Contents lists available at ScienceDirect



Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Sulfur dioxide from the atmospheric chemistry experiment (ACE) satellite



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W.D. Cameron^{a,*}, P. Bernath^{a,b,c}, C. Boone^c

^a Department of Physics, Old Dominion University, Norfolk, VA, United States ^b Department of Chemistry, Old Dominion University, Norfolk, VA, United States ^c Department of Chemistry, University of Waterloo, Waterloo, Ontario, Canada

ARTICLE INFO

Article history: Received 30 April 2020 Revised 16 September 2020 Accepted 16 September 2020 Available online 22 September 2020

Key Words: Sulfur dioxide Atmospheric Chemistry Experiment Fourier transform spectrometer volcanic plume limb sounder

1. Introduction

Sulfur dioxide is one of the primary gases associated with atmospheric aerosol formation [1]. Sulfate aerosols significantly impact the climate through scattering and absorption of solar radiation, as well as serving as cloud condensation nuclei [2]. The global distribution of SO₂ VMRs, resolved by altitude and latitude, including volcanic activity, helps quantify the role SO₂ plays in the Earth's atmosphere.

There are two primary sources of atmospheric SO₂: human activity and volcanic eruptions, with volcanic eruptions being the primary mechanism for SO₂ injection into the lower stratosphere. Human activity has resulted in notable changes in SO₂ production over the last two decades [3]. SO₂ produced by human activity typically reaches no higher than the tropopause. The potential exists for anthropogenic SO₂ to occasionally reach the stratosphere in conjunction with the monsoon phenomena; however, the contribution to stratospheric SO₂ appears to be minor [4]. Volcanic activity can inject SO₂ into the stratosphere as well as the troposphere; but volcanic eruptions that inject significant amounts of SO₂ into the stratosphere are rare, on the order of five to ten eruptions a year [5]. Yet the volcanic contribution to the entire atmospheric

* Corresponding author.

E-mail address: wcame002@odu.edu (W.D. Cameron).

ABSTRACT

The version 4.0 dataset from the Atmospheric Chemistry Experiment – Fourier Transform Spectrometer (ACE-FTS) on SCISAT, released in March of 2019, has sulfur dioxide (SO₂) volume mixing ratio (VMR) profiles as a routine data product. From this dataset, global SO₂ distributions between the altitudes of 10.5 km and 23.5 km are analyzed. The global distribution of all SO₂ VMR data by altitude is broken down into 30° and 5° latitude zones. Seasonality of the global SO₂ distribution is explored. Volcanic SO₂ plumes are isolated in the dataset and compared with extinction data from the ACE-FTS Imager.

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 SO_2 budget is significant; while volcanic emissions may only make up 10% of the global SO_2 source to the atmosphere, due to the longevity of SO_2 and aerosols in the stratosphere they contribute as much as 26% of the SO_2 burden, and are responsible for 14% of the sulfate aerosol burden [6].

In the troposphere, the primary sinks for SO₂ are gas phase oxidation by reaction with OH and aqueous phase oxidation within cloud droplets by reaction with H_2O_2 or O_3 [7]. Ultimately tropospheric SO₂ returns to the surface from the troposphere in a matter of days or weeks in precipitation. In the stratosphere SO₂ eventually oxidizes and ends up in sulfate aerosol, slowly sinking due to gravity with sedimentation velocities on the order of 100 m/month. Stratospheric SO₂ in non-oxidized molecular form is much more persistent than in the troposphere, often remaining confined in latitude bands for one to two months after a volcanic eruption and staying aloft in the stratosphere for several months [8]. A single large volcanic eruption can have a climactic impact lasting 2–3 years [9].

Atmospheric SO₂ can be measured from the Earth's surface, or by balloons or aircraft within the atmosphere using direct or remote sensors, or by remote sensing from spacecraft. Ground based observations are carried out by infrared (IR) and ultraviolet (UV) spectroscopy. Aircraft can take sensors aloft, some even reaching into the stratosphere, with the ability to precisely determine in situ SO₂ VMRs with a precision of 2 parts per trillion (ppt) [4]. Ground and airborne sensors do not provide a global perspective.



