



**Michigan
Technological
University**

Michigan Technological University
Digital Commons @ Michigan Tech

Michigan Tech Publications

1-2-2023

Underestimated Passive Volcanic Sulfur Degassing Implies Overestimated Anthropogenic Aerosol Forcing

U. A. Jongebloed
University of Washington

A. J. Schauer
University of Washington

J. Cole-Dai
South Dakota State University

C. G. Larrick
South Dakota State University

R. Wood
University of Washington

See next page for additional authors

Follow this and additional works at: <https://digitalcommons.mtu.edu/michigantech-p>



Part of the [Geological Engineering Commons](#), and the [Mining Engineering Commons](#)

Recommended Citation

Jongebloed, U., Schauer, A., Cole-Dai, J., Larrick, C., Wood, R., Fischer, T., Carn, S. A., Salimi, S., Edouard, S., Zhai, S., Geng, L., & Alexander, B. (2023). Underestimated Passive Volcanic Sulfur Degassing Implies Overestimated Anthropogenic Aerosol Forcing. *Geophysical Research Letters*, 50(1). <http://doi.org/10.1029/2022GL102061>

Retrieved from: <https://digitalcommons.mtu.edu/michigantech-p/16848>

Follow this and additional works at: <https://digitalcommons.mtu.edu/michigantech-p>



Part of the [Geological Engineering Commons](#), and the [Mining Engineering Commons](#)

Authors

U. A. Jongebloed, A. J. Schauer, J. Cole-Dai, C. G. Larrick, R. Wood, T. P. Fischer, S. A. Carn, S. Salimi, S. R. Edouard, S. Zhai, L. Geng, and B. Alexander



RESEARCH LETTER

10.1029/2022GL102061

Key Points:

- Sulfur isotopes in a Greenland ice core show that passive volcanic degassing contributes 66% of preindustrial Arctic sulfate
- The volcanic inventory used by most climate models underestimates passive degassing, possibly due to missing hydrogen sulfide emissions
- Elevated preindustrial passive volcanic degassing reduces the estimated cooling effect of anthropogenic sulfate in the Arctic

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

B. Alexander,
beckya@uw.edu

Citation:

Jongebloed, U. A., Schauer, A. J., Cole-Dai, J., Larrick, C. G., Wood, R., Fischer, T. P., et al. (2023). Underestimated passive volcanic sulfur degassing implies overestimated anthropogenic aerosol forcing. *Geophysical Research Letters*, 50, e2022GL102061. <https://doi.org/10.1029/2022GL102061>

Received 7 NOV 2022

Accepted 12 NOV 2022

Underestimated Passive Volcanic Sulfur Degassing Implies Overestimated Anthropogenic Aerosol Forcing

U. A. Jongebloed¹ , A. J. Schauer², J. Cole-Dai³ , C. G. Larrick³, R. Wood¹ , T. P. Fischer⁴ , S. A. Carn⁵ , S. Salimi¹, S. R. Edouard², S. Zhai¹ , L. Geng⁶ , and B. Alexander¹

¹Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA, ²Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA, ³Department of Chemistry and Biochemistry, South Dakota State University, Brookings, SD, USA, ⁴Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, USA, ⁵Department of Geological and Mining Engineering and Sciences, Michigan Technological University, Houghton, MI, USA, ⁶School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui, China

Abstract The Arctic is warming at almost four times the global rate. An estimated sixty percent of greenhouse-gas-induced Arctic warming has been offset by anthropogenic aerosols, but the contribution of aerosols to radiative forcing (RF) represents the largest uncertainty in estimating total RF, largely due to unknown preindustrial aerosol abundance. Here, sulfur isotope measurements in a Greenland ice core show that passive volcanic degassing contributes up to $66 \pm 10\%$ of preindustrial ice core sulfate in years without major eruptions. A state-of-the-art model indicates passive volcanic sulfur emissions influencing the Arctic are underestimated by up to a factor of three, possibly because many volcanic inventories do not include hydrogen sulfide emissions. Higher preindustrial volcanic sulfur emissions reduce modeled anthropogenic Arctic aerosol cooling by up to a factor of two ($+0.11$ to $+0.29$ W m⁻²), suggesting that underestimating passive volcanic sulfur emissions has significant implications for anthropogenic-induced Arctic climate change.

Plain Language Summary Sulfate aerosols are particles in the atmosphere that have a net cooling effect on the climate. One of the most uncertain aspects of climate modeling is the abundance of sulfate aerosols during the preindustrial era. Without knowing the amount of sulfate aerosols during the preindustrial, it is difficult to estimate how much anthropogenic sulfate aerosols have offset warming from anthropogenic greenhouse gases. In this study, we examine preindustrial sulfate aerosols in a Greenland ice core. We find that sulfate aerosols from passive (i.e., non-eruptive) volcanic degassing contribute almost two thirds of preindustrial Arctic sulfate aerosols in years without major volcanic eruptions. We compare this result to a state-of-the-art model and find that most climate models use a volcanic emissions inventory that underestimates preindustrial passive volcanic sulfur emissions. That volcanic inventory only includes one type of sulfur emission (sulfur dioxide), but studies have shown that volcanoes emit hydrogen sulfide, which can also form sulfate aerosols. We show that higher emissions of volcanic sulfur during the preindustrial era decrease the estimated cooling effect of anthropogenic aerosols during the industrial era. Thus, the underestimate of preindustrial volcanic emissions in current climate models has significant implications for anthropogenic climate change in the Arctic.

1. Introduction

Anthropogenic aerosols have a net cooling effect on global climate and partially offset warming from greenhouse gases, but represent the largest uncertainty in estimating total anthropogenic radiative forcing (RF) from 1850 to 2019 (Szopa et al., 2021). Aerosol RF results from aerosol-radiation interactions (RF_{ari}), including scattering solar radiation (Twomey, 1967), and aerosol-cloud interactions (RF_{aci}), including changing cloud albedo (Twomey, 1977). Other aerosol effects such as impacts on cloud fraction and lifetime are uncertain, but may be significant in the Arctic (Shindell et al., 2013). Sulfate aerosols have the largest cooling effect of any aerosol and their contribution to RF also has the largest uncertainty (Szopa et al., 2021).

The magnitude of aerosol RF depends on preindustrial aerosol abundance due to the nonlinear relationship between aerosols and cloud albedo: as aerosol abundance increases, cloud sensitivity to aerosol decreases. Thus, one of the largest sources of uncertainty in aerosol RF is poorly constrained natural emissions of aerosol precursors (Carslaw et al., 2013; Gettelman, 2015), especially emissions of volcanic sulfur dioxide (SO₂) and marine dimethyl sulfide (DMS), which are dominant natural sources of Arctic sulfate aerosol (Abbatt et al., 2019;

© 2023. The Authors.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs License](https://creativecommons.org/licenses/by/4.0/), which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

Legrand et al., 1997; Patris et al., 2002; Wasiuta et al., 2006). Other potential sources of sulfate aerosol, including carbonyl sulfide, dust, and biomass burning, are negligible in the Arctic (Abbatt et al., 2019; Kjellström, 1998; Legrand et al., 1997; Patris et al., 2002; Wasiuta et al., 2006). Although volcanic eruptions garner more attention in the climate literature, passive emissions of SO₂ are currently estimated to be about 10 times the typical annual emissions of SO₂ from eruptions (Carn et al., 2017).

Satellites provide global daily observations of volcanic SO₂ emissions from eruptive and passive degassing (Carn et al., 2015, 2017). Ground-based observations show that these satellite observations provide a lower-end estimate on volcanic SO₂ emissions because satellite detection limits are too high to reliably detect passive emissions from weakly degassing volcanoes (Fischer et al., 2019). Furthermore, volcanic SO₂ emissions inventories are primarily derived from UV satellite measurements, which have data gaps at high latitudes in the winter months (Carn et al., 2017). In addition to underestimating SO₂ emissions, these inventories exclude emissions of other sulfur species such as hydrogen sulfide (H₂S), which is difficult to measure from space due to a lack of characteristic absorption bands in the near UV and an overlap of IR absorption bands with those of water vapor (Clarisse et al., 2011). Estimates of volcanic H₂S emissions range from 1 to 35 Tg S yr⁻¹ (Halmer et al., 2002); the upper end of this range is three times the estimated global annual mean eruptive plus passive volcanic SO₂ flux of 11–13 Tg S yr⁻¹ (Carn et al., 2015, 2017). After emission, H₂S is oxidized to SO₂ on the timescale of 1–3 days (D'Alessandro et al., 2009; Kourtidis et al., 2008; Pham et al., 1995), by which point it is too dispersed to be detected by satellite. Thus, satellite observations underestimate volcanic sulfur emissions (Carn et al., 2017; Fischer et al., 2019), but the magnitude of the underestimate and the contribution of volcanic sulfur to the global sulfur burden remains unquantified.

2. Quantifying Preindustrial Sources of Ice Core Sulfate

We quantify volcanic and DMS-derived biogenic contribution to preindustrial (1200–1850 CE) Arctic sulfate aerosols by measuring sulfate concentrations (SO₄²⁻) and sulfur isotopic composition (δ³⁴S(SO₄²⁻)) in ice core samples from Summit, Greenland (see Text S1 in Supporting Information S1 for details on measurement methods). We select samples from years without influence from large volcanic eruptions (Figure 1, Cole-Dai et al., 2013; Gautier et al., 2019).

To estimate the relative contribution of volcanic and DMS-derived biogenic sulfate to total ice core non-sea salt sulfate (nssSO₄²⁻), we assume that δ³⁴S(nssSO₄²⁻) is a concentration-weighted average of the mean biogenic sulfate isotopic composition (δ³⁴S_{bio}) and mean volcanic sulfate isotopic composition (δ³⁴S_{volc}):

$$f_{\text{bio}} + f_{\text{volc}} = 1$$

$$f_{\text{bio}} \delta^{34}\text{S}_{\text{bio}} + f_{\text{volc}} \delta^{34}\text{S}_{\text{volc}} = \delta^{34}\text{S}(\text{nssSO}_4^{2-})$$

where f_{bio} is the fraction of DMS-derived biogenic sulfate and f_{volc} is the fraction of volcanic sulfate. δ³⁴S_{bio} is well constrained by measurements of sulfur isotopic composition of marine biogenic compounds at δ³⁴S_{bio} = +18.8 ± 0.3‰ (Table S1 and Figure S1 in Supporting Information S1). Observations of sulfate from an inland Antarctic ice core far from the marine biogenic source show δ³⁴S_{bio} = +18.6 ± 0.9‰ (Patris et al., 2000), suggesting minimal fractionation due to transport and oxidation of marine biogenic sulfur (Text S2 in Supporting Information S1).

