce et al., 2008), 4–6 Tg N/year is due to agricultural emissions, 1.2–1.5 Tg N/year originates from the energy and industry sector, and 0.7 Tg N/year is from biomass burning (Syakila & Kroeze, 2011).

Although the understanding of N₂O production processes has strongly improved, the contributions from the individual source categories are not well constrained. For example, nitrification appears to dominate oceanic N₂O emissions, but denitrification hot spots have been identified in low oxygen availability areas, coastal sediments, and estuaries (Bange et al., 2005; Ji et al., 2015). Culture studies have revealed more information on the specific organisms and environments responsible for marine N₂O production. Ammonia oxidizing bacteria were long believed to be the main oceanic source, but recently ammonia oxidizing archaea were identified as a key N₂O source (Löscher et al., 2012; Santoro et al., 2011). In terrestrial ecosystems, denitrification appears to control N₂O emissions, while agricultural soils show enhancement in both nitrification and denitrification. Pérez et al. (2001) suggested that fertilizer applications favor nitrification, but it has proven difficult to quantify this on a global scale.

A way to further constrain the N₂O budget is to measure its isotopic composition. Studies have determined the isotopic composition of atmospheric N₂O from atmospheric monitoring locations and in polar firn (Bernard et al., 2006; Ishijima et al., 2007; Park et al., 2012; Prokopiou et al., 2017; Röckmann & Levin, 2005; Röckmann, Kaiser, & Brenninkmeijer, 2003; Sowers et al., 2002; Toyoda et al., 2013) in order to provide additional information on temporal changes of N₂O emissions. Firn air records, though, only cover up to 100 years of recent atmospheric history and most of them only several decades. Air bubbles trapped in polar ice cores provide an air archive that extends much further back in time. The \( ^{18} \text{O} \) and bulk \( ^{15} \text{N} \) content of N₂O are reported in delta notation as \( \delta^{18} \text{O} \) and \( \delta^{15} \text{N}_{\text{av}} \), respectively, and \( \delta^{15} \text{N}_{\text{av}} \) is the average of the \( ^{15} \text{N} \) content of the central (\( \alpha \)) and terminal (\( \beta \)) nitrogen position, \( \delta^{15} \text{N}_{\text{av}} = 0.5 \times (\delta^{15} \text{N}_{\alpha} + \delta^{15} \text{N}_{\beta}) \); see section 2.3 for definition of the delta value.

Only a small number of studies focused on the isotopic composition of N₂O from ice core samples. Sowers et al. (2002) combined ice core data from Greenland Ice Sheet Project (GISP) II, Greenland, with firn air data to reconstruct the \( \delta^{15} \text{N}_{\text{av}} \) and \( \delta^{18} \text{O} \) isotopic history of N₂O between 1785 and 1990 (Common Era [CE]). They suggested that the \( \delta^{15} \text{N}_{\text{av}} \) and \( \delta^{18} \text{O} \) trends possibly varied at different rates during different stages of the industrial period. Such a potential decoupling of \( \delta^{15} \text{N}_{\text{av}} \) and \( \delta^{18} \text{O} \) would imply that the increase of N₂O since PI times is not due to one single anthropogenic source with a certain isotopic composition but consists of several source components. Alternatively, the isotopic composition of the source could have changed over time. On the other hand, Bernard et al. (2006) reported much more consistent \( \delta^{15} \text{N}_{\text{av}} \) and \( \delta^{18} \text{O} \) trends between ice core and firn air studies using samples from North Greenland Ice Core Project, Greenland, and Berkner Island, Antarctica. Both studies analyzed a limited amount of ice core samples, and considering that the analytical errors for ice core measurements are quite large, the question of a possible decoupling of \( \delta^{15} \text{N}_{\text{av}} \) and \( \delta^{18} \text{O} \) remained unresolved.

In an attempt to reconstruct variations of natural sources of N₂O in the past, Schilt et al. (2014) reported the \( \delta^{15} \text{N}_{\text{av}} \) and \( \delta^{18} \text{O} \) isotopic composition of N₂O between 16 and 10 ka before present from Taylor Glacier in Antarctica and concluded that both terrestrial and marine sources contributed roughly equally to the observed increase of N₂O from the glacial to the interglacial periods. Terrestrial emissions dominate
variability on centennial to millenial time scales probably influenced by temperature and precipitation patterns over land surfaces.

In this study we present measurements of the isotopic composition of N₂O in the PI atmosphere from Greenland ice core samples covering the last 3,000 years. The data allow us to tightly constrain the isotopic composition of N₂O in the PI atmosphere, investigate possible variations in the N₂O budget in the PI period, and constrain the decoupling of δ¹⁵N and δ¹⁸O over the industrial period much more precisely than previous studies.

2. Methodology

2.1. Ice Core Collection

Of the new 39 ice core samples that were analyzed in this study, 30 were collected in 2008 as part of the North Eemian Ice Drilling Programme (NEEM) in Greenland. The NEEM drilling site (77.45°N, 51.06°W, 2,450 m elevation) currently has a mean annual temperature of −29 °C and a surface accumulation rate of 22 cm ice equivalent per year (NEEM community paper). An additional nine samples from the Eurocore Greenland project (drilled in 1989) were analyzed (EUROCORE_NM). The site is located at 72.56°N, 38.45°W, 3,240 m altitude and has a mean annual temperature of −32 °C and surface accumulation rate of 21 cm water equivalent per year. For the scientific interpretation we combine these 39 new samples with results from 13 ice core samples collected from the Siple Dome A ice core that were analyzed previously on the same analytical system (Rosen, 2014; Taylor et al., 2004). This core was drilled in 1999 in coastal West Antarctica (81.65°N, 148.81°W) at an elevation of 621 m above sea level.

The age of the NEEM ice was calculated using a gas age chronology, following the GICC05 time scale, which is based on many overlapping data series from three different cores, utilizing the best available data for each time period. Overlap between the different sections ensures consistency between the different parts of the time scale and yield a typical dating error of 0.5% (Vinther et al., 2006). Siple Dome gas age was determined (Rosen, 2014) by matching methane variations with the well dated methane record from the West Antarctic Ice Sheet Divide ice core Mitchell et al. (2011).