Fig. 1. ACE-FTS 2018 occultations by latitude and month. Note that due to the horizontal axis units being occultations, not time, the monthly boundary divisions are not uniform.

Spacecraft can observe SO_2 on a global scale from orbit, operating in the microwave, IR or UV, using either nadir or limb observations. Nadir viewing sensors can collect data across a wide swath; the Ozone Monitoring Instrument (OMI) on the Aura spacecraft has shown the ability to reliably map anthropogenic SO_2 sources on the Earth's surface that produce 70 kT y⁻¹ or more [10] as well as passive (non-erupting) SO_2 flux from volcanoes [11]. The Tropospheric Monitoring Instrument (TROPOMI) aboard the Sentinel-5 Precursor satellite has improved on OMI [12]. In general, nadir sensors are unable to resolve observations by altitude; there are notable exceptions such as the work of Yang et al. [13].

Limb sounders can provide a global distribution of SO₂ concentrations resolved by altitude and location, although the geometry of limb observations requires multiple passes to cover the area that a nadir observer can cover in one pass, and if observations at a specific location at a specific time are desired this may not be possible. The Microwave Limb Sounder (MLS) instrument on the Upper Atmosphere Research Satellite (UARS) made a comprehensive plot of the SO₂ plume from the eruption of Mount Pinatubo in the Philippines in 1991, including tracking the decay of SO₂ levels for a period of about six months after the eruption [8]. The next MLS generation on the Aura satellite has demonstrated the ability to track volcanic SO₂ plumes with VMRs greater than 400 - 500 ppt [14]. The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), a limb sounder on the Envisat satellite, produced an SO₂ data product similar to ACE-FTS and direct comparisons have been made. MIPAS ceased operation on 8 April 2012 [15]. The data obtained for the present study are from a limb sounder, the Fourier transform spectrometer on the Atmospheric Chemistry Experiment (ACE), also known as SCISAT.

2. Observations and retrievals

Launched by NASA on 12 August 2003, ACE continues to function well. The orbit is nearly circular, inclined 73.9° to the equator, and has an altitude of 650 km. The instrument providing the primary data for this research is a high spectral resolution (0.02 cm⁻¹) Fourier Transform Spectrometer (FTS) operating in the 750 cm⁻¹ to 4400 cm⁻¹ wavenumber range. Observations are made by solar occultation (sunrises and sunsets), recording atmospheric transmission spectra of the limb. The period of the orbit is 97.6 min, creating a maximum of about 30 occultations in a 24-hour period [16]. Fig. 1 shows the occultation-latitude plot for 2018.

The limb interferograms are processed on the ground to provide altitude profiles of temperature, pressure and VMRs for more than 40 molecules and related isotopologues [17], including SO₂. The inclination angle of the orbit was chosen so the latitude of the observation locations will be repeated annually [16]. For the data set retrieved for version 4.0 of ACE-FTS processing [18], the SO₂ microwindows used are provided in Table 1. Version 4.0, released in March 2019, uses spectroscopic line parameters from the HITRAN 2016 database [19]. Interferers in this microwindow set whose VMR profiles were retrieved simultaneously were the isotopologues HDO, ¹⁸OCO, and ¹³CH₄. VMR profiles for all other interferers were fixed to the results of previous retrievals. Version 4.0 SO₂ data are provided between 9.5 and 23.5 km in 1 km increments. The lower altitude is limited by interfering molecules such as water and methane; the upper altitude is limited by signal-to-noise ratio. The ACE-FTS altitude resolution in this range is typically about 2.5 km. Due to high relative statis-

Center Frequency (cm ⁻¹)	Microwindow Width (cm ⁻¹)	Lower Altitude (km)	Upper Altitude (km)
1357.44	0.35	9	24
1359.47	0.30	9	18
1361.81	0.45	12	24
1370.18	0.55	10	24
1371.45	0.50	10	24
1376.95	1.30	12	24





Fig. 2. Mean SO₂ VMR resolved by altitude, horizontal bars show 1 standard deviation.

tical errors (SO₂ VMR error/SO₂ VMR) for observations at lower altitudes, the plots shown begin at 11.5 km where typical fractional errors on the order of 5 sharply drop to about 0.7, gradually increasing to a maximum of about 1.5 at 20.5 km, decreasing above 20.5 km to about 0.9 at the top of the altitude range.

