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Elizabeth Asher[1,2a*], Michael Todt[1,2b], Karen Rosenlof[2], Troy Thornberry[2], RuShan Gao[2], Ghassan Taha[3,4], Paul Walter[5], Sergio Alvarez[6], James Flynn[6], Sean Davis[2], Stephanie Evan[7], Jerome Brioude[7], Jean-Marc Metzger[8], Dale F. Hurst[1,9], Emrys Hall[1,9], Kensy Xiong[1,9]

Elizabeth Asher easher@noaa.gov
Michael Todt michael.todt@colorado.edu
Karen Rosenlof karen.h.rosenlof@noaa.gov
Troy Thornberry troy.thornberry@noaa.gov
RuShan Gao rushan.gao@noaa.gov
Ghassan Taha ghassan.taha-1@nasa.gov
Paul Walter pauljw@stedwards.edu
Sergio Alvarez slalvare@central.uh.edu
James Flynn jhflynn@central.uh.edu
Sean Davis Sean.M.Davis@noaa.gov
Stephanie Evan stephanie.evan@univ-reunion.fr
Jerome Brioude jerome.brioude@univ-reunion.fr
Jean-Marc Metzger jean-marc.metzger@univ-reunion.fr
Dale F. Hurst dale.hurst@noaa.gov
Emrys Hall Emrys.Hall@noaa.gov
Kensy Xiong kensy.xiong@noaa.gov

[1] Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, 216 UCB, Boulder, CO 80309, United States
[2] NOAA Chemical Sciences Laboratory, 325 Broadway, Boulder, CO 80305, United States
[3] Morgan State University, 1700 East Cold Spring Lane McMechen Hall Rm 635, Baltimore, MD 21251, United States
[4] NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, United States
[5] St. Edward's University, 3001 South congress, Austin, TX 78704, United States
[6] University of Houston, 4800 Calhoun Rd, Houston, TX 77004, United States
[7] Laboratoire de l'Atmosphère et des Cyclones (LACy), UMR8105, CNRS, Université de La Réunion, Saint-Denis, France
[8]Observatoire des Sciences de l'Univers de la Réunion, UAR 3365 (CNRS, Université de la Réunion, Météo-France), Saint-Denis, France
[9] NOAA Global Monitoring Laboratory, 325 Broadway, Boulder, CO 80305, United States
[a] Now at: NOAA Global Monitoring Laboratory
[b] Now at: Finnish Meteorological Institute (FMI), Helsinki, Finland
[*]Corresponding author

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Abstract

The Hunga Tonga-Hunga Haʿapai (HT-HH) volcanic eruptions on Jan. 13 and 15, 2022 produced a plume with the highest signal in stratospheric aerosol optical depth observed since the eruption of Mt. Pinatubo in 1991. Suites of balloon-borne instruments on a series of launches from Réunion Island intercepted the HT-HH plume within two weeks of the eruptions, yielding observations of the aerosol number and size distribution, and sulfur dioxide (SO_2) and water vapor (H_2O) concentrations. The measurements reveal an unexpected abundance of large particles in the plume, constrain the total sulfur injected to approximately 0.20 Tg, provide information on the altitude of the injection, and indicate that the formation of sulfuric acid aerosol was complete within three weeks. Large H_2O enhancements contributed as much as ~30% to ambient aerosol surface area and likely accelerated SO_2 oxidation and aerosol formation rates in the plume to ~ 3 times faster than under normal stratospheric conditions.

Significance Statement

Large volcanic eruptions can play an important role in Earth's radiative balance through stratospheric injections of sulfur dioxide that form sulfate aerosol. Here, we show that in situ observations are critical to constrain the injection mass of stratospheric sulfur and the stratospheric lifetime of sulfur dioxide. Such information is needed to better represent aerosol microphysics and improve predictions of the impacts of natural (or potentially anthropogenic) sulfur dioxide injections. Measurements in the fresh volcanic Hunga Tonga-Hunga Haʿapai plume in January 2022 revealed that stratospheric aerosol formation ended ~3 times faster than is typical in the presence of a large amount of water vapor, resulting in a high signal in aerosol extinction from an abundance of large particles.

Main

Volcanic plumes that reach the stratosphere can influence Earth's radiative balance and are a significant driver of climate variability (1). Under background conditions, sustaining the stratospheric aerosol burden requires the addition of ~ 0.1 Tg sulfur (S) yr^{-1} from the oxidation of carbonyl sulfide and sulfur dioxide (SO_2) (2), while stratospheric transport (3) and a variety of localized aerosol processes (4) contribute to heterogeneity in aerosol number and size. Simulating an eruption's impact on stratospheric aerosol requires either knowledge or assumptions of its injection height and mass (5), plume composition, location, and atmospheric state. In situ measurements within one to three weeks of an eruption can provide critical information for improving these assumptions.

The energetic eruption of the underwater Hunga Tonga-Hunga Ha'apai (HT-HH) volcano (20.54 °S, 175.38 °W) on Jan. 15 (04:00 UTC) (6), together with a smaller eruption on Jan. 13 (15:20 UTC), injected an estimated 150 Tg water vapor (H_2O) (7) and 0.41 ± 0.01 Tg SO_2 into the stratosphere (7, 8). The combination of its explosivity and the extraordinary amount of H_2O injected into the stratosphere make the Jan. 15 eruption unique in the satellite era. Estimated injection heights for these two eruptions ranged from 20 km on Jan. 13 to > 30 km on Jan. 15, and the SO_2 plumes quickly overlapped, making them difficult to distinguish (8). Radiosonde measurements reveal enhanced H_2O between 19 km and the maximum altitude of balloon soundings, near 30 km (9). The HT-HH aerosol layer generated the highest signal in stratospheric aerosol optical extinction since the eruption of Mt. Pinatubo in 1991 (10). Given the relatively small injections of SO_2 (7, 8) by the HT-HH eruptions, the large signal in aerosol extinction sparked questions regarding the initial S injection (11), the role of H_2O in rapid aerosol formation in this plume and its timeline (12, 13).