We estimate δ³⁴S_{volc} using two methods. First, we estimate δ³⁴S_{volc} by applying a Monte Carlo routine to a Keeling Plot (Keeling, 1958; Keeling et al., 1989; Pataki et al., 2003) of the ice core observations to determine δ³⁴S_{volc} = +4.1 ± 0.5‰ (Figure S2 and Table S3 in Supporting Information S1) using similar assumptions and methods as in Patris et al. (2000, 2002) (Text S2 in Supporting Information S1). Second, we use direct δ³⁴S observations of volcanic gas and ash from 367 measurements of volcanic δ³⁴S(H₂S), δ³⁴S(SO₄²⁻), δ³⁴S(SO₂), and δ³⁴S(bulk S) from 38 volcanoes around the world (Table S2 in Supporting Information S1) to yield δ³⁴S_{volc} = +3.8 ± 0.7‰, where the standard error of the mean is determined using a bootstrapping method (Figure S1 and Text S2 in Supporting Information S1). Both estimates of δ³⁴S_{volc} (+4.1 ± 0.5‰ and +3.8 ± 0.7‰) result in similar values for mean ice core f_{volc} (66% and 64%, respectively; Text S3 in Supporting Information S1), but we focus on δ³⁴S_{volc} = +4.1 ± 0.5‰ because this value more likely represents a regional signature and also incorporates any fractionation effects on δ³⁴S_{volc} during transport to Summit.

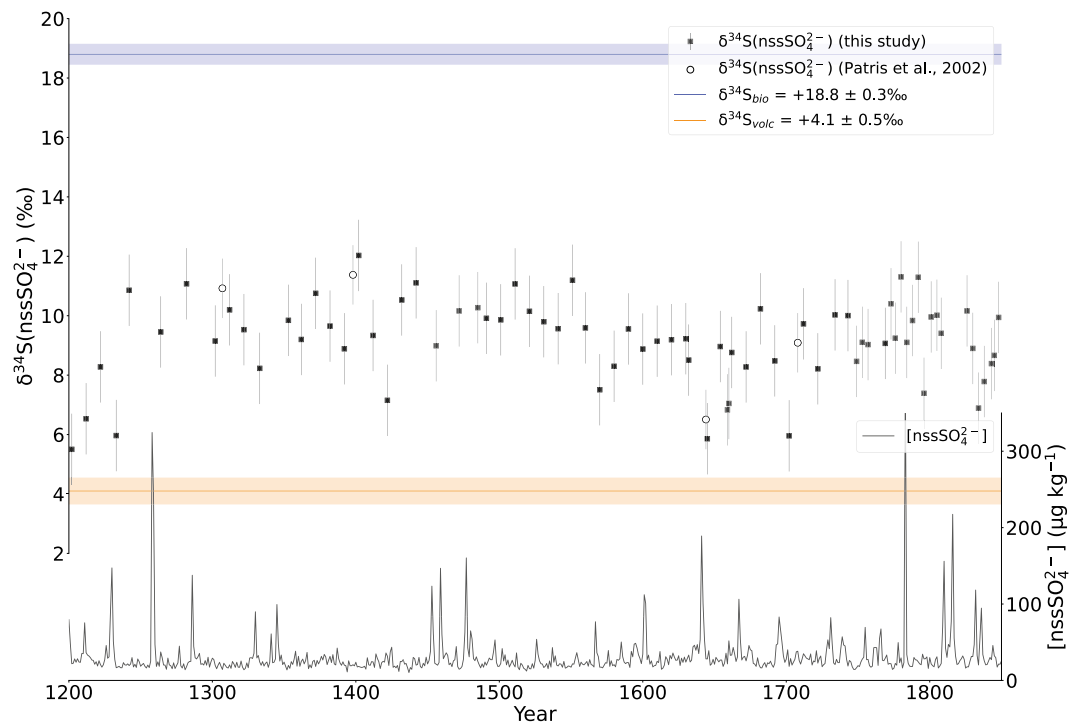


Figure 1. Decadal and sub-decadal ice core $\delta^{34}\text{S}(\text{nssSO}_4^{2-})$ (‰, black symbols) and annual mean nssSO_4^{2-} concentration ($\mu\text{g kg}^{-1}$, gray line). Thick colored bars show the isotopic signatures of volcanic sulfur ($\delta^{34}\text{S}_{\text{volc}} = +4.1 \pm 0.5$ ‰) and DMS-derived biogenic sulfur ($\delta^{34}\text{S}_{\text{bio}} = +18.8 \pm 0.3$ ‰). The $\delta^{34}\text{S}(\text{nssSO}_4^{2-})$ samples were selected as one 2-year sample per decade from 1200 to 1750 CE and one 1-year sample every 4 years from 1750 to 1850 CE from years where nssSO_4^{2-} was not influenced by large tropospheric or stratospheric eruptions (Cole-Dai et al., 2013; Gautier et al., 2019). Data from Patris et al. (2002) is also shown (circle). Error in $\delta^{34}\text{S}(\text{nssSO}_4^{2-})$ measurements is estimated based on replicate analysis of whole-process standards.

Figure 1 shows ice core $\delta^{34}\text{S}(\text{nssSO}_4^{2-})$ and nssSO_4^{2-} concentration between 1200 and 1850 CE. The mean $\delta^{34}\text{S}(\text{nssSO}_4^{2-})$ is $+9.2$ ‰, indicating that the isotopically lighter volcanic sulfur contributes about twice as much on average as the biogenic sulfur source. Figure 2 shows that the mean volcanic sulfate concentration ($19.1 \pm 7.1 \mu\text{g kg}^{-1}$) is 2.0 ± 1.7 times larger than the mean DMS-derived biogenic sulfate concentration ($9.4 \pm 3.0 \mu\text{g kg}^{-1}$) and that the mean fraction of sulfate from volcanoes (f_{volc}) is $66 \pm 10\%$. Using $\delta^{34}\text{S}_{\text{volc}} = +2.5$ ‰ from a small number of observations from volcanoes near Greenland also yields a dominant contribution from volcanic sulfate ($f_{\text{volc}} = 59\%$) (Text S3 in Supporting Information S1). We also consider how our estimate for f_{volc} is affected by including a continental source of sulfur (e.g., H_2S emissions from vegetation, salt marshes, tropical forests, soils, and wetlands) based on Watts (2000), which results in $f_{\text{volc}} = 58\%$ to 60% (Text S4 in Supporting Information S1). These numbers are similar to a previous estimate of $f_{\text{volc}} = 57\%$ from Legrand et al. (1997) in a Summit, Greenland ice core, which was estimated by subtracting an assumed DMS-derived contribution to ice core sulfate based on the summertime peak in nssSO_4^{2-} .

3. Comparing Ice Core Sulfate to a Global Model

To evaluate current estimates of the relative importance of volcanic and DMS-derived biogenic sulfate aerosol abundance in global models, we use the GEOS-Chem global 3-D chemical transport model (version 13.2.1, Text S5 in Supporting Information S1) described in Bey et al. (2001) driven by assimilated meteorology from MERRA-2. Volcanic SO_2 emissions are from Carn et al. (2015, 2017), updated annually in (Carn, 2022). The Carn et al. (2015, 2017) SO_2 emissions inventory is used in many global models and is the upper end of volcanic SO_2 emissions in Climate Model Intercomparison Project (CMIP6) models. The Carn et al. (2015, 2017) inventory includes passive and eruptive volcanic SO_2 emissions measured by the Ozone Monitoring Instrument (OMI) since 2005. Model DMS emissions are based on Lana et al. (2011). To simulate a preindustrial atmosphere, all anthropogenic emissions are turned off (Zhai et al., 2021). We use meteorology and volcanic SO_2 emissions from

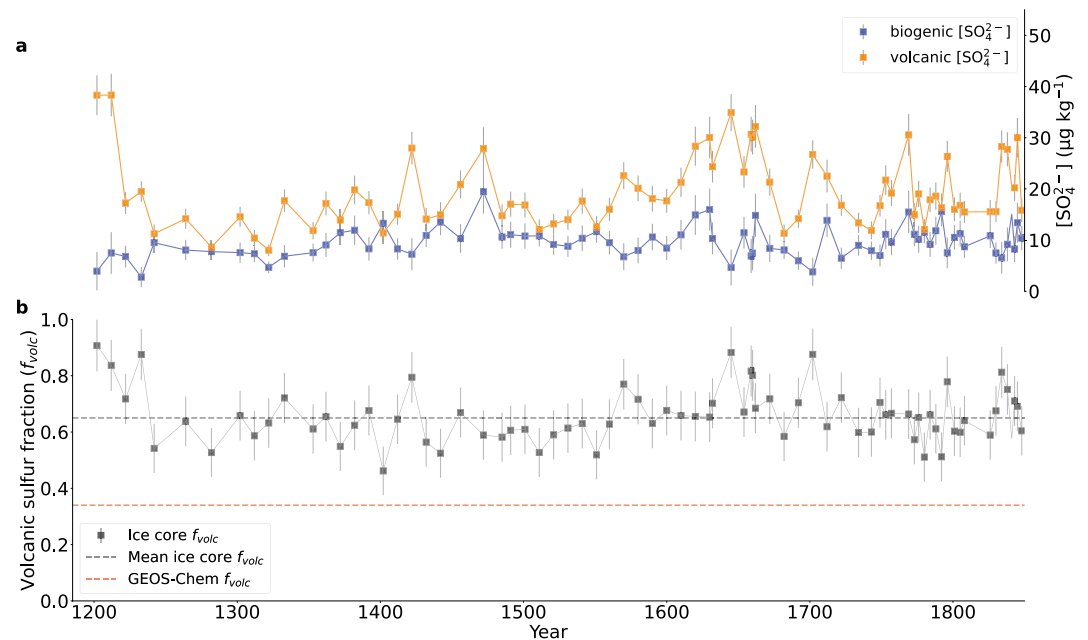


Figure 2. Volcanic and dimethyl sulfide (DMS)-derived biogenic sulfate concentrations and volcanic fraction in ice core samples from preindustrial years (1200–1850 CE) without large volcanic eruptions. (a) Volcanic (orange) and DMS-derived biogenic (blue) sulfate concentrations ($\mu\text{g kg}^{-1}$) calculated with $\delta^{34}\text{S}_{\text{volc}} = +4.1 \pm 0.5 \text{‰}$. (b) Volcanic fraction of ice core nssSO_4^{2-} in each sample during the preindustrial (1200–1850 CE). Dashed gray line shows the mean volcanic fraction of ice core nssSO_4^{2-} ($f_{\text{volc}} = 66\%$). Dashed red line shows the GEOS-Chem simulated volcanic sulfur fraction ($f_{\text{volc}} = 34\%$) in the air-mass source region of Summit with the default volcanic SO_2 emissions from Carn et al. (2015, 2017). Error bars were determined by propagating the uncertainty in isotopic source signatures and sample measurement error in both (a and b).