Measurements of the isotopic composition of trace gases from ice cores must be corrected for firm air fractionation (Severinghaus et al., 2001), notably gravitational and diffusive separation of the different isotopocules in the firm column before the air is trapped in the ice. For N₂O isotopocules, the correction is based on the mass difference between the heavier isotopocules and the most abundant $^{14}$N$^{14}$N$^{16}$O, thus 1 atomic unit for δ¹⁵N and 2 for δ¹⁸O. The corresponding correction is <0.5‰ for the data reported here, and the firm fractionation correction is consistent across the different data sets (Buizert et al., 2013; Severinghaus et al., 2009).

2.2. Isotope Measurement

The isotopic composition of atmospheric N₂O trapped in polar ice was measured by continuous-flow isotope ratio mass spectrometry (IRMS) at the Institute for Marine and Atmospheric research Utrecht, Utrecht University, the Netherlands. The dry extraction measurement technique for ice core samples, which enables simultaneous measurement of the isotopic composition of N₂O and CH₄, has been described in Sapart et al. (2011) and is briefly summarized here.

Ice samples of about 500 g (yielding ≈ (17 ± 1) ng of CH₄ in our extraction system; Sapart et al., 2011) were placed in a perforated ice grating cylinder made of titanium nitride coated stainless steel inside a 6-L-volume stainless steel grating vessel, which was sealed with a copper gasket and fixed in a shaking device mounted in a freezer at −30 °C. The vessel holding the sample was generally evacuated overnight in order to remove all ambient air, reaching a pressure of 10⁻³ mbar. In cases where an analysis of two samples was performed on the same day, the vessel was evacuated until reaching the desired pressure (10⁻³ mbar).

After the system reached the desired pressure (minimum 3 hr of evacuation), the vessel was closed and disconnected from the vacuum line. The ice was grated for ~25 min during which the angle and the speed of the shaking device were changed stepwise to minimize collisions of ice with the metal and to achieve maximum grating efficiency. The grating vessel was then connected to a glass line consisting of three consecutive U-shaped traps where the air released during grating was extracted. The first trap collected water at −80 °C, the second one trapped CO₂ and N₂O at −196 °C, and the third one was filled with Haysep-D.
(mesh 80/100, Alltech GmbH, Germany), a molecular absorbent, cooled to −196 °C, to adsorb CH₄ as well as the major air components (O₂, N₂, and Ar) and other trace gases.

After extraction, all traps were isolated and the contents of traps 2 and 3 (N₂O/CO₂ and CH₄/air, respectively) were flushed with He at ambient temperature to two separated IRMS systems. Before and after each sample was processed, blank measurements were performed by filling the traps with pure helium to make sure that no contaminating gas was present before the measurement and no sample gas was left in the traps after the measurement took place.

The N₂O sample passed through a glass tube filled with an Ascarite II® (mesh 8–20, Aldrich chemistry, USA) where the CO₂ was chemically removed. The remaining N₂O and other condensable gases were cryogenically (−196 °C) preconcentrated. After cryofocusing, the N₂O was purified from remaining traces of CO₂ and other contaminants on a capillary gas chromatography column (PoraPLOT Q, 0.32 mm internal diameter [i.d.], 25 m). To avoid interferences from other atmospheric compounds that have longer retention times, the column is separated into a precolumn and an analytical one (Röckmann, Kaiser, Brenninkmeijer, & Brand, 2003). The purified sample was then transferred to the IRMS via an open split interface.

A laboratory reference air bottle with known composition (NAT 332, air collected at Groningen, the Netherlands was measured daily directly before the ice extraction, following the same procedure as the extraction of air from an ice sample, except for the grating. For this purpose, reference air was released into the evacuated stainless steel pot containing an intact ice sample. The air was then extracted and treated as an ice air sample. NAT 332 has a mole fraction of (332.8 ± 0.8) nmol/mol and an isotopic composition of δ¹⁵Nᵥ = (6.6 ± 0.7), δ¹⁸O = (45.8 ± 1.3)‰, δ¹³C = (15.6 ± 2.1), and δ¹⁵Nᵦ = (−2.5 ± 2.1)‰. The stated errors (1σ) indicate the standard deviation for repeated individual measurements (Sapart et al., 2011).

2.3. Data Processing

Isotope deltas (δ) are used to quantify the relative ¹⁵N/¹⁴N and ¹⁸O/¹⁶O ratio difference of N₂O in sample gas air with respect to a reference ratio R_standard:

\[ \delta^{15}N = \frac{R_{sample}}{R_{standard}} - 1 \]  

where R represents the ¹⁵N/¹⁴N or ¹⁸O/¹⁶O abundance ratio of a standard or a sample. All δ values pertaining to ¹⁵N are reported via air-N₂, and the values for ¹⁸O are reported versus Vienna Standard Mean Ocean Water. The ¹⁵N/¹⁴N and ¹⁸O/¹⁶O isotope ratios were derived from m/z 45/m/z 44 and m/z 46/m/z 44 ion current ratios according to Kaiser et al. (2003), assuming a constant ¹⁷O excess of 0.9‰. For the position-dependent ¹⁵N isotopologues the data reduction scheme accounting for isotopic scrambling in the ion source developed by Kaiser and Röckmann (2008) was adopted.

Isotope measurements of another laboratory reference gas (NAT 335, air collected from Centre for Isotope Research, CIO, Groningen, the Netherlands) were performed directly on the IRMS system before and after the sample measurements and injected air volumes were chosen to closely match the expected sample peak areas. The laboratory standard has an N₂O mole fraction of (318 ± 1) nmol/mol and isotope ratios of δ¹⁵Nᵥ = (6.4 ± 0.2)‰, δ¹⁸O = (44.9 ± 0.4)‰, δ¹³C = (15.4 ± 1.2)‰, and δ¹⁵Nᵦ = (−2.7 ± 1.2)‰. The uncertainties of the reference air cylinder involve transfer of the isotope scale over four carefully calibrated reference air cylinders since the N₂O isotope scale of our laboratory was set up by Kaiser et al. (2003). The calibration of the intramolecular distribution has been converted to the scale of Yoshida and Toyoda (2000). These values are used to convert the δ values to the international scales.