In situ observations of particle number concentration and size distribution complement space-based aerosol retrievals. For the first three months after the HT-HH eruption, the Ozone Mapping and Profiler Suite-Limb Profile (OMPS-LP) sensor onboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite supplied a continuous global record of the main volcanic plume's altitude between 16 – 30 km, its horizontal extent and its impact on stratospheric aerosol optical depth (sAOD) (10). The Tonga volcano Rapid Response Experiment (TR^2Ex) provided high-resolution vertical profiles with relatively low uncertainty of SO_2 (14) and H_2O (15, 16) to ~ 30 km altitude and information on the aerosol size distribution in the main plume, which cannot be reliably inferred from either satellite or ground-based measurements. Here, we leverage a combination of these in situ measurements and OMPS-LP retrievals (17) to address questions regarding the HT-HH eruption's impact on the lifetime of SO_2 and the magnitude and altitude of the initial sulfur injection.

Results

1.Rapid Response Insights

TR^2Ex was a unique deployment of a suite of balloon-borne instrumentation that repeatedly analyzed the composition of the volcanic plume 7 – 10 days after the second, larger HT-HH eruption. Sampling the fresh HT-HH plume yielded in situ observations of aerosol size distribution, SO_2, and H_2O at several pivotal times during its evolution (see Methods, Section 1 for details; Table S1). In situ measurements from this campaign allow us to quantify the S gas/particle phase partitioning within the plume, study the vertical distribution of the S injection,

and explore the role of stratospheric H_2O enhancements in increasing ambient aerosol size and extinction.

Portable Optical Particle Spectrometer (POPS) (18) measurements during TR^2Ex show the impact of the HT-HH eruption on aerosol dry mass and extinction (enhancements ranged from two to three orders of magnitude), driven by high concentrations of large accumulation mode aerosols in the volcanic plume (Fig. 1; see Methods, Section 2 for details). By the time the plume reached La Réunion seven days after the second eruption, wind shear had stretched the initial injection into a thin slanted layer of varying thickness as it moved west (19). Positive altitude gradients in easterly windspeeds resulted in progressively shorter transit times with increasing altitude. TR^2Ex instruments were unable to measure two isolated optically thin volcanic aerosol layer segments detected above 30 km by space-based and ground-based remote sensing instruments (10, 19)— as these were above the operation ceiling of balloon sondes. Parts of the aerosol layer between 25 km and 28 km (Fig. 1c-d) corresponded to a region with a substantial H_2O enhancement (Fig. S1). Particle number concentration of both large and small particles (up to 1.5 μm) was as much as three orders of magnitude higher than in unperturbed air masses. The mode of the size distribution occurred at ~ 560 nm diameter, and the aerosol effective radius exceeded 0.3 μm (Fig. S2). With H_2O enhancements of ~340 ppmv in this part of the plume, H_2O contributed ~ 15% to the aerosol diameter at ~ 560 nm and ~ 30% to the total aerosol surface area (Fig. S3; see Methods, Section 2). Differences in aerosol surface area impact both extinction and stratospheric chemistry (20), highlighting the importance of calculating ambient aerosol size related to the HT-HH eruption. The air was much drier (< 17 ppmv H_2O) in the part of the plume below 25 km, which contained an elevated number concentration of particles < 700 nm in diameter. The highest number concentration below 25 km occurred at the smallest particle size (Fig. 1e-f), and the aerosol effective radius was not noticeably different from baseline values (~ 0.2 μm; Fig. S2). Larger particles appeared more often in the wetter, higher altitude parts of the aerosol layer, presumably due to shorter SO_2 lifetimes and particle coagulation within the plume (12).

On three occasions, simultaneous in situ measurements of SO_2 and aerosol in the volcanic plume reveal varying rates of aerosol formation. Particles in the plume are presumed to be composed of sulfuric acid (H_2SO_4) formed from SO_2 oxidation and are designated estimated H_2SO_4 ($_eH_2SO_4$) (see Methods, Section 2 for details). Comparisons are shown between the mass mixing ratios of S in $_eH_2SO_4$ and SO_2 (Fig. 2a-c). The altitudes of SO_2 enhancements and aerosol accumulations correspond well, and the mass mixing ratios of S in $_eH_2SO_4$ exceeded those of S in SO_2 on two of three flights. Outside of the fresh HT-HH plume, the SO_2 partial pressure was below the detection limit of the SO_2 sonde. If SO_2 gas phase oxidation had proceeded at its typical rate (i.e., an e-folding stratospheric lifetime, τ_{strat} = ~ 30 days) (21) after the two HT-HH eruptions, we would expect a $\leq$30% estimated H_2SO_4 ($_eH_2SO_4$) aerosol to $\geq$70% SO_2 split (by S mass) on Jan. 25,~ 10.5 days after the second, larger eruption. In the wetter, higher altitude region of the plume, measured on Jan. 22, $_eH_2SO_4$ aerosol accounted for 90% of the total S in the plume (Fig. 2d), implying a τ_{strat} = ~ 3 days. In a drier part of the aerosol layer encountered on Jan. 24 at 22 km, $_eH_2SO_4$ aerosol constituted 68% of the total S (τ_{strat} = ~ 8 days), and on Jan. 25 at 20 km, only 35% of the total S (τ_{strat} = ~ 24 days). We infer that SO_2 oxidation in the fresh plume proceeded at different rates as a function of H_2O, namely more quickly where H_2O mixing ratios were higher due to an increased concentration of hydroxyl radicals (22, 23). These measurements also provide information on the vertical distribution of the S injection (i.e., the sum of the S in both SO_2 and in $_eH_2SO_4$ aerosol; Fig. 2d). The total S column mass of the higher

altitude part of the plume measured on Jan. 22 was nearly four times that of the lower altitude part of the plume measured on Jan. 24 and 25, suggesting that the majority of SO_2 was injected above 25 km (Fig. 2d).