the year 2013, during which passive and eruptive volcanic SO_2 emissions in regions affecting the Arctic (i.e., Kamchatka, Alaska, and Iceland) were similar to the 2004–2017 median. To compare model results to ice-core derived estimate of f_{volc} , the average f_{volc} of the modeled tropospheric burden of SO_2 and sulfate is computed in the Summit, Greenland air-mass source region (120°W – 30°E , 42° – 90°N) based on the 5-day average aerosol lifetime in the Arctic and HYSPLIT backward trajectory analysis (Zhai et al., 2021). The modeled f_{volc} is similar when calculated with other methods, including f_{volc} of modeled sulfur deposition in the ice core region (Figure S3 in Supporting Information S1), and when modeled with meteorology from the year 2007 (Text S5 in Supporting Information S1).

Figure 3a shows that the modeled preindustrial f_{volc} over the Summit, Greenland air-mass source region using the SO_2 emissions reported by Carn et al. (2015, 2017) is 34%, which is 3.2 standard deviations lower than the mean ice core f_{volc} . The modeled volcanic sulfur contribution ($f_{\text{volc}} = 34\%$) is lower than the observed f_{volc} in all 74 ice core samples representing 123 years between 1200 and 1850 CE (Figure 2b).

4. Discussion

4.1. Biogenic and Continental Sulfur Emissions and Chemistry

A model underestimate in f_{volc} relative to the ice-core derived estimate f_{volc} could be explained by an overestimate in modeled DMS emissions or an underestimate in modeled volcanic emissions. Modeled preindustrial DMS emissions would have to be overestimated by a factor of three for DMS emissions to explain the model underestimate in f_{volc} . Ice core records show declining concentrations of methanesulfonic acid, an oxidation product of DMS, since the preindustrial (Osman et al., 2019), indicating that it is unlikely that present-day DMS flux is three times higher than that of the preindustrial. It is also unlikely that DMS emissions in the Arctic are overestimated by a factor of three; in fact, GEOS-Chem modeled atmospheric DMS concentrations are biased low in the Arctic (Text S6 in Supporting Information S1; Mungall et al., 2016). Although modeled DMS oxidation

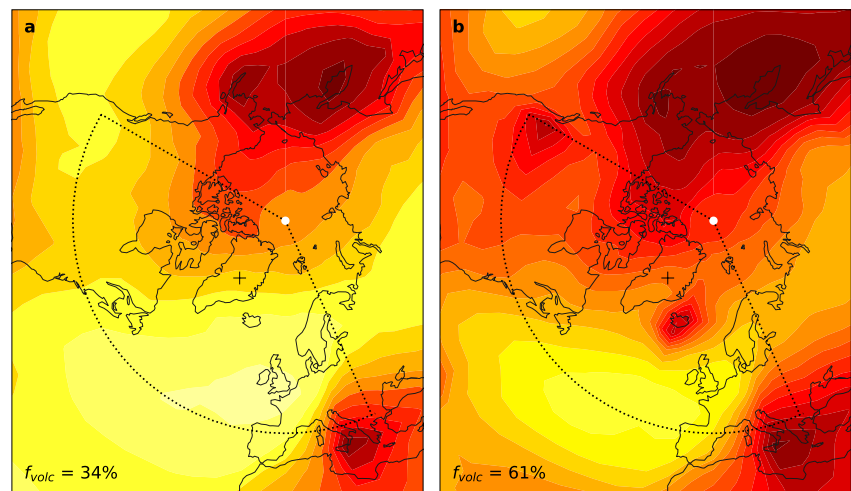


Figure 3. Modeled tropospheric f_{volc} in two preindustrial simulations. (a) Tropospheric f_{volc} in the preindustrial simulation with the default scenario volcanic emissions. (b) Tropospheric f_{volc} in the preindustrial simulation with emissions from the H_2S 1.7 scenario. Dotted black lines outline the 5-day back trajectory region (120°W – 30°E , 42° – 90°N) for the Summit, Greenland ice core (location marked with “+”) as described in Zhai et al. (2021). The mean f_{volc} of the sulfur ($\text{SO}_2 + \text{SO}_4^{2-}$) burden for the air-mass source region are shown in the bottom left.

chemistry is simplified, uncertainty in modeled DMS chemistry cannot explain the discrepancy between modeled and observed f_{volc} (Text S6 in Supporting Information S1).

It is possible that other sources of sulfur not considered in global climate models could contribute to Arctic sulfate. For example, emissions of H_2S from continental sources (e.g., vegetation, salt marshes, tropical forests, soils, and wetlands) contribute approximately 1.5 Tg S yr^{-1} globally (Watts, 2000). However, even if we assume this source contributes up to 4% of ice core sulfate, thereby lowering ice core f_{volc} to 58%–60% from 66% (Text S4 in Supporting Information S1), the model would still underestimate f_{volc} in the Summit, Greenland back trajectory region.

4.2. Underestimate in Passive Volcanic Degassing Emissions

Given the low likelihood of an overestimation of DMS-derived sulfate in the Arctic, the discrepancy between modeled and ice core f_{volc} is best explained by an underestimate in passive volcanic sulfur emissions, which is consistent with comparisons between satellite and ground-based observations of SO_2 (Fischer et al., 2019) and the omission of volcanic H_2S emissions in models. It is also possible that preindustrial passive volcanic degassing was elevated relative to the present day. The sampled time period (1200–1850 CE) is during the “Little Ice Age” (LIA), usually defined as a period of relatively cool climate starting in the mid-thirteenth century and ending around 1850 CE (Grove, 2001). A driving factor in cooling observed during the LIA was an increased frequency of volcanic eruptions (Newhall et al., 2018). It is conceivable that passive volcanic degassing, which increases prior to and following volcanic eruptions (Carn et al., 2017), was also elevated during the preindustrial relative to the present day, which would exacerbate the underestimate in passive sulfur degassing emissions in the preindustrial. Elevated passive sulfur degassing around periods of increased eruption frequency has been suggested to explain differences between early and late nineteenth-century $\delta^{34}\text{S}(\text{nssSO}_4^{2-})$ in Antarctic ice cores (Takahashi et al., 2022).

To quantify and understand the factors contributing to the underestimate in preindustrial volcanic emissions, three volcanic emissions scenarios were prescribed in the model in place of the Carn et al. (2015, 2017) inventory: we label them the 371 scenario, the H_2S scenario, and the H_2S 1.7 scenario (summarized in Table S4 in Supporting Information S1). These emissions scenarios have increased passive degassing of SO_2 relative to Carn et al. (2015, 2017) while leaving eruptive emissions unchanged. In the 371 scenario, volcanic SO_2 emissions are based on comparison between satellite and ground-based passive volcanic sulfur emissions from Fischer et al. (2019) for volcanoes included in the Carn et al. (2015, 2017) SO_2 inventory. The 371 scenario also includes SO_2 fluxes from the 371 volcanoes identified as degassing by Fischer et al. (2019) that are not included in

the Carn et al. (2015, 2017) SO₂ inventory. These 371 volcanoes are classified as either “hydrothermal” or “magmatic” and fluxes are assigned to be 3 or 7 t S day⁻¹ (0.001 or 0.003 Tg S year⁻¹), respectively (Fischer et al., 2019). This includes 16 Icelandic volcanoes each emitting 3 t S day⁻¹ (0.017 Tg S year⁻¹ in total). The 371 scenario results in a modest increase in f_{volc} in the Greenland air mass region from 34% in the default scenario to 36%, still three standard deviations below the mean ice core f_{volc} of 66% (Figure 2b).

In the H₂S scenario, we hypothesize that preindustrial and present-day simulations are missing a significant volcanic sulfur source due to the omission of H₂S from volcanic emissions inventories. Here, H₂S contribution is represented by increasing modeled SO₂ emissions due to the short 1- to 3-day lifetime of H₂S against oxidation to SO₂ (D’Alessandro et al., 2009; Kourtidis et al., 2008; Pham et al., 1995). Accordingly, SO₂ emissions are multiplied by a factor based on measured or predicted SO₂ to H₂S ratios (Halmer et al., 2002; Table S5 in Supporting Information S1). The H₂S scenario results in a f_{volc} of 46%, which is 2 standard deviations below the mean ice core f_{volc} of 66%.

In the H₂S 1.7 scenario, we multiply the SO₂ emissions from the H₂S scenario by 1.7 for each volcano. We choose the factor of 1.7 to approximate the mean ice core f_{volc} of 66%. As expected and shown in Figure 3b, the H₂S 1.7 scenario produces f_{volc} of 61%, which approximately aligns with the mean ice core f_{volc} of 66%. This scenario implies that current estimates of preindustrial volcanic emissions are underestimated due to the omission of H₂S emissions and/or that passive volcanic degassing has decreased since the preindustrial.