2.4. Isotope Budget Calculations

N₂O is almost exclusively emitted from the Earth’s surface, with a minor contribution from in situ production in the troposphere (Dentener & Crutzen, 1994; Röckmann et al., 2001), while its removal takes place almost exclusively in the stratosphere (Ishijima et al., 2007; Park et al., 2012; Röckmann, Kaiser, & Brenninkmeijer, 2003; Rahn and Wahlen, 2000; Sowers et al., 2002). As the isotope effect in the stratospheric removal is well constrained by in situ measurements (e.g. Kaiser et al., 2006), the isotopic composition of the source can be calculated in a simple mass balance model from the observed trend in the isotopic composition of the
Modern Periods

Input Values to Establish the Average Source Isotopic Signature During PI and Modern Periods

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model Parameters</th>
<th>PI &gt; 1750 CE</th>
<th>Modern 1989–2008 CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burden (Tg N)(^a)</td>
<td>1,096 ± 18</td>
<td>1,313 ± 18</td>
<td></td>
</tr>
<tr>
<td>(\frac{\partial \delta_{\text{Trop}}}{\partial t}) (‰/year)(^b)</td>
<td>0</td>
<td>-0.036 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>(\delta_{15}^{\text{N}}) av</td>
<td>-0.014 ± 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta_{15}^\text{O})</td>
<td>-0.024 ± 0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta_{15}^\text{N}) b</td>
<td>-0.040 ± 0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sources (Tg N/year)(^c)</td>
<td>10.6 ± 2.6</td>
<td>15.5 ± 3.9</td>
<td></td>
</tr>
<tr>
<td>(\delta_{\text{Trop}}) (‰)(^d)</td>
<td>9.5 ± 0.1</td>
<td>6.8 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>(\delta_{15}^\text{N}) av</td>
<td>47.1 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta_{15}^\text{N}) b</td>
<td>17.8 ± 0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta_{15}^\text{O})</td>
<td>1.2 ± 0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta_{15}^\text{N}) b</td>
<td>-2.3 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L (Tg N/year)(^e)</td>
<td>10.6 ± 2.6</td>
<td>12.7 ± 3.2</td>
<td></td>
</tr>
<tr>
<td>(\varepsilon) (‰)(^f)</td>
<td>-0.024 ± 0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\varepsilon_{\text{app}})</td>
<td>-13.4 ± 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\varepsilon_{\text{app}})</td>
<td>-23.0 ± 1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\varepsilon_{\text{app}})</td>
<td>-8.7 ± 1.1</td>
<td></td>
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</tbody>
</table>

Note. Uncertainty is expressed as one standard deviation. PI = preindustrial; LI = late industrial; NEEM = North Eemian Ice Drilling Programme; EUROCORE_NM = Eurocore Greenland project.

\(^a\)Burden was calculated using the average mole fraction values for each period (PI, LI), and the uncertainty was assumed to be 25%. \(^b\)\(\frac{\partial \delta_{\text{Trop}}}{\partial t}\) was calculated using the average total change from transitioning from one period to another and dividing it by the number of total years. For PI times it was assumed that there was a balance in the troposphere-stratosphere exchange and this number was null. For modern times the rates were calculated using the tropospheric values from Prokopiou et al. (2017) \(^c\)Our model is based on high-altitude balloon measurements (Kaiser et al., 2006; average of values in Table 2). \(^d\)The values were calculated based on the equations from Prokopiou et al. (2017) \(^e\)We discuss some of these potential biases and possible additional variability in section 4.

The tropospheric reservoir. Several equivalent box models have been used in the past, and we use here the representation of Snider et al. (2015) to calculate the isotopic signature of the total N2O source:

\[
\frac{\partial \delta_{\text{Trop}}}{\partial t} = -P(\delta_{\text{app}} - \delta_{\text{p}}) - L(\delta_{\text{app}} - \delta_{\text{L}})
\]

where \(N_t\) is the tropospheric burden of N2O; \(P\) and \(L\) are the total source and loss strengths, respectively; \(\delta_{\text{app}}\), \(\delta_{\text{p}}\), and \(\delta_{\text{L}}\) are the \(\delta\) values associated with the loss, production, and the tropospheric value, respectively; \(\delta_{\text{p}}\) is the target quantity we want to solve for; and \(\delta_{\text{app}}\) is the deseasonalized linear trend in the isotopic composition of the tropospheric N2O reservoir over the respective period.

Following Park et al. (2012), the loss term can be approximated as

\[
L(\delta_{\text{app}} - \delta_{\text{L}}) \approx L\varepsilon_{\text{app}}
\]

where \(\varepsilon_{\text{app}}\) is the apparent fractional associated with the N2O destruction process in the stratosphere, for which we used the averaged measured values from stratospheric observations using air samples collected on high-altitude balloon flights (Kaiser et al., 2006; average of values in Table 2).

Then, equation (2) can be solved for the isotopic signature of the global average N2O source.

\[
\delta_{\text{p}} = \frac{N_t \varepsilon_{\text{app}}}{P} + L\varepsilon_{\text{app}} + P\delta_{\text{L}}
\]

We solve equation (4) for the PI and present atmosphere. For the PI atmosphere we assume a steady state in the isotopic composition, thus \(\frac{\partial \delta_{\text{Trop}}}{\partial t} = 0\); in agreement with our data (see Tables 1, 2 and section 4.1) and for the present period we use linear trend estimates derived from the new ice core measurements and the firm reconstruction from Prokopiou et al. (2017). The values used as input for our calculations are given in Table 1.

Having calculated the total global average source signatures, we split the source for the present atmosphere into a natural contribution and a time-dependent anthropogenic contribution using a simple mass balance calculation. Here the natural source is the same as the source calculated for the PI atmosphere, and it is assumed constant. The anthropogenic source is assumed to vary in strength but has a constant isotope signature. We acknowledge that these are strong assumptions, which may not be fully adequate. For example, natural emissions may be different during the present climate state compared to 1750, and the time-dependent anthropogenic source may not be isotopically constant over time.

We discuss some of these potential biases and possible additional variability in section 4.

### 3. Results

Figure 1a shows the temporal evolution of the N2O mole fraction and isotopic composition as derived from our NEEM, EUROCORE_NM, and Siple Dome ice core measurements, along with previously published data. The year 1750 CE marks the start of the industrial revolution, and in the following we refer to the period before 1750 as PI. We furthermore split the industrial period into two parts, the early industrial (EI) period (1750–1940) that is mainly represented by ice core samples, which extend to 1940, and a late industrial (LI) period (1940–2008) that is represented by firm air measurements (Prokopiou et al., 2017, see below). We note that this split is largely operational in nature (firm and ice core samples), but it also separates a period of relatively slow increase in N2O before 1940 with a period with faster increase after 1940 (where the transition is...
of course gradual). Average values over the last 20 years (1989–2008) of the reconstruction of Prokopiou et al. (2017) will be referred to as modern values.