ACE SO₂ data, February 2004 to December 2019, were used. This paper describes two studies of the ACE SO₂ observations: (1) a quantification of the typical background abundances of SO₂, and (2) an examination of volcanic SO₂ plumes. The altitude range of interest is the Upper Troposphere/ Lower Stratosphere (UT/LS), because of high concentrations of stratospheric aerosols [20]. High SO₂ concentrations from significant volcanic eruptions show up as anomalous data, so the first step was to find a filter/discriminator to differentiate between normal background SO₂ and volcanic plumes. Empirically, a three Median Absolute Deviation (MAD) filter was found to be suitable. Data within 3 MADs are likely to be background SO₂; any data beyond 3 MADs are likely of volcanic origin or non-physical. Non-physical data points appeared in the data set, showing obvious discontinuities when comparing datapoints within the same data bin. Such points were manually deleted. Deletion of data points only occurred within the bins used to plot SO_2 VMR or extinction in volcanic plumes. A data bin is defined here as the data points over a one-month time period at a specific latitude (5° wide) and altitude (1 km high). The plotted data at a given altitude and latitude is the mean of the corresponding data bin. Only individual points in a bin, not the entire bin, were deleted. A month of data is on the order of 500 occultations. In total 16 occultations had data points manually deleted; in each case only the data at one or occasionally two altitudes were deleted, not the entire occultation.

For observations of volcanic plumes, extinction data from one of the ACE-FTS Imagers were also used in order to detect volcanic sulfate aerosols in regions exhibiting enhanced SO_2 levels. The ACE-FTS Imagers are filtered solar imagers, operating in two wavelength bands, in the visible range at 525 nm and the near infrared at 1020 nm. For this research, the near infrared imager operating at 1020 nm was used [21]. No systematic filtering or processing of the imager data was done; in isolated cases obvious outlier data were manually deleted.



Fig. 3. Mean SO₂ VMR resolved by altitude, divided into latitude zones, horizontal bars show 1 standard deviation. Top left 0° - 30°S, top right 0° - 30°N, middle left 30°S - 60°S, middle right 30°N - 60°N, bottom left 60°S - 90°S, bottom right 60°N - 90°N.



Fig. 4. Mean SO₂ VMR (in ppt), resolved by altitude and latitude.

Table 2						
Volcanic SO ₂	plumes	detected	by	ACE	[5]	

Volcano Name	Lat/Long	Eruption Date	SO ₂ Emitted (kt)	SO ₂ Plume Height (km)
Manam	4.1°S, 145.0°E	27 Jan 2005	140	24
Rabaul	4.3°S, 152.2°E	7 Oct 2006	300	18
Okmok	53.4°N, 168.1°W	12 Jul 2008	150	15
Sarychev	48.1°N, 153.2°W	12 Jun 2009	1200	17
Grimsvotn	64.4°N, 17.3°W	21 May 2011	300	12
Puyehue-Cordon Caulle	40.6°S, 72.1°W	4 Jun 2011	200	14
Nabro	13.4°N, 41.7°E	13 Jun 2011	3650	18
Kelut	7.9°S, 112.3°E	13 Feb 2014	200	19
Calbuco	41.3°S, 72.6°W	22 Apr 2015	400	20
Raikoke	48.3°N, 153.3°E	22 Jun 2019	1500	23

3. Results and discussion

Fig. 2 is the mean of all background SO₂ data, resolved by altitude. Data from an ACE-FTS SO₂ research product (generated prior to v4.0 used in this study) were employed in a study by Rollins et al. [22] who found agreement within 10–15 ppt compared to results from MIPAS. Fig. 3 from that paper compared ACE-FTS results to aircraft in situ measurements taken by NASA's VIRGAS experiment (Volcano-plume Investigation Readiness and Gas-phase and Aerosol Sulfur), showing agreement within 5 ppt.