We also consider a scenario where only Icelandic volcanoes have increased sulfur emissions and that these emissions are much larger than Icelandic emissions in the three aforementioned emissions scenarios (Text S7 in Supporting Information S1). SO₂ emissions from Iceland were 5.1 Tg S yr⁻¹ in this scenario, which is 30 times larger than sulfur emissions from Iceland in the H₂S 1.7 scenario (0.16 Tg S yr⁻¹), but both scenarios are within the estimated range of sulfur emissions from Icelandic volcanoes based on observations from Icelandic hot springs (Text S7 in Supporting Information S1; Supplementary Data File 2). Icelandic volcanic sulfur emissions of this magnitude reconcile the discrepancy between the model and ice core (Text S7 in Supporting Information S1). Given the recent studies indicating that passive volcanic degassing CO₂ emissions in Iceland might be significantly underestimated (e.g., Ilyinskaya et al., 2018), it is possible that underestimated Icelandic volcanic sulfur emissions could explain most or all of the discrepancy between the ice core and modeled f_{volc} . This possibility also has significant radiative forcing implications (Text S7 in Supporting Information S1), and highlights the large uncertainty and disproportionate impact of Icelandic volcanic emissions in the North Atlantic and Greenland.

4.3. Radiative Forcing Implications

Models indicate that the cooling effect of anthropogenic aerosols would be lower than previously thought if the preindustrial sulfate aerosol abundance was higher because of the nonlinear relationship between aerosols and RF_{aci}: as preindustrial aerosol abundance increases, cloud albedo becomes less sensitive to anthropogenic aerosols (Carslaw et al., 2013; Gettelman et al., 2015). To explore the potential RF implications of our emissions scenarios, we consider three possibilities. First, we assume that the default volcanic emissions inventory from Carn et al. (2015, 2017) accurately estimates present-day emissions, but underestimates passive volcanic sulfur emissions in the preindustrial. Second, we assume that passive volcanic sulfur emissions have not changed since the preindustrial, and that both preindustrial and present-day passive degassing emissions are underestimated. Overlapping volcanic and anthropogenic sulfur isotopic source signatures preclude quantifying volcanic sulfate in post-1850 ice core samples (Ghahremaninezhad et al., 2016; Patris et al., 2002; Wasiuta et al., 2006), therefore we cannot use post-1850 ice core measurements to evaluate this possibility. A third possibility is a combination of the first two: volcanic sulfur emissions in both present-day and preindustrial are underestimated and volcanic passive sulfur emissions were higher in the preindustrial relative to the present day. The RF implications of this third possibility will fall in between the first two.

To quantify the RF implications of an underestimate in passive volcanic degassing emissions in the preindustrial (first possibility) or both the preindustrial and present day (second possibility), we estimate RF for each possibility (RF = RF_{ari} + RF_{aci}), where RF_{ari} is calculated using GEOS-Chem (Text S5 in Supporting Information S1) and RF_{aci} is calculated using the simple heuristic model described by Wood (2021) (Text S8 in Supporting Information S1). We estimate ΔRF by subtracting RF with the Carn et al. (2015, 2017) inventory from RF with elevated

Table 1
Radiative Forcing (RF) Estimates for Different Present-Day and Preindustrial Volcanic Scenarios

Emissions scenario	Volcanic emissions scenario in present day (f_{volc} of natural nssSO_4^{2-})	Volcanic emissions scenario in preindustrial (f_{volc} of natural nssSO_4^{2-})	Arctic aerosol SW TOA RF ^a ($\text{RF}_{\text{ari}}^{\text{b}}$ + $\text{RF}_{\text{aci}}^{\text{c}}$) between present day and in preindustrial (W m^{-2})	Difference between default arctic RF and emissions scenario Arctic RF (W m^{-2}) ($\Delta\text{RF}_{\text{ari}}$ + $\Delta\text{RF}_{\text{aci}}$)
Default	Default ($f_{\text{volc}} = 34\%$)	Default ($f_{\text{volc}} = 34\%$)	-0.55 (-0.10 + -0.45)	
Possibility 1	Default ($f_{\text{volc}} = 34\%$)	H ₂ S 1.7 ($f_{\text{volc}} = 61\%$)	-0.26 (-0.07 + -0.19)	+0.29 (0.03 + 0.26)
Possibility 2	H ₂ S 1.7 ($f_{\text{volc}} = 61\%$)	H ₂ S 1.7 ($f_{\text{volc}} = 61\%$)	-0.44 (-0.10 + -0.34)	+0.11 (0.00 ^d + 0.11)

^aThe total shortwave (SW) top-of-atmosphere (TOA) radiative forcing (RF) is estimated as the sum of the RF from aerosol-radiation interactions (RF_{ari}) and RF from aerosol-cloud interaction (RF_{aci}). ^bDifference between present-day radiative effect from aerosol-radiation interactions and preindustrial radiative effect from aerosol-radiation interactions. ^cEstimated present-day RF from aerosol-cloud interactions (Text S8). ^d $\Delta\text{RF}_{\text{ari}}$ between the default possibility and possibility 2 is negligible compared to $\Delta\text{RF}_{\text{aci}}$.

passive degassing emissions representing the first or second possibility (Table S6 in Supporting Information S1). We quantify ΔRF for the first possibility by using the H₂S 1.7 scenario in the preindustrial and using the default scenario in the present day. We quantify ΔRF for the second possibility by using the H₂S 1.7 scenario in both the preindustrial and present day. We focus on the H₂S 1.7 scenario because it results in a preindustrial modeled f_{volc} (61%) approximately equal to the ice core f_{volc} (66%). The resulting ΔRF for both possibilities are summarized in Table 1. ΔRF ranges from +0.29 W m^{-2} ($\Delta\text{RF}_{\text{ari}} = +0.03 \text{ W m}^{-2}$, $\Delta\text{RF}_{\text{aci}} = +0.26 \text{ W m}^{-2}$; Table 1, Figure S4 in Supporting Information S1) where only preindustrial emissions are underestimated, to +0.11 W m^{-2} ($\Delta\text{RF}_{\text{ari}} = 0.0 \text{ W m}^{-2}$, $\Delta\text{RF}_{\text{aci}} = +0.11 \text{ W m}^{-2}$; Table 1, Figure S4 in Supporting Information S1) where both preindustrial and present-day emissions are underestimated. We estimate that underestimating Icelandic passive volcanic sulfur emissions could have an equally large or larger impact on radiative forcing ($\Delta\text{RF} = +0.55 \text{ W m}^{-2}$) (Text S7 in Supporting Information S1). This analysis neglects the effects of cloud adjustments to aerosol (i.e., impacts on cloud fraction, cloud lifetime, and semi-direct aerosol effects). Nevertheless, these calculations show that the impact of underestimating volcanic emissions on RF calculations is potentially large. Future studies using fully coupled atmosphere-ocean global climate models with enhanced volcanic emissions will be useful for more accurately quantifying RF implications and uncertainty.

5. Conclusions

Our results indicate that passive volcanic degassing sulfur emissions influencing the Arctic are underestimated by up to a factor of three. We show that increased volcanic sulfur emissions from passive degassing results in estimated Arctic anthropogenic aerosol cooling that is up to a factor of two lower in magnitude. An overly strong anthropogenic aerosol cooling due to underestimated passive volcanic sulfur degassing could at least partially explain excessively strong aerosol cooling in CMIP6 climate models (Dittus et al., 2020) and the underestimates of modeled Arctic amplification compared to observations (Rantanen et al., 2022).

Quantifying passive volcanic sulfur degassing emissions is critical for constraining anthropogenic aerosol forcing. More observations of SO₂ emissions from passive volcanic degassing are required to constrain the magnitude of the underestimate in the passive volcanic SO₂ emissions inventory based on satellite measurements in Carn et al. (2015, 2017). Additionally, H₂S, which is typically neglected in volcanic emissions inventories used in global climate models, should be considered a potentially important contributor to the global atmospheric sulfur budget and thus climate.

Data Availability Statement

All ice core data and Iceland volcanic gas observations are available in the National Science Foundation (NSF) Arctic Data Center at <https://doi.org/10.18739/A2N873162>. GEOS-Chem version 13.2.1 code is publicly available at <https://doi.org/10.5281/zenodo.5500717>.

Acknowledgments

U.J. and B.A. acknowledge financial support from NSF award PLR 1904128 and AGS 1702266. J.C.-D. is supported by PLR 0612461 and PLR 1904142. R.W. is supported by Lowercarbon, the Pritzker Innovation Fund, and Silver-Lining, through the Marine Cloud Brightening Project. T.F. acknowledges support from the Deep Carbon Observatory, DECADE initiative for work on the global volcanic SO₂ and CO₂ flux inventories. S.C. acknowledges support from NASA Interdisciplinary Research in Earth Science (80NSSC20K1773) and NASA Aura Science Team (80NSSC20K0983). L.G. acknowledges support from National Natural Science Foundation of China (41822605 and 41871051).