2. Aerosol burden and stratospheric lifetime (τ_{strat}) of SO_2

Quantifying the S burden in the tropical HT-HH aerosol layer helps constrain the stratospheric S injection and the τ_{strat} of SO_2, which are critical for model validation and have widespread implications for stratospheric chemistry. The calculation relies on the relationship between the aerosol S column and sAOD calculated using POPS size distributions on launches from La Réunion and on OMPS-LP retrievals of sAOD (see Methods, Section 3). As the plume moved westwards, TR^{2}Ex launches sampled its core on Jan. 22 – 23 and trailing edge on Jan. 24 – 25 (Fig. 3). The S in the $_eH_2SO_4$ aerosol layer grew from 0.03 Tg S on Jan. 18 to 0.15 Tg S on Jan. 26 and reached a maximum of 0.18 Tg S on Feb. 3 (Fig. 4a). We estimate that on Jan. 23, ~ 3/4 of the S mass was located in the higher altitude part of the aerosol layer, west of La Réunion (Fig. 4a; Methods, Section 3). Leading up to the eruptions (i.e., on Jan. 10), the S burden in background $_eH_2SO_4$ aerosol was < 0.001 Tg S. This result suggests that rapid aerosol conversion took place: within ~ 19 days, all the SO_2 released from the eruptions, corresponding to as much as 0.18 Tg S (8), was oxidized and converted to particles ($\geq$ 140 nm). By tracking the accumulation of S in $_eH_2SO_4$ aerosol, we calculate the average τ_{strat} as ~ 10 –13 days in the plume (see Methods, Section 4; Fig. 4b). We note, however, that if a sizeable fraction (e.g., 0.09 Tg) of the aerosol mass were not composed of H_2SO_4, this would yield a longer estimated τ_{strat} (~ 14 – 17 days) given the same SO_2 injection. A short τ_{strat}, compared with the typical value of one month under climatological stratospheric conditions, helps explain the rapid production of large particles in the HT-HH plume and signals greater availability of the hydroxyl radical to react with methane and trace gases in the stratosphere (12, 22, 23).

Discussion

A rapid response to large or unusual volcanic eruptions with in situ observations can provide insight into the resulting aerosol microphysics, complement space-based aerosol retrievals (7, 8, 10), and be essential to evaluate models. Together with satellite retrievals of sAOD, POPS vertical profiles of particle size distributions enable the calculation of the aerosol layer's S mass and the mean τ_{strat} of SO_2. We determined that $_eH_2SO_4$ formation was complete within three weeks, which is consistent with a maximum effective radius (> 0.4 μm) observed in early February (Fig. S2). In situ measurements of SO_2 and $_eH_2SO_4$ and calculations of the aerosol layer's $_eH_2SO_4$ mass provide evidence that the bulk of the total S was injected above 25 km, which cannot be easily deduced from satellite retrievals of SO_2 and aerosol extinction (8, 10). These observations also indicate that SO_2 oxidation and aerosol conversion occurred at varying rates within the plume, corresponding to localized H_2O enhancements. Radiosonde measurements confirm that H_2O mixing ratios within the plume spanned more than an order of magnitude (< 100 ppmv to > 1000 ppmv) (9). Climatological lower stratospheric mixing ratios in the tropics do not typically exceed 4-5 ppmv (24). SO_2 oxidation and aerosol conversion took place ~ 3 times faster, on average, than under climatological stratospheric conditions. SO_2 oxidation accelerates substantially in the presence of H_2O enhancements (12, 22, 23, 25). A short τ_{strat} of SO_2 reflects the heightened oxidative capacity of the atmosphere, with important implications on stratospheric chemistry and composition.

Our measurements clarify the contributions to aerosol extinction from H_2O after the HT-HH eruptions, which has spurred discussion in the scientific community (10–13). We caution against conflating a response in the aerosol extinction with a similar change in aerosol mass for two reasons: H_2O contributed ~30% to aerosol extinction in the fresh HT-HH plume. Light scattering efficiency is closely related to aerosol size, with a maximum efficiency (per unit volume) at 500 nm diameter (20). Due to the 560 nm diameter mode of the measured aerosol size distribution mode, the HT-HH aerosol layer resulted in a high sAOD relative to its injected mass. Radiosonde measurements show similarly elevated H_2O throughout the plume between Jan. 20 and Feb. 1 (one quarter of the observations between 26 – 28 km altitude from all vertical profiles during this period had $7 \leq H2O \leq 130$ ppmv) (26), signifying widespread implications for $_eH_2SO_4$ particle size and the S mass in the higher altitude part of the aerosol layer. Particle size distributions show that differences in the peak and shape of the size distribution result in substantial differences in aerosol extinction (e.g., Fig. 1). Questions remain about how H_2O and other compounds reaching the stratosphere during an eruption might influence aerosol microphysics, including the propensity for new particle formation, condensation onto existing particles, and particle coagulation.