Given the variability of the tropopause by latitude, the data of Fig. 2 can be broken down into latitude zones. Fig. 3 divides the data from Fig. 2 into 30° latitude zones. The plots covering from the equator to 30° North or South are almost identical, both showing an increase in SO₂ VMRs as the altitude increases above 20 km. The remaining plots are similar above 14 km, but the Northern Hemisphere clearly shows higher concentrations of SO₂ in the upper troposphere between 10 and 14 km, highlighting the presence of major anthropogenic sources from North America, Europe, the Middle East and China.

Fig. 4 is the mean of all background SO₂ data, resolved by altitude and latitude, with volcanic activity filtered out through a 3 MAD filter. The highest concentration is about 35 ppt, which occurs in the upper troposphere in the 30°N-60°N latitude range. A similar plot was provided by Höpfner et al. [15] based on bias corrected MIPAS data. Hopfner et al. also see enhanced SO₂ near the equator above 18 km.

Fig. 5 resolves global background SO₂ VMRs by altitude, latitude and season. Similar MIPAS results show some seasonality; specifically, MIPAS shows the summer VMR at 10 km altitude is 80–100 ppt in the mid and upper northern latitudes; this anomaly is inconsistent with the ACE data depicted in Fig. 5. Both MIPAS and ACE show the highest SO₂ concentration at the bottom of the UTLS (around 10 km altitude); MIPAS shows VMRs at around 50– 60 ppt in that region, while ACE shows around 30–40 ppt. Both MI-PAS and ACE show the VMR decreasing as altitude increases with the lower layer gone by around 16 km, and then the VMR is constant at around 10 ppt. Note the seasonality to Fig. 5: in Jun-Aug a slightly higher concentration of SO₂ forms at 24 km near the South Pole and persists into Sep-Nov; in Dec-Feb a slightly higher con-



Fig. 5. Seasonal mean SO₂ VMRs (in ppt) resolved by altitude and latitude. Top left Mar-May, top right Jun-Aug, bottom left Sep-Nov, bottom right Dec-Feb.



Fig. 6. Sarychev volcano eruption. Eruption occurred 12 Jun 2009 at 48.1°N, 153.2°W; July 2009 data shown. Left SO₂ VMR; right aerosol extinction.













Fig. 7. Raikoke erupted on 22 Jun 2019 at 48.3°N, 153.3°E; the SO₂ plume drifted to 80°N by September 2019. Left column SO₂ VMR, right column aerosol extinction. Top row Jul 2019 data, middle row Sep 2019 data, bottom row Oct 2019 data. Note the Ulawun volcano erupted at 5.05°S 151.33°E between June and Oct 2019 but does not significantly appear in the plots.

centration of SO₂ forms at 24 km near the North Pole and persists into Mar-May. We suspect these phenomena are due to descending air within the polar vortex. The suspected source of the SO₂ enhancement is atmospheric OCS. There is an enhancement feature above 22 km near the equator. Some research data retrievals indicate this SO₂ enhancement to be the bottom of a larger, higher feature. Future ACE-FTS data processing will explore this topic. In Jun-Aug and Sep-Nov, a slightly higher concentration of SO₂ spans the equatorial region at 13–14 km.