References

- Abbatt, J. P. D., Leaitch, W. R., Aliabadi, A. A., Bertram, A. K., Blanchet, J. P., Boivin-Rioux, A., et al. (2019). Overview paper: New insights into aerosol and climate in the Arctic. *Atmospheric Chemistry and Physics*, 19(4), 2527–2560. <https://doi.org/10.5194/acp-19-2527-2019>
- Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., et al. (2001). Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation. *Journal of Geophysical Research*, 106(D19), 23073–23095. <https://doi.org/10.1029/2001JD000807>
- Carn, S. A. (2022). Multi-satellite volcanic sulfur dioxide L4 long-term global database V4.
- Carn, S. A., Fioletov, V. E., McLinden, C. A., Li, C., & Krotkov, N. A. (2017). A decade of global volcanic SO₂ emissions measured from space. *Scientific Reports*, 7(1), 44095. <https://doi.org/10.1038/srep44095>
- Carn, S. A., Yang, K., Prata, A. J., & Krotkov, N. A. (2015). Extending the long-term record of volcanic SO₂ emissions with the Ozone Mapping and Profiler Suite nadir mapper. *Geophysical Research Letters*, 42(3), 925–932. <https://doi.org/10.1002/2014GL062437>
- Carlsaw, K. S., Lee, L. A., Reddington, C. L., Pringle, K. J., Rap, A., Forster, P. M., et al. (2013). Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*, 503(7474), 67–71. <https://doi.org/10.1038/nature12674>
- Clarisse, L., Coheur, P. F., Chédéville, S., Lacour, J. L., Hurtmans, D., & Clerbaux, C. (2011). Infrared satellite observations of hydrogen sulfide in the volcanic plume of the August 2008 Kasatochi eruption. *Geophysical Research Letters*, 38(10). <https://doi.org/10.1029/2011GL047402>
- Cole-Dai, J., Ferris, D. G., Lanciki, A. L., Savarino, J., Thieme, M. H., & McConnell, J. R. (2013). Two likely stratospheric volcanic eruptions in the 1450s C.E. found in a bipolar, subannually dated 800 year ice core record. *Journal of Geophysical Research: Atmospheres*, 118(14), 7459–7466. <https://doi.org/10.1002/jgrd.50587>
- D'Alessandro, W., Brusca, L., Kyriakopoulos, K., Michas, G., & Papadakis, G. (2009). Hydrogen sulphide as a natural air contaminant in volcanic/geothermal areas: The case of Sousaki, Corinthia (Greece). *Environmental Geology*, 57(8), 1723–1728. <https://doi.org/10.1007/s00254-008-1453-3>
- Dittus, A. J., Hawkins, E., Wilcox, L. J., Sutton, R. T., Smith, C. J., Andrews, M. B., & Forster, P. M. (2020). Sensitivity of historical climate simulations to uncertain aerosol forcing. *Geophysical Research Letters*, 47(13). <https://doi.org/10.1029/2019GL085806>
- Fischer, T. P., Arellano, S., Carn, S., Aiuppa, A., Galle, B., Allard, P., et al. (2019). The emissions of CO₂ and other volatiles from the world's subaerial volcanoes. *Scientific Reports*, 9(1), 18716. <https://doi.org/10.1038/s41598-019-54682-1>
- Gautier, E., Savarino, J., Hoek, J., Erbland, J., Caillon, N., Hattori, S., et al. (2019). 2600-years of stratospheric volcanism through sulfate isotopes. *Nature Communications*, 10(1), 466. <https://doi.org/10.1038/s41467-019-08357-0>
- Gettelman, A. (2015). Putting the clouds back in aerosol-cloud interactions. *Atmospheric Chemistry and Physics*, 15(21), 12397–12411. <https://doi.org/10.5194/acp-15-12397-2015>
- Ghahremaninezhad, R., Norman, A. L., Abbatt, J. P. D., Levasseur, M., & Thomas, J. L. (2016). Biogenic, anthropogenic and sea salt sulfate size-segregated aerosols in the Arctic summer. *Atmospheric Chemistry and Physics*, 16(8), 5191–5202. <https://doi.org/10.5194/acp-16-5191-2016>
- Grove, J. M. (2001). The onset of the Little Ice Age. In Jones (Ed.), *History and climate: Memories of the future?* (pp. 153–185). Kluwer Academic/Plenum Publishing.
- Halmer, M. M., Schmincke, H.-U., & Graf, H.-F. (2002). The annual volcanic gas input into the atmosphere, in particular into the stratosphere: A global data set for the past 100 years. *Journal of Volcanology and Geothermal Research*, 115(3–4), 511–528. [https://doi.org/10.1016/S0377-0273\(01\)00318-3](https://doi.org/10.1016/S0377-0273(01)00318-3)
- Ilyinskaya, E., Mobbs, S., Burton, R., Burton, M., Pardini, F., Pfeffer, M. A., et al. (2018). Globally significant CO₂ emissions from Katla, a subglacial volcano in Iceland. *Geophysical Research Letters*, 45(19). <https://doi.org/10.1029/2018GL079096>
- Keeling, C. D. (1958). The concentration and isotopic abundances of atmospheric carbon dioxide in rural areas. *Geochimica et Cosmochimica Acta*, 13(4), 322–334. [https://doi.org/10.1016/0016-7037\(58\)90033-4](https://doi.org/10.1016/0016-7037(58)90033-4)
- Keeling, C. D., Bacastow, R. B., Carter, A. F., Piper, S. C., Whorf, T. P., Heimann, M., et al. (1989). A three-dimensional model of atmospheric CO₂ transport based on observed winds: 1. Analysis of observational data. In D. H. Peterson (Ed.), *Aspects of climate variability in the Pacific and the Western Americas* (Vol. 55, pp. 165–236). AGU. <https://doi.org/10.1029/GM055p0165>
- Kjellström, E. (1998). A three-dimensional global model study of carbonyl sulfide in the troposphere and the lower stratosphere. *Journal of Atmospheric Chemistry*, 29(2), 151–177. <https://doi.org/10.1023/A:1005976511096>
- Kourtidis, K., Kelesis, A., & Petrakakis, M. (2008). Hydrogen sulfide (H₂S) in urban ambient air. *Atmospheric Environment*, 42(32), 7476–7482. <https://doi.org/10.1016/j.atmosenv.2008.05.066>
- Lana, A., Bell, T. G., Simó, R., Vallina, S. M., Ballabrera-Poy, J., Kettle, A. J., et al. (2011). An updated climatology of surface dimethylsulfide concentrations and emission fluxes in the global ocean. *Global Biogeochemical Cycles*, 25(1). <https://doi.org/10.1029/2010GB003850>
- Legrand, M. (1997). Ice-core records of atmospheric sulphur. *Philosophical Transactions of the Royal Society of London*, 352(1350), 241–250. <https://doi.org/10.1098/rstb.1997.0019>
- Legrand, M., Hammer, C., de Angelis, M., Savarino, J., Delmas, R., Clausen, H., & Johnsen, S. J. (1997). Sulfur-containing species (methanesulfonate and SO₂) over the last climatic cycle in the Greenland Ice Core Project (central Greenland) ice core. *Journal of Geophysical Research*, 102(C12), 26663–26679. <https://doi.org/10.1029/97JC01436>
- Mungall, E. L., Croft, B., Lizotte, M., Thomas, J. L., Murphy, J. G., Levasseur, M., et al. (2016). Dimethyl sulfide in the summertime Arctic atmosphere: Measurements and source sensitivity simulations. *Atmospheric Chemistry and Physics*, 16(11), 6665–6680. <https://doi.org/10.5194/acp-16-6665-2016>
- Newhall, C., Self, S., & Robock, A. (2018). Anticipating future Volcanic Explosivity Index (VEI) 7 eruptions and their chilling impacts. *Geosphere*, 14(2), 572–603. <https://doi.org/10.1130/GES01513.1>
- Osman, M. B., Das, S. B., Trusel, L. D., Evans, M. J., Fischer, H., Grieman, M. M., et al. (2019). Industrial-era decline in subarctic Atlantic productivity. *Nature*, 569(7757), 551–555. <https://doi.org/10.1038/s41586-019-1181-8>
- Pataki, D. E., Ehleringer, J. R., Flanagan, L. B., Yakir, D., Bowling, D. R., Still, C. J., et al. (2003). The application and interpretation of Keeling plots in terrestrial carbon cycle research. *Global Biogeochemical Cycles*, 17(1). <https://doi.org/10.1029/2001GB001850>
- Patris, N., Delmas, R. J., & Jouzel, J. (2000). Isotopic signatures of sulfur in shallow Antarctic ice cores. *Journal of Geophysical Research*, 105(D6), 7071–7078. <https://doi.org/10.1029/1999JD900974>
- Patris, N., Delmas, R. J., Legrand, M., de Angelis, M., Ferron, F. A., Stiévenard, M., & Jouzel, J. (2002). First sulfur isotope measurements in central Greenland ice cores along the preindustrial and industrial periods. *Journal of Geophysical Research*, 107(11), ACH6-1–ACH6-11. <https://doi.org/10.1029/2001jd000672>
- Pham, M., Miiller, J., Brasseur, G. P., Granier, C., & Megie, G. (1995). A three-dimensional study of the tropospheric sulfur cycle. *Journal of Geophysical Research*, 100(D12), 61–87. <https://doi.org/10.1029/95JD02095>

- Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., et al. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth and Environment*, 3(1), 168. <https://doi.org/10.1038/s43247-022-00498-3>
- Shindell, D. T., Lamarque, J. F., Schulz, M., Flanner, M., Jiao, C., Chin, M., et al. (2013). Radiative forcing in the ACCMIP historical and future climate simulations. *Atmospheric Chemistry and Physics*, 13(6), 2939–2974. <https://doi.org/10.5194/acp-13-2939-2013>
- Szopa, S., Naik, V., Adhikary, B., Artaxo, P., Berntsen, T., Collins, W. D., et al. (2021). Short-lived climate forcers. In *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 817–922). Cambridge University Press. <https://doi.org/10.1017/9781009157896.008>
- Takahashi, K., Sahoo, Y. V., Nakai, Y., Motoyama, H., & Motizuki, Y. (2022). Annually resolved profiles of $\delta^{34}\text{S}$ and sulfate in shallow ice core DF01 (Dome Fuji, Antarctica) spanning the nineteenth century and their geochemical implications. *Journal of Geophysical Research: Atmospheres*, 127(9). <https://doi.org/10.1029/2021JD036137>
- Twomey, S. (1967). Pollution and the planetary albedo. *Elsevier Atmospheric Environment*, 8(12), 1251–1256. [https://doi.org/10.1016/0004-6981\(74\)90004-3](https://doi.org/10.1016/0004-6981(74)90004-3)
- Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *Journal of the Atmospheric Sciences*, 34(7), 1149–1152. [https://doi.org/10.1175/1520-0469\(1977\)034<1149:TIPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1977)034<1149:TIPOT>2.0.CO;2)
- Wasiuta, V., Norman, A.-L., & Marshall, S. (2006). Spatial patterns and seasonal variation of snowpack sulphate isotopes of the Prince of Wales Icefield, Ellesmere Island, Canada. *Annals of Glaciology*, 43, 390–396. <https://doi.org/10.3189/172756406781812311>
- Watts, S. F. (2000). The mass budgets of carbonyl sulfide, dimethyl sulfide, carbon disulfide and hydrogen sulfide. *Atmospheric Environment*, 34(5), 761–779. [https://doi.org/10.1016/S1352-2310\(99\)00342-8](https://doi.org/10.1016/S1352-2310(99)00342-8)
- Zhai, S., Wang, X., McConnell, J. R., Geng, L., Cole-Dai, J., Sigl, M., et al. (2021). Anthropogenic impacts on tropospheric reactive chlorine since the preindustrial. *Geophysical Research Letters*, 48(14). <https://doi.org/10.1029/2021GL093808>