TR^2Ex serves as a roadmap for future rapid response campaigns to volcanic eruptions and other stratospheric perturbations. Campaigns such as TR^2EX further the understanding of aerosol processes in the stratosphere and inform models predicting climate impacts under a variety of past and potential future conditions. Stratospheric aerosol injection (SAI), one proposed method of climate intervention, would entail a large anthropogenic addition of stratospheric aerosol. The suite of instruments described here is capable of identifying potential SAI implementations, providing insight into the aerosol composition (i.e., sulfate or other) and hygroscopic effect, and could enable quantifying the mass (and altitude) of SAI.

Methods

1. Rapid Response Overview

POPS in situ observations (18) of aerosol size distributions were made as part of the National Oceanic and Atmospheric Administration (NOAA) Earth Radiation Budget program's Baseline Balloon Stratospheric Aerosol Profiles (B^2SAP) project (27). The B^2SAP project combines intensive periods of operation (IOP) with routine baseline measurements in the northern and southern hemispheres. For the Tonga volcano Rapid Response Experiment (TR^2Ex) between Jan. 21 and Jan. 26, B^2SAP IOP activities were coordinated with additional sonde and lidar measurements at the Maïdo Observatory (28) on La Réunion (21 °S, 55 °E). TR^2Ex balloon payloads consisted of either: (A) a POPS, a sulfur dioxide (SO_2) sonde, an Electrochemical Concentration Cell (ECC) ozonesonde and a radiosonde, or (B), an ECC ozonesonde, a Compact Optical Back-scatter Aerosol Detector (COBALD) instrument and a radiosonde (Table S1; COBALD, ozonesonde, and lidar measurements are discussed elsewhere (19). The ground-based lidars and the COBALD provided information on aerosol extinction (18) and backscattering, respectively. Unfortunately, quantitative information on the aerosol depolarization in the plume during TR^2Ex does not exist because the lidar at the Maïdo observatory was not calibrated for depolarization. Subsequent POPS and NOAA Frost point Hygrometer (FPH) launches in February, March, and June 2022 at the Maïdo Observatory were part of what are now routine B^2SAP soundings (Table S1) (27).

SO_2 sonde (14) measurements have lower uncertainty and considerably better vertical resolution than satellite SO_2 retrievals (8), particularly after an energetic volcanic eruption. A

modified ECC ozonesonde, the SO_2 sonde removes ozone from the sample prior to detection using a filter, allowing stratospheric as well as tropospheric SO_2 to be quantified using pre-flight calibrations (14). The SO_2 sonde has a ~ 25 sec response time, similar to that of an ozonesonde. SO_2 data (Fig. 2) reflect a correction for this time (and altitude) lag (29, 30). CFH (31) and FPH (16) instruments measuring H_2O were used to calculate ambient particle size, and Ozone Mapping and Profiler Suite-Limb Profile (OMPS-LP) retrievals (17) were used to calculate the volcanic plume's aerosol burden, as described below.

2. The POPS measurements and inherent assumptions

Particle sizing inherently requires assumptions about particle morphology and refractive index related to aerosol composition (18). Here, we assume that particles are spherical and composed of sulfuric acid (H_2SO_4) and water, with a corresponding refractive index of 1.45 at 405 nm (the wavelength of the POPS laser), leading to a reported particle number and size distribution between 140 nm – 2.5 µm in diameter. Telemetered data are quality assured based on available engineering parameters, including the instrument temperature, measured with a thermistor located on the POPS laminar flow element, and the instrument flow (27). Particles are expected to be at (or close to) equilibrium with the instrument temperature at the time of detection, given a particle transit time of 60 – 90 ms. We note that POPS particle transit times exceeded modeled timescales required for aerosol growth or evaporation within the plume, in line with similar calculations from Kovilakam and Deshler (32) and Jonsson et al. (33).

The S in the ${}_eH_2SO_4$ aerosol column mass and mass mixing ratios are calculated from the measured aerosol size distribution and particle density. The aerosol weight (wt.%) ${}_eH_2SO_4$ can be determined using the partial pressure of H_2O at a range of temperatures (34–37). We apply the formulation of Tabazedah et al. (37), which is suitable for low temperatures observed in the lower stratosphere (when ${}_eH_2SO_4 \leq 80$ wt. %) and is based on Steele and Hamill (35), and the expression of Gmitro and Vermeulen when ${}_eH_2SO_4 > 80$ wt. % (34). In the stratosphere, particles have a calculated $\geq 80\%$ wt% ${}_eH_2SO_4$ at the time of detection due to instrument temperatures (268 – 278 K) that are considerably higher than ambient stratospheric air (ΔT = 50 – 75 K). Particle density at the time of detection is both wt.% and temperature dependent (38–40). We use two parameterizations valid for temperatures between 233 – 298 K given different wt. % (39, 40).

Ambient particle diameter is calculated according to Steele and Hamill (35) from the measured (dehydrated) particle diameter, the particle wt. % and density both at the time of detection and in ambient air, assuming that the particle was at equilibrium in both cases, and that only water (not H_2SO_4) was lost from the particle during sampling (Fig. S2a). Measured aerosol size distributions were averaged into 100 m altitude bins, to improve counting statistics and facilitate the requisite merges with frost point hygrometer data from other launches. Possible errors in measured particle sizing are driven primarily by Mie resonances (18). Uncertainty in H_2O (<=6%), air temperature (< 1%), and uncertainties in the parameterizations of the wt. % and density contribute additionally to possible errors in calculated ambient sizing (Fig. S2), and the calculated S in ${}_eH_2SO_4$ mass mixing ratios and column mass (Fig. 2).