The hunt for volcanic SO₂ plumes began by studying the Smithsonian Institution's Global Volcanism Program webpage at http: //volcano.si.edu/ [5]. The search focused on volcanic emissions where the SO₂ plume reached 10 km or more in altitude. Those volcanic eruptions where the SO₂ plume height met or exceeded 10 km and the mass of SO₂ emissions met or exceeded 80 kt are typically visible in a plot of SO2 VMR resolved by altitude and latitude. At the time of writing 113 volcanic eruptions in the Smithsonian database meet both criteria. For reference, the average SO₂ emission for the 113 volcanoes with SO₂ plume heights at or beyond 10 km is 421 kt; 37 out of the 113 eruptions exceed 80 kt. The final discriminator in locating a specific volcanic plume is whether the ACE-FTS measured near the plume latitude between the time of eruption and up to about 2 months afterwards. For example, the eruption of the Kasatochi volcano in August of 2008 in Alaska's Aleutian Islands produced about 2000 kt of SO₂ with a plume height of 15 km; but was not viewed by ACE occultations. The 10 eruptions that meet all the preceding criteria, including timely and nearby ACE occultations, are listed in Table 2.

In order to obtain enough limb observations to observe a volcanic plume, one month of data are used. Plumes from the larger eruptions were clearly visible two months after the eruption. Local VMRs in the 500–1000 ppt range are typical for the eruptions depicted. The latitudes of the plumes match the latitudes of the eruptions with slight shifts becoming more pronounced over time. Plume altitudes in Table 2 are in general agreement with the altitudes from the Smithsonian database. To the right of each SO_2 plot is a similar plot of the atmospheric extinction from the near infrared imager at 1020 nm for the same time period. The altitudelatitude distribution plot showing the Sarychev volcanic eruption is shown in Fig. 6 for July 2009.

In Fig. 7 are three altitude-latitude plots for the Raikoke volcanic eruption, located in Russia's Kuril Islands. It erupted on 22 Jun 2019 and made a large, persistent signature in the ACE-FTS data. The first plot is for July 2019; the second shows data from September 2019. Raikoke's June 2019 eruption is chronicled in the Smithsonian database. The estimated plume height shown in the table is based on ACE-FTS data. It shows that the SO₂ plume from a large eruption can remain visible for two to three months after eruption. Because of ACE's orbit no suitable occultations are available in Fig. 6 for August.

The Raikoke eruption was observed by ACE for 4 months. These observations afford the opportunity to evaluate the decay of the SO₂ plume. As shown by McKeen et al. [23], the reaction that controls the conversion rate of SO₂ to sulfuric acid (H_2SO_4) in the stratosphere is

$$SO_2 + OH \xrightarrow{M} HSO_3.$$
 (1)

• •

From this reaction the SO₂ decay rate can be approximated:

$$\frac{d[\text{SO}_2]}{dt} = -k[\text{SO}_2][\text{OH}][\text{M}]$$
(2)

where the square brackets denote number density; M is the total number density and k is a temperature dependent rate constant [23]. For constant [OH] and [M] pseudo-first order kinetics are obtained. For the Raikoke SO₂ plume, the portion of the plume at 14 km altitude between 55°N and 60°N appears relatively stationary and was used to make a rough estimate of the e-folding time of about 27 days. While only a rough estimate, this number compares well with similar calculations made by Read et al. using data from MLS on UARS for the 1991 Mt. Pinatubo eruption [8], 33 days, as well as those made by Pumphrey et al. using data from MLS on Aura for multiple volcanic eruptions between 2005 and 2014, 24 days and an uncertainty of 3 days [14].

Using extinction data from its Imager, ACE also provides the data to determine the decay of H_2SO_4 aerosol cloud for the same time period:

$$\frac{d[H_2SO_4]}{dt} = k_{SO_2}[SO_2] - k_{H_2SO_4}[H_2SO_4]$$

Using the same latitude/altitude section as used for determination of decay of SO_2 yields the approximate e-folding time for the H_2SO_4 aerosol cloud to be about 111 days. As the aerosol cloud is fed by the decaying SO_2 plume, the concentration of H_2SO_4 increases for about 50 days and then begins to decrease.