References From the Supporting Information

- Aiuppa, A., Inguaggiato, S., McGonigle, A. J. S., O'Dwyer, M., Oppenheimer, C., Padgett, M. J., et al. (2005). H_2S fluxes from Mt. Etna, Stromboli, and Vulcano (Italy) and implications for the sulfur budget at volcanoes. *Geochimica et Cosmochimica Acta*, 69(7), 1861–1871. <https://doi.org/10.1016/j.gca.2004.09.018>
- Alexander, B., Thiemens, M. H., Farquhar, J., Kaufman, A. J., Savarino, J., & Delmas, R. J. (2003). East Antarctic ice core sulfur isotope measurements over a complete glacial-interglacial cycle. *Journal of Geophysical Research*, 108(24). <https://doi.org/10.1029/2003jd003513>
- Alexander, B., Park, R. J., Jacob, D. J., & Gong, S. (2009). Transition metal-catalyzed oxidation of atmospheric sulfur: Global implications for the sulfur budget. *Journal of Geophysical Research*, 114(2), D02309. <https://doi.org/10.1029/2008JD010486>
- Allard, P. (1980). Caractéristiques géochimiques des volatils émis par l'éruption volcanique de novembre 1978 dans le rift d'Asal. *Bulletin de la Société Géologique de France*, 7(6), 825–830. <https://doi.org/10.2113/gssgfbull.S7-XXII.6.825>
- Allard, P., Maiorani, A., Tedesco, C. D., Cortecchi, G., & Turi, B. (1991). Isotopic study of the origin of sulfur and carbon in Solfatara fumaroles, Campi Flegrei caldera. *Journal of Volcanology and Geothermal Research*, 48(1–2), 139–159. [https://doi.org/10.1016/0377-0273\(91\)90039-3](https://doi.org/10.1016/0377-0273(91)90039-3)
- Alt, J. C., Shanks, W. C., & Jackson, M. C. (1993). Cycling of sulfur in subduction zones: The geochemistry of sulfur in the Mariana Island Arc and back-arc trough. *Earth and Planetary Science Letters*, 119(4), 477–494. [https://doi.org/10.1016/0012-821X\(93\)90057-G](https://doi.org/10.1016/0012-821X(93)90057-G)
- Amrani, A., Said-Ahmad, W., Shaked, Y., & Kiene, R. P. (2013). Sulfur isotope homogeneity of oceanic DMSP and DMS. *Proceedings of the National Academy of Sciences of the United States of America*, 110(46), 18413–18418. <https://doi.org/10.1073/pnas.1312956110>
- Angleton, G. M., & Bonham, C. D. (1995). Least squares regression vs. Geometric mean regression for ecotoxicology studies. *Applied Mathematics and Computation*, 72(1), 21–32. [https://doi.org/10.1016/0096-3003\(94\)00161-V](https://doi.org/10.1016/0096-3003(94)00161-V)
- Armienta, M. A., de la Cruz-Reyna, S., Soler, A., Cruz, O., Cenicerros, N., & Aguayo, A. (2010). Chemistry of ash-leachates to monitor volcanic activity: An application to Popocatepetl volcano, central Mexico. *Applied Geochemistry*, 25(8), 1198–1205. <https://doi.org/10.1016/j.apgeochem.2010.05.005>
- Barry, P. H., Hilton, D. R., Füre, E., Halldórsson, S. A., & Grönvold, K. (2014). Carbon isotope and abundance systematics of Icelandic geothermal gases, fluids and subglacial basalts with implications for mantle plume-related CO_2 fluxes. *Geochimica et Cosmochimica Acta*, 134, 74–99. <https://doi.org/10.1016/j.gca.2014.02.038>
- Bindeman, I. N., Eiler, J. M., Wing, B. A., & Farquhar, J. (2007). Rare sulfur and triple oxygen isotope geochemistry of volcanogenic sulfate aerosols. *Geochimica et Cosmochimica Acta*, 71(9), 2326–2343. <https://doi.org/10.1016/j.gca.2007.01.026>
- Borisov, O. G. (1970). Source of native volcanogenic sulphur. *Geokhimiya*, 963, 332–343.
- Böttcher, M. E., Brumsack, H. J., & Dürselen, C. D. (2007). The isotopic composition of modern seawater sulfate: I. Coastal waters with special regard to the North Sea. *Journal of Marine Systems*, 67(1–2), 73–82. <https://doi.org/10.1016/j.jmarsys.2006.09.006>
- Burke, A., Moore, K. A., Sigl, M., Nita, D. C., McConnell, J. R., & Adkins, J. F. (2019). Stratospheric eruptions from tropical and extra-tropical volcanoes constrained using high-resolution sulfur isotopes in ice cores. *Earth and Planetary Science Letters*, 521, 113–119. <https://doi.org/10.1016/j.epsl.2019.06.006>
- Burkholder, J. B., Sander, S. P., Abbatt, J. P. D., Barker, J. R., Huie, R. E., Kolb, C. E., et al. (2015). *Chemical kinetics and photochemical data for use in atmospheric studies, Evaluation number 18*, JPL Publication 15-10, Jet Propulsion Laboratory.
- Calhoun, J. A., Bates, T. S., & Charlson, R. J. (1991). Sulfur isotope measurements of submicrometer sulfate aerosol particles over the Pacific Ocean. *Geophysical Research Letters*, 18(10), 1877–1880. <https://doi.org/10.1029/91GL02304>
- Carnat, G., Said-Ahmad, W., Fripiat, F., Wittek, B., Tison, J. L., Uhlir, C., & Amrani, A. (2018). Variability in sulfur isotope composition suggests unique dimethylsulfoniopropionate cycling and microalgae metabolism in Antarctic sea ice. *Communications Biology*, 1(1), 212. <https://doi.org/10.1038/s42003-018-0228-y>
- Chatfield, R. J., & Crutzen, P. J. (1990). Are there interactions of iodine and sulfur species in marine air photochemistry? *Journal of Geophysical Research*, 95(D13), 22319–22341. <https://doi.org/10.1029/jd095id13p22319>
- Chen, Q., Schmidt, J. A., Shah, V., Jaeglé, L., Sherwen, T., & Alexander, B. (2017). Sulfate production by reactive bromine: Implications for the global sulfur and reactive bromine budgets. *Geophysical Research Letters*, 44(13), 7069–7078. <https://doi.org/10.1002/2017GL073812>
- Chen, Q., Sherwen, T., Evans, M., & Alexander, B. (2018). DMS oxidation and sulfur aerosol formation in the marine troposphere: A focus on reactive halogen and multiphase chemistry. *Atmospheric Chemistry and Physics*, 18(18), 13617–13637. <https://doi.org/10.5194/acp-18-13617-2018>
- Chin, M., Jacob, D. J., Gardner, G. M., Foreman-Fowler, M. S., Spiro, P. A., & Savoie, D. L. (1996). A global three-dimensional model of tropospheric sulfate. *Journal of Geophysical Research*, 101(13), 18667–18690. <https://doi.org/10.1029/96jd01221>