As in situ size distribution measurements provide no information on aerosol composition, we cannot rule out the possibility that aerosol could have consisted of ash or some other material, such as sea salt, coated (or internally mixed) with H_2SO_4. Contributions from HNO_3 aerosol or mixtures containing HNO_3 and H_2SO_4 were considered but dismissed based on equilibrium calculations (33, 41, 42). Although volcanic lightning on Jan. 15 (43) may have injected NO

directly into the stratosphere, HNO_3 hardly condenses at temperatures $\geq$ 220 K observed in the plume, despite large enhancements in stratospheric H_2O.

The assumptions made here regarding particle composition and morphology are supported by space-based Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) retrievals and geostationary satellite RGB-Ash composite imagery within the first few days of the HT-HH eruption on Jan. 15 (11). CALIOP retrievals showed particles with low depolarization, indicating spherical H_2SO_4 particles moving westward towards La Réunion on Jan. 20. The geostationary satellite RGB-Ash composite images depicted a concomitant light green SO_2 plume (with little to no ash) during this period.

3. Calculating the aerosol column and plume S burden

Vertical profiles of aerosol extinction at 997 nm, corresponding to the native wavelength of the OMPS-LP sensor, are calculated using publicly available Mie codes (44, 45) and the calculated particle size distribution in ambient air. POPS stratospheric ambient aerosol optical depth (sAOD) is the sum of calculated ambient aerosol extinction above the tropopause. Similarly, the POPS stratospheric S column in ${}_eH_2SO_4$ aerosol (g S m^{-2}) at a single geographic location is quantified as the sum of the S in ${}_eH_2SO_4$ aerosol (µg S m^{-2} air) in each 100 m altitude bin above the tropopause. A baseline value of the S column in ${}_eH_2SO_4$ aerosol, calculated from a vertical profile outside the plume on Jan. 23 (14 UTC), was subtracted from each measurement that encountered the plume to determine the S in the aerosol layer (g S m^{-2}). Because SO_2 measurements were below the SO_2 sonde's limit of detection outside the plume, no similar subtraction of the S column in SO_2 under baseline conditions was made following integration for comparisons in Figure 2d.

A linear regression between the POPS calculated ambient sAOD and S in ${}_eH_2SO_4$ column mass enables global retrievals of OMPS-LP sAOD to be used to infer the S column mass across the entire aerosol layer and track the S aerosol burden as the plume evolves. Estimates of the ${}_eH_2SO_4$ aerosol layer mass, based on relationships between the POPS measured (dehydrated) sAOD and POPS stratospheric S column ($\pm$ uncertainty) and the calculated ambient sAOD and POPS stratospheric S column ($\pm$ uncertainty) over La Réunion between Jan. 22 and Jun. 9 are shown in Figure S4a. The reported uncertainty in OMPS-LP sAOD signal in the stratosphere (10% at $\lambda = 997\ nm$) (17) is negligeable compared to the differences in the slope and intercept POPS sAOD vs. mass relationships (Fig. S4a). We note that recent debate with respect to potential OMPS-LP retrieval biases (46) is beyond the scope of this work but would lead to a lower ${}_eH_2SO_4$ aerosol layer mass. The maximum value of daily sAOD from the OMPS-LP sensor on Jan. 10 (50 °S – 50 °N) was used as the sAOD threshold to identify the geographic extent of the tropical HT-HH aerosol layer (Fig. S4b); its median (0.0025) was used as a background sAOD value in the tropics. The linear relationships from Fig. S4a were applied to each daily sAOD value in the aerosol layer to infer the S column (g S m^{-2}) in each (2° latitude x 24° longitude) grid cell. The resulting S column using the relationship between the ambient sAOD and S in ${}_eH_2SO_4$ column mass is shown in Figure 3. For reference, the H_2O plume extent, calculated from MLS retrieval levels between 10 and 46 hPa using MLS H_2O anomalies between Jan. 21 – Jan. 23 (defined as the median ± 3 x the mean absolute deviation) is also shown in Figure 3c, compared to the aerosol layer.

The S column was then multiplied by the area of the corresponding geographic grid cell (m^2) and summed to determine the total stratospheric S burden (Tg S) over that area. By applying the relationships from Fig. S4a to the background sAOD value, multiplied by the

aerosol layer's geographic area, we similarly calculated the corresponding S burden under background conditions in each case. The S burden under background conditions was then subtracted from the total stratospheric aerosol S burden to yield the volcanic aerosol layer's S burden ± uncertainty (Tg S) shown in Figure 4. The uncertainty in the S burden (the shaded black region) reflects the range of the estimates shown in Figure S4a. The S mass in the upper part of the plume was approximated as the sum of the S burden (in $_eH_2SO_4$ aerosol) west of La Réunion (55° E), when the higher altitude part of the aerosol layer was last observed on Jan. 23 00 UTC (Fig. 1d)(19). La Réunion is located near the latitudinal edge (48° E) of two adjacent OMPS-LP grid-cells. Thus, this estimate represents the arithmetic mean (± the standard deviation) of the S burden in the adjacent OMPS-LP grid cells centered at 36° E and 60° E (Fig. 4).