4. Conclusion

The ACE mission has more than 16 years of SO₂ data that spans many significant volcanic eruptions and provides a large data set from which to derive background SO₂ atmospheric data. Background SO₂ VMRs are in the 30 ppt range at altitudes between 10 and 14 km and then fall to less than 10 ppt as altitude increases. SO₂ VMRs in the upper troposphere are consistently 5 to 10 ppt higher above 30° latitude in the Northern Hemisphere in comparison to the Southern Hemisphere. Some seasonality has been measured, primarily in the polar and equatorial regions. Volcanic SO₂ plumes can persist for up to three months. Extinction data for sulfate aerosols from the ACE mission has been used to corroborate the detection of volcanic plumes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

W.D. Cameron: Writing - original draft, Formal analysis, Investigation. **P. Bernath:** Supervision, Conceptualization. **C. Boone:** Data curation, Software.

Acknowledgements

The ACE mission is supported by the Canadian Space Agency (9F045-180032/001/MTB).

Appendix

ACE offers simultaneous observations of both SO₂ plumes and sulfate aerosol distributions in the form of extinction plots. Addi-



Fig 8. Manam erupted on 27 Jan 2005 at 4.1°S, 145.0°E; Feb 2005 data shown. Left SO₂ VMR, right aerosol extinction.





Fig. 9. Rabaul erupted on 7 Oct 2006 at 4.3°S, 152.2°E; Oct 2006 data shown. Left SO₂ VMR, right aerosol extinction.







Fig. 11. Grimsvotn erupted on 21 May 2011 at 64.4°N, 17.3°W; May 2011 data shown. Left SO₂ VMR, right aerosol extinction.





Fig. 12. Puyehue-Cordon Caulle erupted on 4 Jun 2011 at 40.6°S, 72.1°W; Jun 2011 data shown. Left SO₂ VMR, right aerosol extinction. Plume at 20°N is Nabro (Fig 13); partially visible plume in vicinity of 50°N is Grimsvotn (Fig 11).



Fig. 13. Nabro erupted on 13 Jun 2011 at 13.4°N, 41.7°W; Jun 2011 data shown. Left SO₂ VMR, right aerosol extinction. The plume is somewhat obscured by Puyehue-Cordon Caulle (Fig 12) and the Grimsvotn eruption (Fig 11). SO₂ VMR data cells beyond 300 ppt have been removed to minimize masking from Puyehue-Cordon Caulle.

60 80



Fig. 14. Kelut erupted on 13 Feb 2014 at 7.9°S, 112.3°E; Feb 2014 data shown. Left SO₂ VMR, right aerosol extinction.



Fig. 15. Calbuco erupted on 22 Apr 2015 at 41.3°S, 72.6°W; Jun 2015 data shown. Left SO₂ VMR, right aerosol extinction.

tional volcanic eruptions from Table 2 with SO₂ VMR plots shown beside extinction plots for the same time period for comparison are included in the Appendix. Each figure caption includes the latitude of eruption as well as the month the data was taken from (typically one or two months after the eruption) (Figs. 8–15).