- Cole-Dai, J., Budner, D. M., & Ferris, D. G. (2006). High speed, high resolution, and continuous chemical analysis of ice cores using a melter and ion chromatography. *Environmental Science and Technology*, 40(21), 6764–6769. <https://doi.org/10.1021/es061188a>
- Delmelle, P., Bernard, A., Kusakabe, M., Fischer, T. P., & Takano, B. (2000). Geochemistry of the magmatic-hydrothermal system of Kawah Ijen volcano, East Java, Indonesia. *Journal of Volcanology and Geothermal Research*, 97(1–4), 31–53. [https://doi.org/10.1016/S0377-0273\(99\)00158-4](https://doi.org/10.1016/S0377-0273(99)00158-4)
- de Moor, J. M., Fischer, T. P., Sharp, Z. D., Hauri, E. H., Hilton, D. R., & Atudorei, V. (2010). Sulfur isotope fractionation during the May 2003 eruption of Anatahan volcano, Mariana Islands: Implications for sulfur sources and plume processes. *Geochimica et Cosmochimica Acta*, 74(18), 5382–5397. <https://doi.org/10.1016/j.gca.2010.06.027>
- de Moor, J. M., Fischer, T. P., Sharp, Z. D., King, P. L., Wilke, M., Botcharnikov, R. E., et al. (2013). Sulfur degassing at Erta Ale (Ethiopia) and Masaya (Nicaragua) volcanoes: Implications for degassing processes and oxygen fugacities of basaltic systems. *Geochemistry, Geophysics, Geosystems*, 14(10), 4076–4108. <https://doi.org/10.1002/ggge.20255>
- Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial cloud brightening from shipping in subtropical low clouds. *AGU Advances*, 1(1). <https://doi.org/10.1029/2019av000111>
- Fry, B., Silva, S. R., Kendall, C., & Anderson, R. K. (2002). Oxygen isotope corrections for online $\delta^{34}\text{S}$ analysis. *Rapid Communications in Mass Spectrometry*, 16(9), 854–858. <https://doi.org/10.1002/rcm.651>
- Galí, M., & Simó, R. (2010). Occurrence and cycling of dimethylated sulfur compounds in the Arctic during summer receding of the ice edge. *Marine Chemistry*, 122(1–4), 105–117. <https://doi.org/10.1016/j.marchem.2010.07.003>
- Galí, M., Levasseur, M., Devred, E., Simó, R., & Babin, M. (2018). Sea-surface dimethylsulfide (DMS) concentration from satellite data at global and regional scales. *Biogeosciences*, 15(11), 3497–3519. <https://doi.org/10.5194/bg-15-3497-2018>
- Gautier, E., Savarino, J., Erbland, J., & Farquhar, J. (2018). SO_2 oxidation kinetics leave a consistent isotopic imprint on volcanic ice core sulfate. *Journal of Geophysical Research: Atmospheres*, 123(17), 9801–9812. <https://doi.org/10.1029/2018JD028456>
- Giggenbach, W. F., & Matsuo, S. (1991). Evaluation of results from second and third IAVCEI field workshops on volcanic gases, Mt Usu, Japan, and White Island, New Zealand. *Applied Geochemistry*, 6(2), 125–141. [https://doi.org/10.1016/0883-2927\(91\)90024-J](https://doi.org/10.1016/0883-2927(91)90024-J)
- Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., & Wang, X. (2012). The model of emissions of gases and aerosols from nature version 2.1 (MEGAN2.1): An extended and updated framework for modeling biogenic emissions. *Geoscientific Model Development*, 5(6), 1471–1492. <https://doi.org/10.5194/gmd-5-1471-2012>
- Gutierrez-Rodríguez, A., Pillet, L., Biard, T., Said-Ahmad, W., Amrani, A., Simó, R., & Not, F. (2017). Dimethylated sulfur compounds in symbiotic protists: A potentially significant source for marine DMS(P). *Limnology & Oceanography*, 62(3), 1139–1154. <https://doi.org/10.1002/lno.10491>
- Hattori, S., Iizuka, Y., Alexander, B., Ishino, S., Fujita, K., Zhai, S., et al. (2021). Isotopic evidence for acidity-driven enhancement of sulfate formation after SO_2 emission control. *Science Advances*, 7(5). <https://doi.org/10.5281/zenodo.3403111>
- Heald, C. L., Ridley, D. A., Kroll, J. H., Barrett, S. R. H., Cady-Pereira, K. E., Alvarado, M. J., & Holmes, C. D. (2014). Contrasting the direct radiative effect and direct radiative forcing of aerosols. *Atmospheric Chemistry and Physics*, 14(11), 5513–5527. <https://doi.org/10.5194/acp-14-5513-2014>
- Holland, H. D. (1978). *The chemistry of the atmosphere and oceans*. Wiley-Interscience.
- Huang, J., & Jaeglé, L. (2017). Wintertime enhancements of sea salt aerosol in polar regions consistent with a sea ice source from blowing snow. *Atmospheric Chemistry and Physics*, 17(5), 3699–3712. <https://doi.org/10.5194/acp-17-3699-2017>
- Jaeglé, L., Quinn, P. K., Bates, T. S., Alexander, B., & Lin, J. T. (2011). Global distribution of sea salt aerosols: New constraints from in situ and remote sensing observations. *Atmospheric Chemistry and Physics*, 11(7), 3137–3157. <https://doi.org/10.5194/acp-11-3137-2011>
- Kasasaku, K., Minari, T., Mukai, H., & Murano, K. (1999). Stable sulfur isotope ratios of the gases from Mt. Sakurajima and Satsuma-Iwojima volcanoes - Assessment of volcanic sulfur on rainfall sulfate in Kagoshima Prefecture. *Nippon Kagaku Kaishi*(7), 479–486. <https://doi.org/10.2165/00003495-199141040-00008>
- Kay, J. E., & Gettelman, A. (2009). Cloud influence on and response to seasonal Arctic sea ice loss. *Journal of Geophysical Research*, 114(18), D18204. <https://doi.org/10.1029/2009JD011773>
- Kettle, A. J., Andreae, M. O., Amouroux, D., Andreae, T. W., Bates, T. S., Berresheim, H., et al. (1999). A global database of sea surface dimethylsulfide (DMS) measurements and a procedure to predict sea surface DMS as a function of latitude, longitude, and month. *Global Biogeochemical Cycles*, 13(2), 399–444. <https://doi.org/10.1029/1999GB900004>
- Krouse, H. R., & Grinenko, V. A. (1991). Stable isotopes: Natural and anthropogenic. In *Sulphur in the environment* (Vol. SCOPE 43). J. Wiley and Sons.
- Labidi, J., Cartigny, P., Birck, J. L., Assayag, N., & Bourrand, J. J. (2012). Determination of multiple sulfur isotopes in glasses: A reappraisal of the MORB $\delta^{34}\text{S}$. *Chemical Geology*, 334, 189–198. <https://doi.org/10.1016/j.chemgeo.2012.10.028>
- Labidi, J., Cartigny, P., & Moreira, M. (2013). Non-chondritic sulphur isotope composition of the terrestrial mantle. *Nature*, 501(7466), 208–211. <https://doi.org/10.1038/nature12490>
- Latimer, R. N. C., & Martin, R. V. (2019). Interpretation of measured aerosol mass scattering efficiency over North America using a chemical transport model. *Atmospheric Chemistry and Physics*, 19(4), 2635–2653. <https://doi.org/10.5194/acp-19-2635-2019>
- Laws, E. (1997). *Mathematical methods for oceanographers*. John Wiley.
- Leck, C., & Persson, C. (1996). The central Arctic Ocean as a source of dimethyl sulfide seasonal variability in relation to biological activity. *Tellus Series B Chemical and Physical Meteorology*, 48(2), 156–177. <https://doi.org/10.3402/tellusb.v48i2.15834>
- le Gendre, E., Martin, E., Villemant, B., Cartigny, P., & Assayag, N. (2017). A simple and reliable anion-exchange resin method for sulfate extraction and purification suitable for multiple O- and S-isotope measurements. *Rapid Communications in Mass Spectrometry*, 31(1), 137–144. <https://doi.org/10.1002/rcm.7771>
- Lewicki, J. L., Fischer, T., & Williams, S. N. (2000). Chemical and isotopic compositions of fluids at Cumbal Volcano, Colombia: Evidence for magmatic contribution. *Bulletin of Volcanology*, 62(4–5), 347–361. <https://doi.org/10.1007/s004450000100>
- Li, J., Michalski, G., Davy, P., Harvey, M., Katzman, T., & Wilkins, B. (2018). Investigating source contributions of size-aggregated aerosols collected in Southern Ocean and Baring Head, New Zealand using sulfur isotopes. *Geophysical Research Letters*, 45(8), 3717–3727. <https://doi.org/10.1002/2018GL077353>
- Li, S., & Barrie, L. A. (1993). Biogenic sulfur aerosol in the Arctic troposphere: 1. Contributions to total sulfate. *Journal of Geophysical Research*, 98(D11), 613–633. <https://doi.org/10.1029/93JD02234>
- Lin, C. T., Baker, A. R., Jickells, T. D., Kelly, S., & Lesworth, T. (2012). An assessment of the significance of sulphate sources over the Atlantic Ocean based on sulphur isotope data. *Atmospheric Environment*, 62, 615–621. <https://doi.org/10.1016/j.atmosenv.2012.08.052>
- Liotta, M., Rizzo, A., Paonita, A., Caracausi, A., & Martelli, M. (2012). Sulfur isotopic compositions of fumarolic and plume gases at Mount Etna (Italy) and inferences on their magmatic source. *Geochemistry, Geophysics, Geosystems*, 13(5), Q05015. <https://doi.org/10.1029/2012GC004118>