4. Estimating the SO_2 lifetime

By monitoring the aerosol loading following an eruption, we can estimate the initial injection of S and subsequently deduce the stratospheric lifetime (τ_{strat}) of SO_2. We assume that all the SO_2 is converted to H_2SO_4:

$$1.\ \frac{d[H_2SO_4]}{dt} = -\frac{d[SO_2]}{dt}, \text{and } [SO_2] = [SO_{2\ t=0}] - ([H_2SO_4] - [H_2SO_{4_{t=0}}])$$

Making these substitutions into the first order rate law $\frac{d[SO_2]}{[SO_2]} = -kdt$ and integrating demonstrates that the amount of H_2SO_4 produced depends on the initial injection of SO_2 and on the background H_2SO_4 burden (together with any initial injection of aerosol) and enables us to calculate τ_{strat} of SO_2 through linear regression against t (elapsed days since 4:00 UTC on Jan. 15), where *k* is the slope of the line and $\tau_{strat} = 1/k$:

$$2.\ ln\frac{[SO_{2\ t=0}]}{[SO_{2\ t=0}] - ([H_2SO_4] - [H_2SO_{4_{t=0}}])} = kt$$

The initial injection of S, $SO_{2\ t=0}$, is based on satellite retrievals of SO_2, which are slightly greater than the maximum accrual of S in $_eH_2SO_4$ aerosol after the eruption (0.190 Tg; Fig. 4a). τ_{strat} was calculated using a range of values for the initial SO_2 injection (0.195 – 0.215 Tg S in SO_2). Prior to the eruption (e.g, on Jan. 10), the initial S burden in the aerosol layer is close to zero (0.0005 Tg S in $_eH_2SO_4$), which is used as the value for $H_2SO_{4\ t=0}$. If as much as 0.09 Tg of aerosol mass were not composed of H_2SO_4 (0.03 Tg S is in 0.09 Tg $_eH_2SO_4$) this would result in an estimated τ_{strat} of 15-17 days. Equation 2 ignores a potential time lag required for either particle formation or aerosol growth through condensation to particle diameter ≥ 0.14 µm from H_2SO_4 gas, considered negligible in this case.

Data Availability

The processed POPS aerosol size distribution data from all launches used in this study may be found under the supporting data tab for this manuscript at https://csl.noaa.gov/projects/b2sap/data.html, where processed SO_2 and H_2O data from TR^{2}Ex, and processed daily files of OMPS-LP sAOD and MLS H_2O plume areas and anomalies from 21 hPa are also available. Raw OMPS-LP and MLS H2O data may be found at

https://disc.gsfc.nasa.gov/datasets/OMPS_NPP_LP_L2_AER_DAILY_2/summary and https://disc.gsfc.nasa.gov/datasets/ML2H2O_004/summary?keywords=aura, respectively. Code is publicly available at https://github.com/elizabethasher/hthhPY.

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Competing interests

The authors declare no competing financial interests.

Materials and Correspondence

Corresponding author, Elizabeth Asher (Elizabeth.asher@noaa.gov) should be contacted with any questions or requests for material.

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Figures

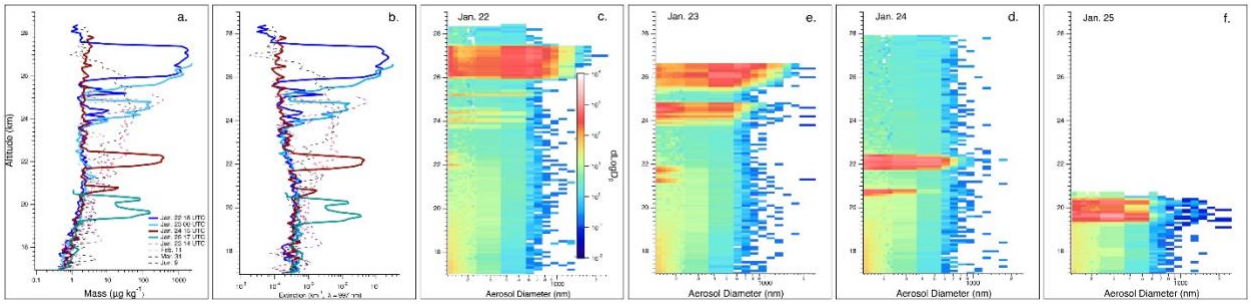

Figure 1. Vertical profiles of calculated bulk aerosol properties between January and June 2022 (from POPS size distribution data), including mass mixing ratios (a) and ambient extinction using Steele and Hamill (35)(b), both of which use the legend in panel (a), and vertical profiles of the measured aerosol size distributions from TR^{2}Ex launches when the fresh HT-HH aerosol plume was encountered (c, d, e, f). Aerosol size distributions (dN/dLogD$_p$) for the four TR^{2}Ex soundings (c, d, e, f) use the color scale in panel (c).