During the PI period, the N2O mole fraction was (267 ± 2) nmol/mol (uncertainty given is standard error of the mean) and showed only minor variability, between 262 and 270 nmol/mol. During the EI period the N2O mole fraction gradually increased, reaching (285 ± 2) nmol/mol in 1940 (CE). We show all mole fraction data from both hemispheres combined because the interhemispheric difference is very small for N2O and only detectable in modern high precision and high time resolution measurement series (Hirsch et al., 2006).

Figures 1b–1e show the new ice core record of δ15Nav, δ18O, δ15Nβ, and δ15Nβ from NEEM, EUROCORE_NM, and Siple Dome along with data from GISP II (Sowers et al., 2002) and North Greenland Ice Core Project and Berkner Island (Bernard et al., 2006). Ice core samples from Siple Dome and Bernard et al. (2006) were measured with the same analytical system as the NEEM samples, whereas the samples from Sowers et al. (2002) were measured in a different laboratory. Unfortunately, no direct intercomparison between the two laboratories has been made; thus, there may be some scale differences. However, Figure 1 shows that such differences are likely not very large and they will not affect the conclusions below. Similar to the mole fraction it is not possible to detect interhemispheric differences in isotopic composition with the existing data sets over the PI period.

The average isotopic composition of N2O in the PI period is δ15Nav,PI = (33.7 ± 0.2)‰, δ18OPI = (5.3 ± 0.2)‰, δ18Osource,LI = (45.8 ± 0.5)‰, and δ18Osource,LI decreases to (0.6 ± 0.5)‰. We realize that taking averages over periods with clear temporal trends like the EI period likely introduce an additional error that is hard to quantify. The averages reported here are simple arithmetical averages (not mole fraction weighted) and may be biased by uneven sampling, so they should be interpreted with caution.

Assuming that the natural (=PI) source remained unchanged in strength and isotopic signature yields an average isotopic signature of the total anthropogenic source of δ15Navsource,anthrop = (−15.0 ± 2.6)‰ and

<table>
<thead>
<tr>
<th>δ15Nav</th>
<th>δ18O</th>
<th>δ15Nβ</th>
<th>δ15Nβ</th>
<th>SP = δ15Nα – δ15Nβ</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ15Nav</td>
<td>δ18O</td>
<td>δ15Nβ</td>
<td>δ15Nβ</td>
<td>SP = δ15Nα – δ15Nβ</td>
</tr>
</tbody>
</table>


δ15Nav (‰)  −6.8 ± 0.1  −5.3 ± 0.2  −9.5 ± 0.9  −8.3 ± 4.0  −15.0 ± 2.6  −18.2 ± 2.6  −15.6 ± 1.2  −6 to −19  −11.5  −7 to −13
δ18O (‰)    33.7 ± 0.2  32.0 ± 0.2  32.5 ± 0.8  31.7 ± 13.9  30.0 ± 2.6  27.2 ± 2.6  32.0 ± 1.3  20 to 40  31.3  17 to 26
δ15Nβ (‰)   −5.2 ± 0.4  −3.3 ± 1.0  −5.0 ± 1.4  NA       −4.5 ± 1.7  −8.1 ± 1.7  −7.6 ± 6.2  NA       −5.6  NA
δ15Nβ (‰)   −7.5 ± 0.4  −7.5 ± 1.1  −12.8 ± 2.2  NA       −24.0 ± 8.4  −26.1 ± 8.4  −20.5 ± 7.1  NA       −17.8  NA
SP = δ15Nα – δ15Nβ  2.3 ± 0.7  4.2 ± 1.5  7.8 ± 2.6  NA       19.5 ± 8.6  18.0 ± 8.6  12.9 ± 9.4  NA       12.2  NA

Note. PI = preindustrial; SP = site preference; NA = Not Available.
δ18Osource,anthrop = (30.0 ± 2.6)‰. As has been shown in previous studies, the present N2O source is isotopically lighter than the natural source, and the anthropogenic component is depleted in 15N and 18O relative to the natural source. The relative depletion is even larger for 15N than for 18O.

Figure 2b shows a similar plot for δ15Nα versus δ15Nβ. The total average source isotopic signatures of δ15Nα and δ15Nβ for the modern period are δ15Nsource,mod = (−5.0 ± 1.4)‰ and δ15Nsource,mod = (−12.8 ± 2.2)‰, respectively, while the corresponding PI values are δ15Nsource,PI = (−5.2 ± 0.4)‰ and δ15Nβsource,PI = (−7.5 ± 0.4)‰, respectively. The calculated total average anthropogenic source signatures are δ15Nαsource,anthrop = (−4.5 ± 1.7)‰ and δ15Nβsource,anthrop = (−24.0 ± 8.4)‰.

4. Discussion

4.1. The Isotopic Composition of N2O in the PI Atmosphere

Our experimental results are generally consistent with two earlier studies that have analyzed the isotopic composition of N2O in PI and EI ice (Bernard et al., 2006; Sowers et al., 2002; Table 3). However, the data...
Figure 2. (a) $\delta^{15}$N and $\delta^{18}$O of the tropospheric N$_2$O reservoir for PI (cyan circle) and modern (green circle) periods, and total average source for the same period with uncertainty bars (same coloring in diamonds). The red circle indicates the average anthropogenic source signature as calculated from this study. Results are compared with previous studies as stated in the legend, and the shaded areas in corresponding colors show the estimated range of the sources. The arrows represent the isotopic enrichment associated with the stratospheric loss. PI = preindustrial.

Table 3

Isotopic Signature of Tropospheric N$_2$O in the PI Atmosphere, and Change Between the PI and Modern Periods Derived in This Study Compared to Previous Studies on Firn Air (Park et al., 2012; Röckmann, Kaiser, & Brenninkmeijer, 2003) and Combined Firn and Ice Core Air (Bernard et al., 2006; Sowers et al., 2002)