- Loeb, N. G., Doelling, D. R., Wang, H., Su, W., Nguyen, C., Corbett, J. G., et al. (2018). Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) top-of-atmosphere (TOA) edition-4.0 data product. *Journal of Climate*, *31*(2), 895–918. <https://doi.org/10.1175/JCLI-D-17-0208.1>
- Longhurst, A. (1998). *Ecological geography of the sea*. Academic Press.
- Loose, B., McGillis, W. R., Schlosser, P., Perovich, D., & Takahashi, T. (2009). Effects of freezing, growth, and ice cover on gas transport processes in laboratory seawater experiments. *Geophysical Research Letters*, *36*(5), L05603. <https://doi.org/10.1029/2008GL036318>
- Marini, L., Gambardella, B., Principe, C., Arias, A., Brombach, T., & Hunziker, J. C. (2000). Characterization of magmatic sulfur in the Aegean island arc by means of the $\delta^{34}\text{S}$ values of fumarolic H_2S , elemental S, and hydrothermal gypsum from Nisyros and Milos islands. *Earth and Planetary Science Letters*, *200*(1-2), 15–31. [https://doi.org/10.1016/S0012-821X\(02\)00611-8](https://doi.org/10.1016/S0012-821X(02)00611-8)
- Martin, E., Bekki, S., Ninin, C., & Bindeman, I. (2014). Volcanic sulfate aerosol formation in the troposphere. *Journal of Geophysical Research: Atmospheres*, *119*(22), 12660–12673. <https://doi.org/10.1002/2014JD021915>
- Martin, R. S., Roberts, T. J., Mather, T. A., & Pyle, D. M. (2009). The implications of H_2S and H_2 kinetic stability in high-T mixtures of magmatic and atmospheric gases for the production of oxidized trace species (e.g., BrO and NO_x). *Chemical Geology*, *263*(1–4), 143–150. <https://doi.org/10.1016/j.chemgeo.2008.12.028>
- Mather, T. A., McCabe, J. R., Rai, V. K., Thiemens, M. H., Pyle, D. M., Heaton, T. H. E., et al. (2006). Oxygen and sulfur isotopic composition of volcanic sulfate aerosol at the point of emission. *Journal of Geophysical Research*, *111*(18), D18205. <https://doi.org/10.1029/2005JD006584>
- Matrai, P. A., & Vernet, M. (1997). Dynamics of the vernal bloom in the marginal ice zone of the Barents Sea: Dimethyl sulfide and dimethylsulfoniopropionate budgets. *Journal of Geophysical Research C: Oceans*, *102*(C10), 22965–22979. <https://doi.org/10.1029/96JC03870>
- McCoy, D. T., Bender, F. A. M., Grosvenor, D. P., Mohrmann, J. K., Hartmann, D. L., Wood, R., & Field, P. R. (2018). Predicting decadal trends in cloud droplet number concentration using reanalysis and satellite data. *Atmospheric Chemistry and Physics*, *18*(3), 2035–2047. <https://doi.org/10.5194/acp-18-2035-2018>
- McDuffie, E. E., Smith, S. J., O'Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E. A., et al. (2020). A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): An application of the Community Emissions Data System (CEDS). *Earth System Science Data*, *12*(4), 3413–3442. <https://doi.org/10.5194/essd-12-3413-2020>
- Millet, D. B., Baasandorj, M., Farmer, D. K., Thornton, J. A., Baumann, K., Brophy, P., et al. (2015). A large and ubiquitous source of atmospheric formic acid. *Atmospheric Chemistry and Physics*, *15*(11), 6283–6304. <https://doi.org/10.5194/acp-15-6283-2015>
- Mizutani, Y., & Sugiura, T. (1982). Variations in chemical and isotopic compositions of fumarolic gases from Showashinzan volcano, Hokkaido, Japan. *Geochemical Journal*, *16*(2), 63–71. <https://doi.org/10.2343/geochemj.16.63>
- Nielsen, H., Pilot, J., Grinenko, L. N., Grinenko, V. A., Lein, A. Y., Smith, J. W., & Pankina, R. G. (1991). Lithospheric sources of sulphur. In H. R. Krouse & V. A. Grinenko (Eds.), *Stable isotopes: Natural and anthropogenic sulphur in the environment*. John Wiley.
- Norman, A. L., Barrie, L. A., Toom-Sauntry, D., Sirois, A., Krouse, H. R., Li, S. M., & Sharma, S. (1999). Sources of aerosol sulphate at alert: Apportionment using stable isotopes. *Journal of Geophysical Research*, *104*(D9), 11619–11631. <https://doi.org/10.1029/1999JD900078>
- Norman, A. L., Belzer, W., & Barrie, L. (2004). Insights into the biogenic contribution to total sulphate in aerosol and precipitation in the Fraser Valley afforded by isotopes of sulphur and oxygen. *Journal of Geophysical Research*, *109*(5), D05311. <https://doi.org/10.1029/2002jd003072>
- Novak, G. A., Fite, C. H., Holmes, C. D., Veres, P. R., Neuman, J. A., Faloon, I., et al. (2021). Rapid cloud removal of dimethyl sulfide oxidation products limits SO₂ and cloud condensation nuclei production in the marine atmosphere. *Proceedings of the National Academy of Sciences*, *118*(42), e2110472118. <https://doi.org/10.1073/pnas.2110472118/-DCSupplemental>
- Nriagu, J. O., & Coker, R. D. (1978). Isotopic composition of sulfur in precipitation within the Great Lakes Basin. *Tellus*, *30*(4), 365–375. <https://doi.org/10.1111/j.2153-3490.1978.tb00852.x>
- Oduro, H., van Alstyne, K. L., & Farquhar, J. (2012). Sulfur isotope variability of oceanic DMSP generation and its contributions to marine biogenic sulfur emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(23), 9012–9016. <https://doi.org/10.1073/pnas.1117691109>
- Park, R. J. (2004). Natural and transboundary pollution influences on sulfate-nitrate-ammonium aerosols in the United States: Implications for policy. *Journal of Geophysical Research*, *109*(D15), D15204. <https://doi.org/10.1029/2003jd004473>
- Perrette, M., Yool, A., Quartly, G. D., & Popova, E. E. (2011). Near-ubiquity of ice-edge blooms in the Arctic. *Biogeosciences*, *8*(2), 515–524. <https://doi.org/10.5194/bg-8-515-2011>
- Rafter, T. A., Wilson, S. H., & Shilton, B. W. (1958). Sulphur isotopic measurements on the discharge from fumaroles on White Island. *Sulphur isotopic variations in nature* (Vol. 1, pp. 154–171). N. J. Z. Sci.
- Rees, C. E., Jenkins, W. J., & Monster, J. (1978). The sulphur isotopic composition of ocean water sulphate. *Geochimica et Cosmochimica Acta*, *42*(4), 377–381. [https://doi.org/10.1016/0016-7037\(78\)90268-5](https://doi.org/10.1016/0016-7037(78)90268-5)
- Robinson, B. W. (1985). Sulphur and sulphate-oxygen isotopes in New Zealand geothermal systems and volcanic discharges. In *Studies on sulphur isotope variations in nature* (pp. 31–48). International Atomic Energy Agency.
- Rye, R. O., Luhr, J. F., & Wasserman, M. D. (1984). Sulfur and oxygen isotopic systematics of the 1982 eruptions of El Chichón Volcano. *Journal of Volcanology and Geothermal Research*, *23*(1–2), 109–123. [https://doi.org/10.1016/0377-0273\(84\)90058-1](https://doi.org/10.1016/0377-0273(84)90058-1)
- Sakai, H. (1957). Fractionation of sulphur isotopes in nature. *Geochimica et Cosmochimica Acta*, *12*(1–2), 160–169. [https://doi.org/10.1016/0016-7037\(57\)90025-x](https://doi.org/10.1016/0016-7037(57)90025-x)
- Sakai, H., Casadevall, T. J., & Moore, J. G. (1982). Chemistry and isotope ratios of sulfur in basalts and volcanic gases at Kilauea Volcano, Hawaii. *Geochimica et Cosmochimica Acta*, *46*(5), 729–738. [https://doi.org/10.1016/0016-7037\(82\)90024-2](https://doi.org/10.1016/0016-7037(82)90024-2)
- Sakai, H., & Nagasawa, H. (1958). Fractionation of sulphur isotopes in volcanic gases. *Geochimica et Cosmochimica Acta*, *15*(1–2), 32–39. [https://doi.org/10.1016/0016-7037\(58\)90007-3](https://doi.org/10.1016/0016-7037(58)90007-3)
- Sanusi, A. A., Norman, A. L., Burrige, C., Wadleigh, M., & Tang, W. W. (2006). Determination of the S isotope composition of methanesulfonic acid. *Analytical Chemistry*, *78*(14), 4964–4968. <https://doi.org/10.1021/ac0600048>
- Sharma, S., Chan, E., Ishizawa, M., Toom-Sauntry, D., Gong, S. L., Li, S. M., et al. (2012). Influence of transport and ocean ice extent on biogenic aerosol sulfur in the Arctic atmosphere. *Journal of Geophysical Research*, *117*(12). <https://doi.org/10.1029/2011JD017074>
- Siegel, K., Karlsson, L., Zieger, P., Baccarini, A., Schmale, J., Lawler, M., et al. (2021). Insights into the molecular composition of semi-volatile aerosols in the summertime central Arctic Ocean using FIGAERO-CIMS. *Environmental Science: Atmosphere*, *1*(4), 161–175. <https://doi.org/10.1039/d0ea00023j>
- Stjern, C. W., Muri, H., Ahlm, L., Boucher, O., Cole, J. N. S., Ji, D., et al. (2018). Response to marine cloud brightening in a multi-model ensemble. *Atmospheric Chemistry and Physics*, *18*(2), 621–634. <https://doi.org/10.5194/acp-18-621-2018>
- Symonds, R. B., Janik, C. J., Evans, W. C., Ritchie, B. E., Counce, D., Poreda, R. J., & Iven, M. (2003). Scrubbing masks magmatic degassing during repose at cascade-range and Aleutian-Arc Volcanoes. *US Geological Survey Open-File Report*, *03*(435).
- Tian, L., & Curry, J. A. (1989). Cloud overlap statistics 1 2. *Journal of Geophysical Research*, *94*(D7), 9925–9935.

- Torssander, P. (1988). Sulfur isotope ratios of Icelandic lava incrustations and volcanic gases. *Journal of Volcanology and Geothermal Research*, 35(3), 227–235. [https://doi.org/10.1016/0377-0273\(88\)90019-4](https://doi.org/10.1016/0377-0273(88)90019-4)
- Vinogradov, V. I. (1980). Isotopic composition of elements and the problem of mantle degassification and the formation of the gas-water cover of the Earth. *Degazatsiya Zemli i Geotektonika*, 1, 23–30.
- Wadleigh, M. A. (2004). Sulphur isotopic composition of aerosols over the Western North Atlantic Ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(5), 817–825. <https://doi.org/10.1139/F04-073>
- Wang, X., Jacob, D. J., Eastham, S. D., Sulprizio, M. P., Zhu, L., Chen, Q., et al. (2019). The role of chlorine in global tropospheric chemistry. *Atmospheric Chemistry and Physics*, 19(6), 3981–4003. <https://doi.org/10.5194/acp-19-3981-2019>
- Wasserman, L. (2004). The bootstrap. In *All of statistics* (pp. 107–118). Springer Science+Business Media. https://doi.org/10.1007/978-0-387-21736-9_8
- Webb, M. J., Andrews, T., Bodas-Salcedo, A., Bony, S., Bretherton, C. S., Chadwick, R., et al. (2017). The Cloud Feedback Model Intercomparison Project (CFMIP) contribution to CMIP6. *Geoscientific Model Development*, 10(1), 359–384. <https://doi.org/10.5194/gmd-10-359-2017>
- Williams, S. N., Sturchio, N. C., Calvache, V. M. L., Mendez, F. R., Londoño, C. A., & García, P. N. (1990). Sulfur dioxide from Nevado del Ruiz volcano, Colombia: Total flux and isotopic constraints on its origin. *Journal of Volcanology and Geothermal Research*, 42(1–2), 53–68. [https://doi.org/10.1016/0377-0273\(90\)90069-r](https://doi.org/10.1016/0377-0273(90)90069-r)
- Wood, R. (2021). Assessing the potential efficacy of marine cloud brightening for cooling Earth using a simple heuristic model. *Atmospheric Chemistry and Physics*, 21(19), 14507–14533. <https://doi.org/10.5194/acp-21-14507-2021>
- Zemmelink, H. J., Dacey, J. W. H., Houghton, L., Hints, E. J., & Liss, P. S. (2008). Dimethylsulfide emissions over the multi-year ice of the Western Weddell Sea. *Geophysical Research Letters*, 35(6), L06603. <https://doi.org/10.1029/2007GL031847>