References

- Thomason L, Peter T. Assessment of Stratospheric Aerosol Properties (ASAP); 2006. SPARC Rep No 4 p. xi-xii.
- [2] Riccobono F, Schobesberger S, Scott CE, Dommen J, Ortega IK, Rondo L, et al. Oxidation products of biogenic emissions contribute to nucleation of atmospheric particles. Science 2014;344:717–21.
- [3] Aas W, Mortier A, Bowersox V, Cherian R, Faluvegi G, Fagerli H, et al. Global and regional trends of atmospheric sulfur. Sci Rep 2019;9:953.
- [4] Rollins AW, Thornberry TD, Atlas E, Navarro M, Schauffler S, Moore F, et al. SO₂ observations and sources in the western Pacific tropical tropopause region. J Geophys Res-Atm 2018;123(13):549–59.
- [5] Global Volcanism Program. Venzke E, editor. Smithsonian Institution; 2013. Downloaded 11 Sep 2019 https://doi.org/10.5479/si.GVP.VOTW4-2013.
- [6] Stevenson D, Johnson C, Collins W, Derwent R. The tropospheric sulphur cycle and the role of volcanic SO₂. Geol Soc Sp 2003;213:295–305.
- [7] Hoyle CR, Fuchs C, Järvinen E, Saathoff H, Dias A, El Haddad I, et al. Aqueous phase oxidation of sulphur dioxide by ozone in cloud droplets. Atmos Chem Phys 2016;16:1693–712.
- [8] Read WG, Froidevaux L, Waters JW. Microwave Limb Sounder measurement of stratospheric SO₂ from the Mt. Pinatubo volcano. Geophys Res Lett 1993;20:1299–302.
- [9] Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, et al. (eds). Climate change 2013: the physical science basis. ipcc 2013; Cambridge Univ Press, Cambridge, UK and New York, NY, 1535pp.
- [10] Fioletov VE, McLinden CA, Krotkov N, Moran MD, Yang K. Estimation of SO₂ emissions using OMI retrievals. Geophys Res Lett 2011;38:L21811.

- [11] Carn SA, Fioletov VE, McLinden CA, Li C, Krotkov NA. A decade of global volcanic SO₂ emissions measured from space. Sci Rep 2017;7:44095.
- [12] Fioletov V, McLinden C, Griffin D, Theys N, Loyola D, Hedelt P, et al. Anthropogenic and volcanic point source SO₂ emissions derived from TROPOMI onboard Sentinel 5 Precursor: first results. Atmos Chem Phys 2020;20:5591–607.
- [13] Yang K, Liu X, Krotkov NA, Krueger AJ, Carn SA. Estimating the Altitude of Volcanic Sulfur Dioxide Plumes from Space Borne Hyper-Spectral UV Measurements. Geophys Res Lett 2009;36:L10803.
- [14] Pumphrey HC, Read WG, Livesey NJ, Yang K. Observations of volcanic SO₂ from MLS on Aura. Atmos Meas Tech 2015;8:195–209.
- [15] Höpfner M, Boone C, Funke B, Glatthor N, Grabowski U, Günther A, et al. Sulfur dioxide (SO₂) from MIPAS in the upper troposphere and lower stratosphere 2002–2012. Atmos Chem Phys 2015;12:7017–37.
- [16] Bernath PF. The Atmospheric Chemistry Experiment (ACE). J Quant Spectrosc Radiat Transf 2017;186:3–16.
- [17] Boone CD, Bernath PF, Cok D, Steffen J, Jones SC. Version 4 Retrievals for the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) and Imagers. J Quant Spectrosc Radiat Transf 2020;247:106939.
- [18] ACE-FTS data, version 4.0, http://databace.scisat.ca/level2/ace_v4.0.
- [19] Gordon IE, Rothman LS, Hill C, Kochanov RV, Tan Y, Bernath PF, et al. The HI-TRAN 2016 molecular spectroscopic database. J Quant Spectrosc Radiat Transf 2017;203:3–69.
- [20] Kremser S, Thomason LW, von Hobe M, Herrman M, Deshler T, Timmreck C, et al. Stratospheric aerosol–Observations, processes, and impact on climate. Rev Geophys 2016;54:278–335.
- [21] Gilbert KL, Turnbull DN, Walker KA, Boone CD, McLeod SD, Butler M, et al. The onboard imagers for the Canadian ACE SCISAT-1 mission. J Geophys Res 2007;112:D12207.
- [22] Rollins AW, Thornberry TD, Watts LA, Yu P, Rosenlof KH, Mills M, et al. The role of sulfur dioxide in stratospheric aerosol formation evaluated by using in situ measurements in the tropical lower stratosphere. Geophys Res Lett 2017;44:4280–6.
- [23] McKeen SA, Liu SC, Kiang CS. On the Chemistry and Stratospheric SO₂ from Volcanic Eruptions. J Geophys Res 1984;89:4873–81.