<table>
<thead>
<tr>
<th></th>
<th>This study$^a$</th>
<th>Bernard et al. (2006)$^a$</th>
<th>Sowers et al. (2002)$^a$</th>
<th>Park et al. (2012)$^{a,b}$</th>
<th>Röckmann, Kaiser, &amp; Brenninkmeijer (2003)$^{a,b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta^{15}$N($%o$)</td>
<td>9.5 ± 0.1</td>
<td>9.6 ± 0.1</td>
<td>10.1 ± 0.6</td>
<td>9.3 ± 0.2</td>
<td>8.8 ± 0.1</td>
</tr>
<tr>
<td>$\delta^{18}$O($%o$)</td>
<td>47.1 ± 0.2</td>
<td>46.2 ± 0.6</td>
<td>47.4 ± 1.0</td>
<td>45.5 ± 0.2</td>
<td>45.8 ± 0.3</td>
</tr>
<tr>
<td>$\delta^{15}$N($%o$)</td>
<td>17.8 ± 0.4</td>
<td>19.0 ± 1.1</td>
<td>N/A</td>
<td>18.8 ± 1.0</td>
<td>19.0 ± 0.6</td>
</tr>
<tr>
<td>$\delta^{15}$N($%o$)</td>
<td>1.2 ± 0.5</td>
<td>0.1 ± 0.7</td>
<td>N/A</td>
<td>0.6 ± 1.1</td>
<td>0.4 ± 0.6</td>
</tr>
<tr>
<td>SP ($%o$)</td>
<td>16.6 ± 0.6</td>
<td>18.7 ± 1.3</td>
<td>N/A</td>
<td>19.4 ± 1.5</td>
<td>19.4 ± 0.8</td>
</tr>
<tr>
<td>PI to modern</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$\delta^{15}$N (%)</td>
<td>2.7 ± 0.2</td>
<td>2.8 $^{+1.0}_{-0.6}$</td>
<td>3.3 ± 0.8</td>
<td>2.5 ± 0.6</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>$\delta^{18}$O (%)</td>
<td>2.5 ± 0.4</td>
<td>1.6 $^{+0.3}_{-0.9}$</td>
<td>2.8 ± 1.3</td>
<td>0.9 ± 0.9</td>
<td>1.2 $^{+0.2}_{-0.3}$</td>
</tr>
<tr>
<td>$\delta^{15}$N (%)</td>
<td>2.0 ± 0.7</td>
<td>3.2 $^{+1.0}_{-0.8}$</td>
<td>N/A</td>
<td>3.0 ± 2.2</td>
<td>2.2 $^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>$\delta^{18}$O (%)</td>
<td>3.5 ± 0.8</td>
<td>2.4 $^{+0.9}_{-1.1}$</td>
<td>N/A</td>
<td>1.7 ± 2.1</td>
<td>1.8 $^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>SP (%)</td>
<td>−1.5 ± 0.9</td>
<td>0.8 $^{+0.9}_{-1.7}$</td>
<td>N/A</td>
<td>1.0 ± 3.1</td>
<td>0.4 $^{+0.3}_{-0.4}$</td>
</tr>
</tbody>
</table>

Note. PI = preindustrial; SP = site preference; NEEM = North Eemian Ice Drilling Programme; EUROCORE_NM = Eurocore Greenland project.

$^a$PI average isotopic composition was calculated using NEEM, EUROCORE_NM, and Siple Dome data. The differences between the PI and the modern period were calculated using average tropospheric values of the last 20 years (1989–2008) of the firn air reconstruction from Prokopiou et al. (2017), $\delta^{15}$N = (6.8 ± 0.2)$^\%o$, $\delta^{18}$O = (44.6 ± 0.1)$^\%o$, $\delta^{15}$N = (15.8 ± 0.1)$^\%o$, and $\delta^{15}$N = (−2.3 ± 0.2)$^\%o$. $^b$Values from Park et al. (2012) and Röckmann, Kaiser, and Brenninkmeijer (2003) are based on model estimates constrained by twentieth century observations.
set presented here constrains the PI isotopic composition more tightly than the previous studies. This is largely due to the higher number of samples analyzed in our study, which reduces the standard error of the mean when averaging but partly also to an increased measurement precision.

Table 3 includes the results from two studies where the isotopic composition of N$_2$O in the PI period are extrapolated from firn air measurements (Park et al., 2012, Röckmann, Kaiser, & Breninkmeijer, 2003). When this approach is taken, the isotopic composition in the PI period is apparently underestimated, slightly for $\delta^{15}$N$_{av}$ but in a more pronounced way for $\delta^{18}$O, where the extrapolated difference between the present and PI values is only half of the measured one. This shows that simple extrapolation from the firn air measurements to the PI period is problematic, which indicates that the parameters used for the extrapolation may not have been constant in time. This will be investigated in more detail in section 4.2.

Figure 1 shows no significant variations for $\delta^{15}$N$_{av}$ and $\delta^{18}$O of N$_2$O during the PI period. There are a few outliers for $\delta^{18}$O that prevent detection of possible small systematic changes. For the $^{15}$N isotopomers, the data set indicates potential small contrasting variations in $\delta^{15}$N$_a$ and $\delta^{15}$N$_b$ before 500 CE and in the period between 1500 and 1700 CE. Given the analytical precision of our measurements these variations are not statistically significant, but we will qualitatively investigate processes that could cause such deviations below. The agreement between NEEM and Siple Dome measurements provides evidence that this could be a real atmospheric signal, but it should also be noted that (if $\delta^{15}$N$_{av}$ remains constant) $\delta^{15}$N$_a$ and $\delta^{15}$N$_b$ by definition show opposite variations, because $\delta^{15}$N$_b$ is calculated from $\delta^{15}$N$_{av}$ and $\delta^{15}$N$_a$.

4.2. Changes in the Isotopic Composition of N$_2$O Over the Industrial Period

In order to investigate possible changes in the isotopic composition of N$_2$O during the industrial period, we combined the ice core data with firn air results from a recent multilayer reconstruction (Prokopiou et al., 2017). The firn study used data from six different locations, from both hemispheres to reconstruct the atmospheric history since 1940. Combining firn and ice data results extends our mole fraction and isotopic composition record to 2008 and results in a continuous isotope history from the PI period to present. A close-up view of the results for the industrial period after 1750 is provided in Figure 3.

The mole fraction records for the firn and ice measurements overlap very well, and the mole fraction continues to increase after 1940 to $(322 \pm 1)$ nmol/mol in 2008 (Figure 3a).

4.2.1. $\delta^{15}$N$_{av}$ and $\delta^{18}$O

All isotope signatures $\delta^{15}$N$_{av}$, $\delta^{18}$O, $\delta^{15}$N$_a$, and $\delta^{15}$N$_b$ decreased from the PI to the modern period (Figures 3b–3e). The total decrease of $\delta^{15}$N$_{av}$ and $\delta^{18}$O are similar, $\delta^{15}$N$_{av}$$_{PI-mod} = (2.7 \pm 0.2)$‰ and $\delta^{18}$O$_{PI-mod} = (2.5 \pm 0.4)$‰. In contrast, the respective changes over the LI period, from 1940 determined from the firn air samples (Prokopiou et al., 2017), are clearly different: $\delta^{15}$N$_{av}$ decreased by $(2.1 \pm 0.2)$‰ between 1940 and 2008, whereas $\delta^{18}$O decreased only by $(0.9 \pm 0.4)$‰. This indicates that $\delta^{18}$O must have decreased much more strongly than $\delta^{15}$N$_{av}$ over the 1750–1940 period, to achieve a comparable total change between PI times and the modern period. The difference between the signatures is too large to be caused by the corrections for firn fractionation (see above).

