Tracking and analysis of the Hunga plume in the stratosphere

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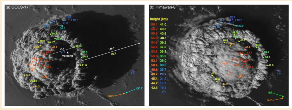
PRESENTATION

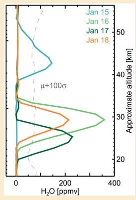
The phreato-magmatic eruption of Hunga (20°S, 175°W) on 15 January 2022 was exceptional in several respects. Its **explosive intensity was close to that of the eruption of Pinatubo** in 1991 with a Volcanic Explosivity Index of ~6 (Poli & Shapiro, 2022).
The induced atmospheric Lamb wave circled the globe at least 4 times with an amplitude comparable to that of the 1883 Krakatau eruption (Matoza et al., 2022; Vergoz et al., 2022, Wright et al., 2022).
We report here about the impact of the eruption in the stratosphere based on the following works of the ASTuS - PyroStrat consortium :
Sellitto et al., 2022, Nat. Com., DOI: 10.1038/s43247-022-00618-z
Legras et al., 2022, ACP, DOI: 10.5194/acp-22-14957-2022
Kloss et al., 2022, GRL, DOI: 10.1029/2022GL099394
Khaykin et al., 2022, Nat. Com., DOI: 10.1038/s43247-022-00652-x
Duchamp et al., 2023, GRL, DOI: 10.1029/2023GL105076



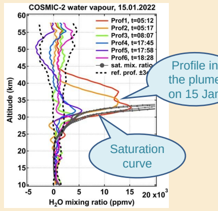
Estimation of plume altitude from stereoscopic processing of GOES 17 and Himawari 8 images
Carr et al., GRL, 2022

The **plume reached 56 km altitude** within 30 minutes following the paroxysmal explosion. The bulk of the plume was produced between 26 and 34 km.

Water vapour recorded within the plume and its vicinity displayed extremely large, never seen, values in the stratosphere with a saturated profile at least up to 33 km altitude within the plume in the hours following the eruption.
The water in excess generated precipitating ice and a rapid washout of the ashes.
The remaining water vapour in the stratosphere was estimated at **+ 140 Tg** (Millan et al., 2022), that is an instantaneous **10 % increase of the stratospheric content**.



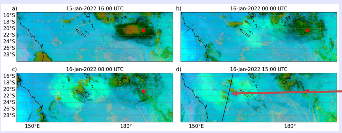
MLS H_2O profiles
Millán et al., GRL, 2022



COSMIC-2 radio occultations
Khaykin et al., Nat. Com., 2022

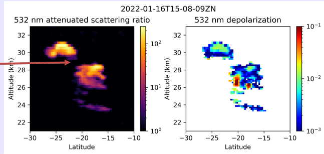
COMPOSITION OF THE PLUME

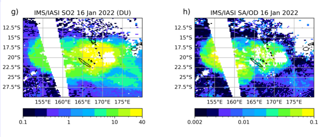
Eumetsat RGB Ash recipe using Himawari IR channels
Brown and dark blue: ash and ice; Greenish: sulfur



The initial ash + ice plume dissipates rapidly leaving a double plume mostly with sulfur compounds.
Fast conversion to sulfates due to the large amount of water vapour, especially in the southern and highest cloud which is also the one with largest amount of water (Sellitto et al., 2022).

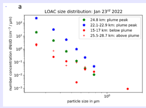
On 16 Jan, **CALIOP** sees two aerosol clouds at 31 and 28 km, mostly with very large scattering ratio and **no depolarization** => liquid droplets. There are also two areas of high depolarization close to 35% which could correspond to **remaining ice crystals** (stay only for a few days).