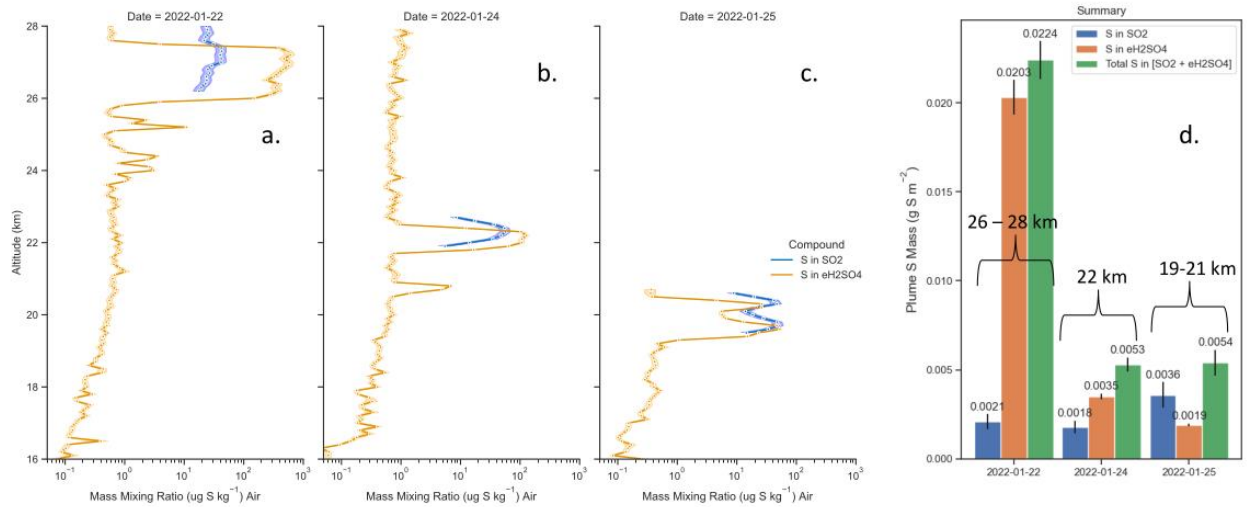

Figure 2. On three different dates, vertical profiles of S in SO_2 mass mixing ratios and calculated S in $_eH_2SO_4$ mass mixing ratios based on aerosol size distributions, when both instruments measured the volcanic plume with low uncertainties (a-c), and a summary of the S column mass in SO_2, the S column mass in $_eH_2SO_4$, and the total S column mass ([S in SO2] + [S in $_eH_2SO_4$] observed within the plume (d). Shaded areas and error bars show the uncertainty in SO_2 sonde measurements (≤20%) and the uncertainty in calculated eH_2SO_4 mass mixing ratios and S mass including possible error related to aerosol sizing and aerosol density.

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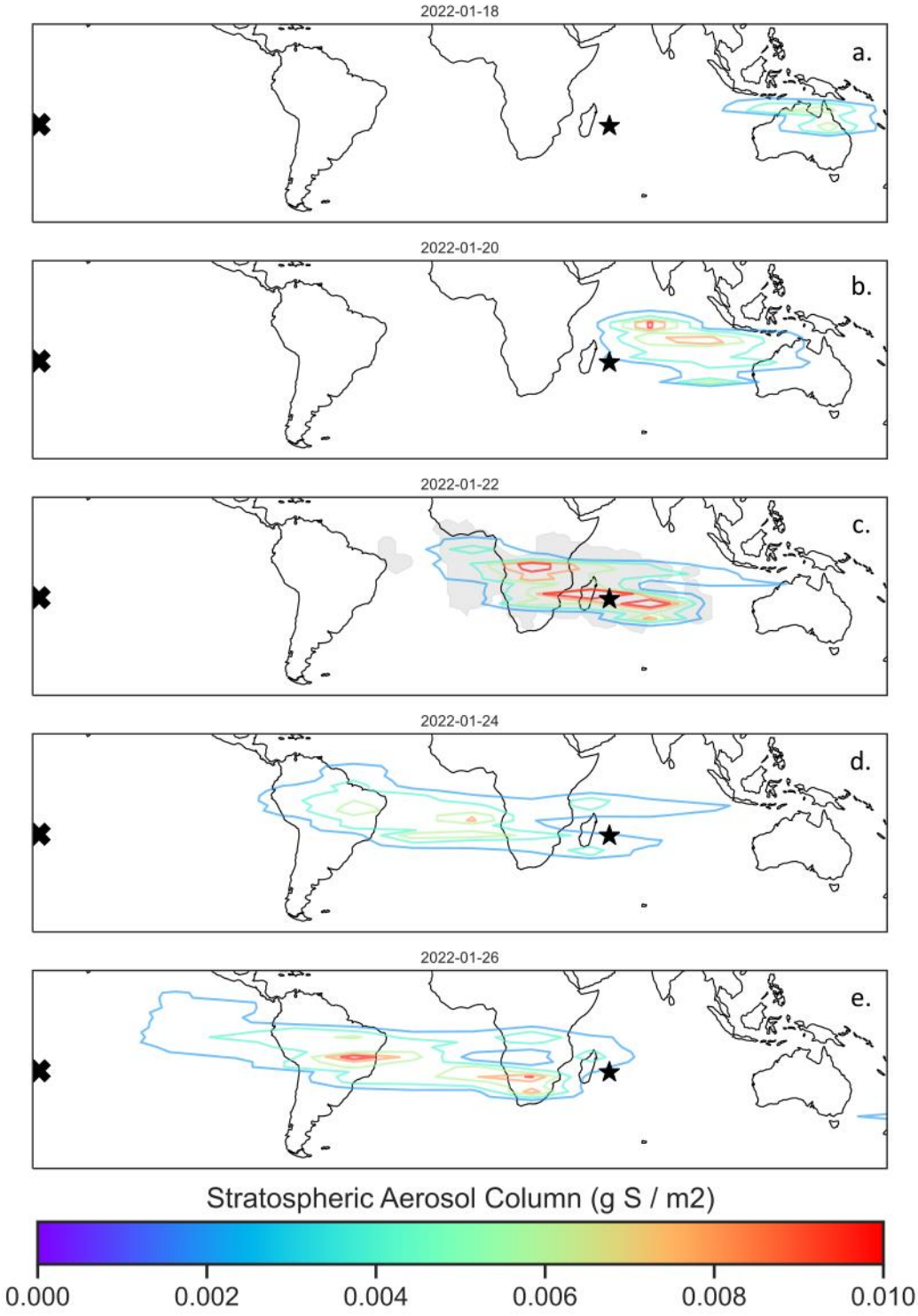