Figures 4a and 4b present the firn and ice core $\delta^{15}$N$_{av}$ and $\delta^{18}$O data as a function of the inverse N$_2$O mole fraction in order to check whether the isotope data from firn and ice core data can be explained by a single source with constant isotopic composition. If that is the case, all the data will appear along a linear regression line in the plot, which originates at the isotopic composition and mole fraction of N$_2$O in the PI period. We note that this is not a traditional Keeling plot which is strictly applicable only for a system without a removal term. In fact, the removal of N$_2$O has a significant influence on the slope and intercept of such a plot, which precludes the conventional application of obtaining an isotopic source signature. However, in Appendix A we verify that in the present situation, despite the sink term, assuming realistic source and sink strengths of N$_2$O, the Keeling plot approach can still be used to linearly extrapolate backward to the starting (i.e., PI) isotopic composition, which is our purpose. Errors introduced by the sink term are below 0.1‰.

Given the relatively large analytical error for the ice core measurements, no meaningful trends can be fitted to only the ice data. The firn air reconstructions, however, are much more tightly constrained (Figure 4). A feature that becomes apparent from these Keeling plots is the deviation from a linear trend for the oldest firn air data. This is related to the fact that the firn air reconstruction yields almost linear temporal trends for the isotope signatures, whereas the mole fraction increases quasi-exponentially as discussed by Prokopiou et al.
When these data are used to reconstruct source signatures, extremely depleted sources are required during the early part of the firn record to close the isotope budget. However, Prokopiou et al. (2017) also showed that there are isotope trajectories within the error bounds of the firn air reconstruction that do not require such depleted emissions. These scenarios result in straight lines in the Keeling plot. Hence, the very depleted source signatures that cause the curvature in the Keeling plot are not significant and are possibly due to a bias in the firn air reconstruction. Therefore, we do not use the earliest firn air data and apply a linear fit to the firn air reconstruction after year 1970. In the case of δ¹⁵N⁰², this fit line intersects with the average of the ice core samples (Figure 4), which indicates that the two data sets can be used together in the nonconventional application of the Keeling plot (Appendix A). As a result it shows that for δ¹⁵N⁰² the increase in N₂O since PI times can be approximated by one single representative source with a constant isotopic composition (within the experimental uncertainty). In addition, the agreement also indicates that for δ¹⁵N⁰² there is no conceptual inconsistency between the independent isotope reconstructions from firn air and ice core air, respectively.

**Figure 3.** EUROCORE_NM and Siple Dome N₂O ice core and firn data (mole fraction and isotopic composition) covering the industrial period. (a) N₂O mole fraction from EUROCORE_NM (green diamonds), Law Dome (yellow diamonds; MacFarling Meure, 2006), Berkner Island (white diamonds; Bernard et al., 2006), and a combination of ice and firn studies (black line; Meinschaeunen et al., 2017), GISP II (orange diamonds; Sowers et al., 2002), GRIP (purple diamonds), EUROCORE_FCR (pink diamonds; Flückiger et al., 2002), and NGRIP (red diamonds; Bernard et al., 2006). The firn data from Prokopiou et al. (2017) are shown as magenta line. (b–e) δ¹⁵N⁰², δ¹⁸O, δ¹⁵N α, and δ¹⁵N β in per mille. The color coding is the same as for mole fraction; cyan diamonds show data from Siple Dome (Rosen, 2014). The firn data from Prokopiou et al. (2017) are shown as magenta line. NEEM = North Eemian Ice Drilling Programme; EUROCORE_NM = Eurocore Greenland project; GISP = Greenland Ice Sheet Project; NGRIP = North Greenland Ice Core Project.
However, the same does not hold for $\delta^{18}$O. Here the extrapolation of the Keeling plot regression to the firm air data after 1970 does not intersect with the average isotopic composition of PI N$_2$O derived from the ice core measurements as shown in Figure 4. Apparently, in this case the modified Keeling plot model, that is, assuming one source with constant isotopic composition to be responsible for the observed increase in concentration, is not applicable. The combination of high-precision ice core data for the PI period and a well-constrained firm air history over the 1940–2008 period (Prokopiou et al., 2017) thus presents a picture of an apparent decoupling of $\delta^{15}$N$^\alpha$ and $\delta^{18}$O from the PI to the industrial period. This strongly supports the conclusion that Sowers et al. (2002) suggested based on a much smaller data set. The decoupling also resolves the apparent discrepancies between extrapolations from firm air data and ice core measurements in the past (Table 3; Bernard et al., 2006), because it means that the trend derived from firm air measurements cannot be simply extrapolated back to the PI atmosphere. As mentioned above for the apparent decoupling of $\delta^{15}$N$^\alpha$ and $\delta^{18}$O, the difference in the PI isotopic composition determined from the firm and ice core data is larger than the uncertainty in the firm air correction.

4.2.2. $\delta^{15}$N$^\alpha$ and $\delta^{15}$N$^\beta$

Next, we analyze the consistency between the changes in $\delta^{15}$N$^\alpha$ and $\delta^{15}$N$^\beta$ derived from firm and ice core data. As shown in Table 3, both signatures show an overall decrease since PI times, but the decrease for
δ¹⁵N is (−2.0 ± 0.7)‰, whereas the decrease δ¹⁵Nβ is about twice as large, (−3.5 ± 0.7)‰. These results suggest that the site preference (SP) of tropospheric N₂O increased since PI times by (1.5 ± 0.9)‰. The large uncertainties in δ¹⁵Nα and δ¹⁵Nβ of the previous ice core measurements prevented strong quantitative constraints on the trend in SP, but in our data set the trend is statistically significant (Table 3). The change in δ¹⁵Nα since PI times agrees within combined error bars with previously published studies, and the same is true for δ¹⁵Nβ, except for the firn air study of Rückmann, Kaiser, and Brenninkmeijer (2003), who showed significantly smaller change in the PI period from extrapolation of their firn air data.