RAL IMS/IASI double retrieval of SO_2 (DU) & sulfate aerosol optical depth

LOAC measurements at La Reunion OPAR, 21°S, show **submicronic mainly non absorbing particles** (for 23 Jan)



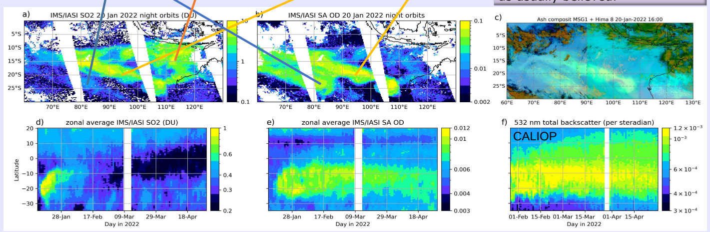
Kloss et al., GRL, 2022

Western strip: Complete conversion to sulfates (no SO_2 left)

Mainly SO_2 cloud at lower level (not seen by CALIOP and the ASH RGB and no anomalous moisture)

Eastern strip : Incomplete conversion to sulfates

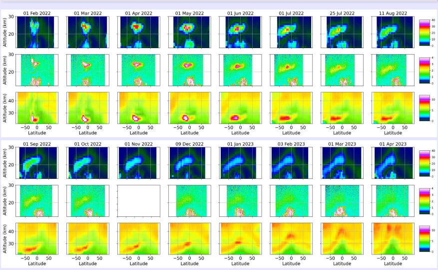
RGB Ash shows sulfates, not SO_2 as usually believed!



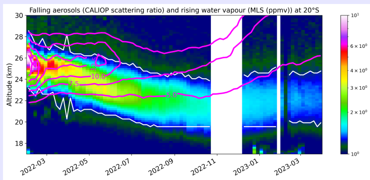
After a few days, the two clouds are turned into **elongated strips** (higher, southern and moistiest -> western strip, lower, northern -> eastern strip) which exhibit **different conversion rates** to sulfates according to their moisture and altitude.
SO_2 returns to background value by the end of January whereas sulfate aerosols persist in the stratosphere. IMS/IASI SA optical depth and CALIOP total extinction distributions evolve in the same way.

EVOLUTION OF THE ZONAL MEAN PLUME

OMPS-LP 745 nm daily zonal average aerosol extinction ratio
CALIOP 532 nm daily zonal average attenuated aerosol scattering ratio
MLS water vapour daily zonal average mixing ratio (ppmv)



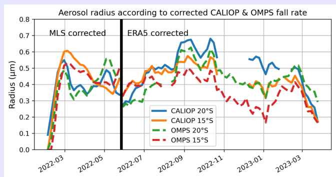
The initial fast descent of aerosols and water (>100 m/day) was attributed to **intense longwave cooling by water vapour** (Sellitto et al., 2022). Cooling is reduced but persists until June producing **temperature anomaly** (Schoeberl et al., 2022) and anomalous warming in ERA5 (here).



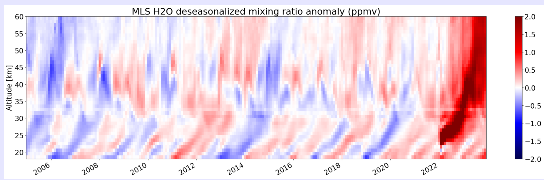
Plume's latitudinal extension stops at 20 in the NH while it extends close to the pole in the SH.
AEROSOLS : (CALIOP + OMPS-LP)

- After a period of **initial fast descent**, the plume stabilises near 24-25 km and descends slowly.
- Since 2023, **tropical ascent** linked to the Brewer Dobson circulation (BDC).
- In the same time, close to the South Pole, **fall towards the troposphere** through sedimentation.

WATER VAPOUR : (MLS)
Initially mixed with the aerosols, **water vapour separates by rising with air while aerosol sediment under gravity**, until the moist and aerosol layers are, respectively, above and below 25 km (see also Schoeberl et al., 2022). Since 2023, water vapour has behaved like aerosols, but at higher altitudes.

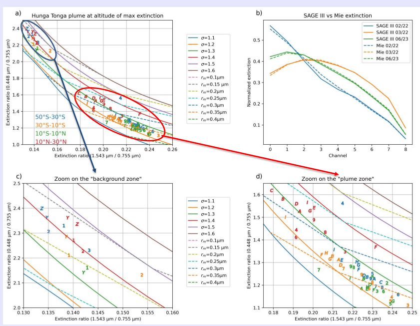


The aerosol size is estimated from fall speed using Stokes formula. Fall speed is estimated from the apparent descent speed corrected by the MLS water vapour ascent or by the ERA5 ascent (valid when the cooling effect of water vapour has ceased).
In the long term, **aerosols radius** seems to be around **0.4 μm**.