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557 **Figure 3.** Contour plots of the ${}_{e}H_2SO_4$ aerosol column (g m^{-2}), calculated using the equation in
558 the Fig. S4a caption, for 5 days from Jan. 18 to Jan 26 (a-e). On Jan. 22, the gray shaded area

559 shows the maximum plume extent between Jan. 21 – Jan. 23 as determined from MLS H_2O
560 anomalies at 21 hPa. Locations of HT-HH and La Réunion are marked with a cross and star,
561 respectively.
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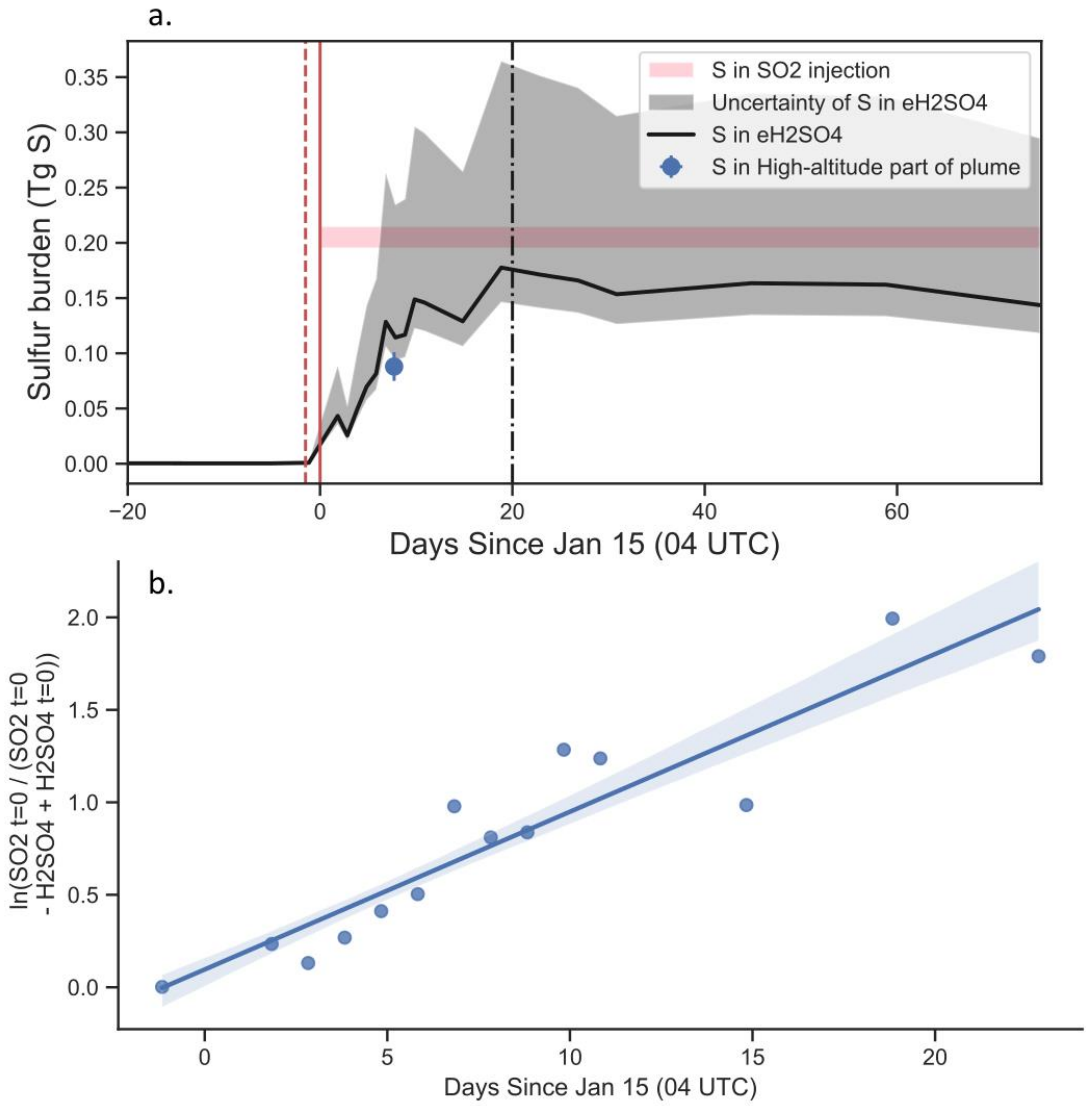

563
564 **Figure 4.** A time series of the calculated S burden in $_eH_2SO_4$ aerosol, calculated using a
565 combination of POPS measurements and OMPS-LP retrievals (a) and the estimation of the τ_{strat}
566 (b). The calculated S burden in $_eH_2SO_4$ aerosol (black line) represents the relationship between
567 calculated ambient sAOD and the mass, and agrees with estimates of the S injected as SO_2 from
568 satellites (7, 8) (pink shaded region). The uncertainty (black shaded region) represents the range
569 of assumptions considered in Figure S4a. The approximated S mass in the higher altitude part of
570 the plume, west of La Réunion on Jan. 23 00 UTC is also shown. OMPS-LP Dashed vertical
571 lines depict the period of $_eH_2SO_4$ aerosol accumulation. The S burden from this period is used to
572 calculate the stratospheric lifetime of SO_2, $\tau_{strat} = 1/k$, as shown in equation 3 (Methods

573 Section 3). Assuming an SO_2 injection of 0.205 Tg S in SO_2 (7, 8) k = 0.10 (r^2 = 0.87; p <
574 1.23E-6; 1 standard deviation of the slope is ± 0.011), suggesting a τ_{strat} for SO_2 of ~ 10 days (b).
575