Results from Keeling plots (Figures 4c and 4d) imply general consistency between firn and ice data sets for both position-dependent ¹⁵N signatures. Once more this indicates that from the nitrogen isotope perspective the increase in N₂O can be approximated reasonably well by one typical anthropogenic source with an unchanged isotopic composition through time and that there are no conceptual problems when combining the isotope histories derived from firm and ice core data.

4.3. Possible Causes for Isotopic Variability in the PI and Industrial Periods

4.3.1. Decoupling of δ¹⁵Nα and δ¹⁸O Over the Industrial Period

A decoupling of the evolution of δ¹⁵Nα and δ¹⁸O indicates a change in source composition from the PI to the industrial period. Conceptually this can be caused by either a change in the source mix (assuming constant isotopic composition for the individual source components) or changes in the isotopic composition of one or more components (assuming a constant source mix) or a combination of both. Also, it is important to realize that only processes that have clearly different effects on δ¹⁵Nα and δ¹⁸O but collectively match our observation can lead to the apparent decoupling in the temporal trends.

As an example for a temporally changing isotopic signature, Sowers et al. (2002) suggested a shift in the latitudinal distribution of biogenic soil emissions from tropical to temperate areas as a potentially important process that could lead to a shift in δ¹⁸O without a corresponding shift in δ¹⁵Nα. The δ¹⁸O signature of biogenic N₂O is determined to a large degree by oxygen exchange processes involving soil water (Kool et al., 2009). Due to the latitude effect of δD and δ¹⁸O in precipitation, meteoric water at higher latitudes is depleted in ¹⁸O compared to the tropics, so N₂O emitted from temperate soils is expected to be depleted in ¹⁸O compared to N₂O from tropical soils based on the isotopic difference of the soil waters between these regions. We note that this dependence has not yet been shown experimentally, and it may be masked by multiple other processes that affect the isotopic composition of the emitted N₂O. But in principle a poleward shift in the terrestrial emissions could lead to a decrease in δ¹⁸O without a simultaneous change in δ¹⁵Nα. This could have caused the larger trend in δ¹⁸O compared to δ¹⁵Nα during the EI period.

As shown in Tables 1 and 2 and discussed in section 3, the δ¹⁵Nα and δ¹⁸O source signatures of the anthropogenic source are depleted relative to the natural source. N₂O emissions from oceans and industrial sources (automobiles, industry, and coal combustion) have δ¹⁵Nα and δ¹⁸O isotopic signatures close to the tropospheric average, while N₂O emitted from soils is depleted in both heavy isotopes (Boß et al., 2003; Dore et al., 1998; Goldberg et al., 2010; Harris et al., 2015; Kim & Craig, 1993; Naqvi et al., 1998; Opdyke et al., 2009; Pérez et al., 2001; Popp et al., 2002; Snider et al., 2015; Toyoda et al., 2008; Yoshinari et al., 1997). The fact that soil-related emissions are the main isotopically depleted source category for both natural and anthropogenic sources indicates that the agricultural soil emissions are relatively more important for the anthropogenic source than the natural soil emissions are for the natural source. There are large uncertainties to the bottom-up determination of the global average source signature of N₂O from individual source types (Snider et al., 2015), but the best estimate for soil emissions is more depleted relative to the tropospheric value for δ¹⁵Nα than for δ¹⁸O (Snider et al., 2015; Tables 1 and 2). Thus, the large impact of agricultural soil emissions could in principle affect δ¹⁵Nα more than δ¹⁸O. The expected larger decrease of δ¹⁵Nα relative to δ¹⁸O could have been offset by an additional depletion of δ¹⁸O by a shift in the latitudinal distribution during the EI period, as argued above and in Sowers et al. (2002), but the uncertainties are too large to draw firm conclusions.

4.3.2. Temporal Variations in δ¹⁵Nβ and δ¹⁵N⁰

Unlike δ¹⁵Nα, the ¹⁵N SP of N₂O is largely independent of the isotopic signature of the precursor N species, and it has been proposed to provide more information on its production process (nitrification and denitrification; Denk et al., 2017; Popp et al., 2002; Sutka et al., 2006; Toyoda et al., 2015). Sutka et al. (2006) proposed...
that nitrification and denitrification could be regarded as two end-members with strongly different SP, $SP_{\text{nitrif}} = (33 \pm 5)\%$ and $SP_{\text{denitr}} = (0 \pm 5)\%$. Subsequent research has indicated that the interpretation may be more complicated (Lewicka-Szczebak et al., 2014; Ostrom et al., 2007; Park et al., 2011; Schmidt et al., 2004; Sutka et al., 2006; Tilsner et al., 2003; Well et al., 2006; Well et al., 2008; Well & Flessa, 2009). Both nitrification and denitrification are multistep processes and consist of several individual steps that affect the isotopic composition. For example, Lewicka-Szczebak et al. (2014) showed that the reduction of $N_2O$ by denitrifiers causes enrichment in heavy isotopes and can also affect research. Nevertheless, Lewicka-Szczebak et al. (2014) concluded that SP values for denitrification are much more consistent across a wide range of conditions than conventional $N_2O$ fractionation signatures. Their recommended value for $SP_{\text{denitr}} = -5\%$ is consistent within the uncertainty bars with the estimate from Sutka et al. (2006).

Figure 2b shows that the anthropogenic source signature for $\delta^{15}N$ is more enriched compared to $\delta^{15}N$. Soil studies support these observations reporting enrichments in $\delta^{15}N$ in $N_2O$ signatures emitted from soils (Bol et al., 2003; Pérez et al., 2001). Another study by Park et al. (2011) provided evidence of a correlation between $\delta^{15}N$ and $\delta^{15}N$ and $\delta^{18}O$ on emissions from soils. This is not applicable in our case since our study focuses on the total average source isotopic signature rather than an individual one.

Even though the two-end-member model has weaknesses and may not be as simple as initially proposed, we follow the original mass balance approaches to investigate possible shifts between nitrification and denitrification based on SP measurements (Park et al., 2012; Prokopiou et al., 2017). As described in section 3, two periods where opposite variations in $\delta^{15}N$ and $\delta^{15}N$ may have occurred are the period before 500 CE and that between 1500 and 1700 CE.