'Tape recorder' water vapour signal in the tropical stratosphere between 10°S and 10°N.
Very large water vapour disturbance which has no equivalent since at least 2006.
The **maximum perturbation is 5.36 ppmv** in March 2022 at 24.5 km altitude.

AEROSOL PLUME ANALYSIS (SAGE III)



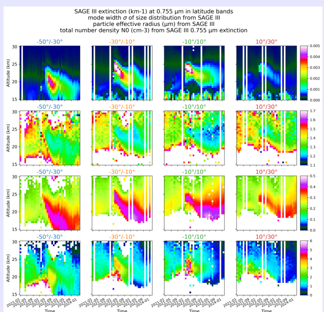
Retrieval of the **sulfate aerosols (SA) size distribution** based on the **two color ratios** 449 nm / 755 nm and 1543 nm / 755 nm for the aerosol extinction coefficients (Wrana et al., 2021).

Fig. a) : the curves for equal **mode width *σ*** and **median radius r_m** form a skewed grid in the domain of interest allowing the identification of the two parameters.

The good performance of the method can be appreciated from Fig. b) where modeled Mie extinctions using *σ* and r_m drawn from Fig. a) are compared to the SAGE III measured extinctions. The **agreement is excellent over the whole range** which is another indicator of the **absence of ash** in the plume.

Fig. c) & d) : observed extinction ratios at the level of maximum extinction in the **plume** are distributed over a domain of the diagram that clearly differs from the **background** points.

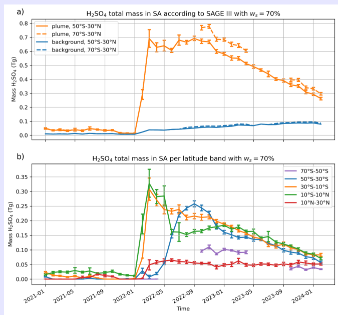
The **particle effective radius r_{eff}** can be estimated and then the **total number density N_0** using the extinction at 755 nm.



- *σ* : **1.2-1.3** in the plume, 1.4-1.5 for the background (Wrana et al., 2021) and 1.8-2.0 for other recent stratospheric volcanic plumes together with smaller sizes (Wrana et al., 2023).
- r_{eff} : ~ **0.4 μm** in the plume, 0.2 μm or less for the background (with Khaykin et al., 2022).
- N_0 : **3-5 cm^{-3}** in the plume, 20-30 cm^{-3} for other stratospheric volcanic plumes from recent eruptions with similar sulfur injection but much smaller particles (Wrana et al., 2023).

Recent comparison cases : Ambae in 2018, Raikoke & Ulawun in 2019 and La Soufrière in 2021.

H_2SO_4 mass in SA (H_2SO_4 weight percentage : 70%).
Between March and November 2022 : **0.66 Tg ± 0.1 Tg**, remarkably **constant** in spite of a **considerable redistribution in latitude** (b).
Matches initial SO_2 injection of 0.4-0.5 Tg (Carn et al., 2022; Millan et al., 2022).



CONCLUSIONS

- Main injection of the plume by 26-34 km with a saturated water profile. No ash remains after a few days in this range of altitudes.
- Fast conversion of SO_2 to sulfates, due to the presence of water. Persistent plume for at least 2 years.
- Fast initial descent of the plume (water and aerosol) until 20 Feb due to water vapour cooling.
- Following months : unmixing and separation of water which is rising in the BDC and aerosols which are sedimenting.
- The size distribution is characterized by larger particles than recent stratospheric eruptions with an unusually small mode width.
- The unusual size distribution of aerosols is related to the fast conversion of SO_2 to sulfates (Legras et al., 2022).
- The total mass of stratospheric H_2SO_4 is estimated at 0.66 Tg (matches estimates of the stratospheric SO_2 source of ~ 0.4-0.5 Tg).
- This mass has been found to be very stable over the period March 2022 to November 2022 after which it slowly declines linearly.

OTHER PARTNERS

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