Rosen (2014) investigated the isotope variability during the latter period with a mass balance model in a Monte Carlo approach and concluded that only a change in nitrification versus denitrification (in the simple two-end-member model) could explain the observed opposite variations for the two $^{15}N$ signatures. Other processes (i.e., simple isotope source-sink disequilibrium effects, changes in troposphere-stratosphere exchange or the stratospheric sink, or varying contributions from terrestrial and oceanic sources) could not explain the observed opposite changes in $\delta^{15}N$ and $\delta^{15}N$. The opposing trends for $\delta^{15}N$ and $\delta^{15}N$ between 1500 and 1700 (CE) occur during the Little Ice Age. It has been shown that mole fractions of CO$_2$ and CH$_4$ decreased during the same period, which was attributed to reduced respiration of the terrestrial biosphere due to cooler temperatures for CO$_2$ and to cooling and predominance of dry conditions in Asia for CH$_4$ (Bauska et al., 2015; Mitchell et al., 2013). These conditions are expected to favor nitrification over denitrification (Butterbach-Bahl et al., 2013), in qualitative agreement with the results obtained from the SP data.

The overall trend of increasing SP from the PI to the modern period (Table 3) can be interpreted in the two-end-member (nitrification-denitrification) framework as a trend toward more nitrification with time, in agreement with earlier studies. Park et al. (2012) and Prokopiou et al. (2017) assumed the SP values for nitrification and denitrification from Sutka et al. (2006) as representative end-members. Neglecting influences from other processes, we performed the same analysis and calculated that the relative contribution of nitrification from natural sources was (7 ± 2)% and nitrification today from all sources is (24 ± 11)% meaning that the relative importance of nitrification versus denitrification production if $N_2O$ has increased by 17 (±11)% from PI times (1750 CE) to today, in agreement with previous estimates.

### 5. Conclusions

We have determined the $N_2O$ mole fraction and isotopic composition of 38 ice core samples from the Northern Hemisphere and combined them with 13 from the Southern Hemisphere covering the past three millennia. During the PI period, the isotopic composition of $N_2O$ was $\delta^{15}N^{av} = (9.5 \pm 0.1)\%$ (vs. air-$N_2$), $\delta^{18}O = (47.1 \pm 0.2)\%$ (vs. Vienna Standard Mean Ocean Water), $\delta^{15}N^{av} = (17.8 \pm 0.4)\%$, and $\delta^{15}N = (1.2 \pm 0.4)\%$ with an average $N_2O$ mole fraction of (267 ± 1) nmol/mol. There are no significant temporal variations in the isotopic composition of $N_2O$ in the PI period. Small possible opposite variations in $\delta^{15}N^{av}$ and $\delta^{15}N^{av}$ may have occurred before 500 CE and between 1500 and 1700 CE, but they are also not significant.

The statistically significant increase in $^{15}N$ SP since PI times, together with a simplified two-end-member mixing model of denitrification and nitrification, supports earlier postulations that the relative fraction of nitrification may have increased by more than 10% since PI times.
The isotopic composition of N₂O has changed toward more depleted values for all signatures since PI times. This is not only due to a source sink imbalance, but it is likely that the isotopic signature of the total source has also decreased. Thus, the anthropogenic source of N₂O is depleted in heavy isotopes compared to the natural source, which implicates the dominance of agricultural sources, as shown in previous studies.

Our data set, combined with the firn air reconstruction from Prokopiou et al. (2017), provides strong evidence for a decoupling of the temporal evolution of δ¹⁵N and δ¹⁸O over the industrial period, with larger changes of δ¹⁸O before 1940 and larger changes in δ¹⁵N after 1940, which was postulated by Sowers et al. (2002). We propose that the stronger depletion in δ¹⁵N compared to δ¹⁸O expected from the increase in soil sources could have been offset by an additional depletion in δ¹⁸O due to a latitudinal shift in sources as first suggested by Sowers et al. (2002). Due to this decoupling, previous studies that extrapolated the PI isotopic composition of N₂O from firn air measurements predicted about a factor 2 too small changes for δ¹⁸O; for the δ¹⁵N isotope signatures the results between firn air extrapolations and the new ice core data set generally agree much better than for δ¹⁸O. Due to the large variations in the isotopic composition of N₂O from different source categories, it is not possible to clearly identify which changes were responsible for the decoupling, but it is clear that such scenarios must involve processes that change δ¹⁵N differently than δ¹⁸O.

Appendix A: Removal term on Keeling plot

In section 4.2.2 we used a Keeling plot to illustrate the decoupling of sources contributing to the evolution of N₂O and its isotopic composition since PI times, although the Keeling plot approach is not technically applicable to a system with a removal term. Here we analyze forward calculations with our mass balance model, taking into account realistic source and sink strengths and isotope effects for N₂O, to show that the N₂O removal term does not introduce a significant error when the Keeling plot is used to extrapolate back to the PI isotopic composition.

In the model, the N₂O temporal evolution is taken from the high-resolution reconstruction of Meinshausen et al. (2017) who combined all published firn and ice records, to date, and constructed a continuous N₂O mole fraction history starting from year 1840 CE. The model starts with a steady state N₂O budget (for both mole fraction and isotopic composition) at year 1840 CE, the last minimum in the Meinshausen et al. (2017) reconstruction before the continuous increase. In the model we then apply an annual sink strength equivalent to a lifetime of 120 years; that is, we remove 1/120 of the atmospheric reservoir per year. The 120-year lifetime is very similar to the residence time in the atmosphere as used in the main text (123±29 year). The fractionation in the sink is equal to the effective fractionation constant of the stratospheric removal as determined by Kaiser et al. (2006). After the removal step, a source of N₂O is added to fit the mole fraction history of Meinshausen et al. (2017). The fraction of the source that is needed to compensate for the sink in the PI equilibrium state is assigned the PI source signature from Table 2, and the additional fraction that causes the N₂O increase is assigned the anthropogenic signature (Table 2). This means that the isotopic composition of the total source in the model changes with time.

The results (Figure A1) show that the fractionation in the removal term changes the temporal evolution of the isotopic signature and it is not possible to use the Keeling plot in the conventional way to derive the source isotopic composition from the y axis intercept of the linear fit to the data. However, we do not use the Keeling plot in the traditional manner but extrapolate back from the firn air measurements (1970–2008 CE) to the PI period. We apply exactly the same approach to the time series that was created by the forward model using a constant signature for the
anthropogenic source constrained by the well-documented mole fraction evolution of Meinshausen et al. (2017) and using a realistic sink fractionation and isotopic composition of the source. Figure A1 shows that the linear extrapolation back to the PI atmosphere is still possible, and in all cases the effect of the sink is < 0.06‰, which allows us to use the Keeling plots as done in the main text. We note that the back-extrapolated linear fit to the 100,000-year lifetime scenario shows similar offset, which reflects the changing isotopic signature of the total source (constant natural plus anthropogenic fraction).

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