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Perspective

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Indirect stratospheric moisture increase after a Pinatubo-magnitude eruption can be comparable to direct increase after 2022 Hunga

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The 2022 Hunga eruptions injected an observationally unprecedented amount of moisture directly into the stratosphere. However, stratospheric moisture can also be indirectly increased following a volcanic eruption, when heating from volcanic sulfate aerosol raises the tropical cold-point temperatures. In this work, we demonstrate that a 1 K increase in tropical cold-point temperatures can lead to indirect moisture increases in the stratosphere of comparable or even larger magnitude than observed for the direct injections during the Hunga eruptions. We base our reasoning on first-principle thermodynamic arguments combined with climate model and reanalysis output as well as observational data. We argue that following the next large-magnitude explosive eruption in the tropics, the strength of indirect increases in stratospheric moisture should be quantified using current measurement techniques.

Direct and indirect moisture pathways into the stratosphere after volcanic eruptions

Stratospheric water vapour is an important greenhouse gas and plays a key role in stratospheric chemistry[1–4]. Explosive volcanic eruptions can enhance the stratospheric moisture content both directly and indirectly. In the direct pathway, moisture is directly injected into the stratosphere from within the volcanic plume leading to anomalies in water vapour concentrations that are initially very large and highly localized. For the vast majority of direct injections, the corresponding moisture increases observed in the satellite era were negligible and short-lived[5,6]. However, it was proposed that direct moisture injections caused by explosive eruptions that entrain sea-water could lead to substantial and immediate increases in stratospheric moisture mass[7]. In 2022 the eruptions of Hunga—a submarine volcano—led to a substantial and clearly observable water vapour increase in the stratosphere via the direct pathway for the first time. Estimates for the directly injected water vapour include 139 ± 8[8], 146 ± 5[9], 50[10] and 70–150 Tg[11], which is approximately equal to 5–10% of the stratospheric background water vapour burden. In contrast, the observed emitted sulfur dioxide (SO_2) mass amounts to only 0.6–1.0 Tg SO_2[12,13]. Even when considering potential low-biases in the observational-based SO_2 estimates caused by the speedup of aerosol formation due to the increased availability of moisture within the plume[14,15], the injected water vapour amount is still at least one order of magnitude larger than the SO_2 amount. The interaction between sea-water and magma (phreato-magmatic eruption) also enhanced the explosivity of the Hunga eruptions, with the volcanic plume reaching a maximum altitude of 57 km[16]. In the first three weeks after the eruption, changes in infra-red forcing attributable to the enhanced water vapour at altitudes above 25 km led to the descent of the plume to lower altitudes in the stratosphere[17,18].

In contrast to the direct pathway, the indirect pathway results from the diabatic heating caused by the volcanic sulfate aerosol layer and relies on the control of moisture fluxes entering the stratosphere by the lowest temperatures between troposphere and stratosphere in the tropical tropopause layer (TTL)—the tropical cold-point temperatures[19,20]. In detail, volcanic sulfate aerosol not only scatters incoming solar shortwave radiation back to space, leading to surface cooling, but also absorbs near-infra-red and terrestrial longwave radiation. If sulfate aerosol is present in the TTL and lowermost tropical stratosphere, the associated tropical temperature increase will then allow for higher saturation specific humidity values and enhanced moisture fluxes into the stratosphere[21,22]. The increase in water vapour attributable to the indirect pathway depends on the magnitude and duration of volcanic sulfate aerosol heating in the TTL and, therefore, does not occur immediately after the climactic phase of an eruption but over a

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longer timescale in the aftermath of an eruption. For a tropical eruption of similar magnitude to the 1991 Mt. Pinatubo eruption (hereafter termed "Pinatubo-magnitude eruptions") TTL temperature increases reach peak values around three to six months after the eruption. Elevated TTL temperatures can then persist for around two years[23,24].

Apart from diabatic heating, the presence of volcanic sulfate aerosols may also influence cloud formation processes, thus impacting the upper tropospheric moisture budget by introducing additional cloud condensation nuclei. The overall impact on upper tropospheric clouds remains a subject of ongoing research, given the only recently emerging model capability to simulate corresponding aerosol-cloud-microphysical processes in global convection-resolving models with the required temporal and vertical resolution. However, based on observational data, 80% of the stratospheric moisture budget can be explained by slowly ascending water vapour, with the remaining portion being transported into the stratosphere by deep convection with no noteworthy contribution from transport in cirrus clouds[25]. Observation-based studies also suggest that explicitly accounting for changes in cloud condensation nuclei may not be necessary to sufficiently explain the stratospheric moisture budget even under volcanically perturbed conditions[26,27].

A quantitative comparison between the direct and indirect moisture transport pathway after volcanic eruptions is complicated, as the 1991 Mt. Pinatubo eruption—the most-relevant volcanic eruption for the indirect pathway in the satellite era to date—occurred during a time with observational data coverage inferior to today's standards and limited due to the presence of the sulfate aerosol layer, which led to retrieval problems making the corresponding stratospheric water vapour products unreliable[28–31]. Deducing the water vapour entry values from measurements at higher altitudes one year after the eruption will yield results that are biased low because water vapour is a reactant in the oxidation process of the emitted volcanic sulfur dioxide to sulfuric acid vapour. Additionally, an extremely unusual stratospheric eddy heat flux opposed the aerosol heating during this specific event, which further obscured the signal[32]. Nevertheless, the Stratosphere-troposphere Processes And their Role in Climate (SPARC) report in 2000[33] describes a positive trend in stratospheric water vapour for the years 1992–1996, amounting, in total, to an additional 0.5–0.7 ppmv at 20 and 40 km altitude, respectively, based on Halogen Occultation Experiment (HALOE) data. The SPARC authors also confirm that the corresponding signal is characteristic of an episodic event such as the 1991 eruption of Mt. Pinatubo. Some frost point hygrometer measurements even report temporal and local moisture increases in the TTL and lower stratosphere of 1–2 ppmv following the 1991 Mt. Pinatubo eruption[34]. These measurements are in agreement with results from modelling studies of volcanic eruptions of different magnitudes[35]. Importantly, microwave sounding units (MSU) temperature measurements in the TTL at the time of the 1991 Mt. Pinatubo eruption also show increases in the lower stratosphere and TTL temperatures of 0.5–1.5 K[36,37], although the heating is not as pronounced at the tropopause level as for the 1982 El Chichón eruption, potentially due to the aforementioned extremely unusual meteorological background conditions in 1991. Radiosonde measurements with a higher vertical resolution, however, documented cold-point temperature increases of 0.5–1.5 K, which were found to be in good agreement with changes in the water vapour entry values of up to 0.5 ppmv[30,38–40]. Based on these temperature changes, inferences of the stratospheric moisture increase can be made by using reanalysis data, which integrate the corresponding temperature measurements, in trajectory model calculations[26,27] and comparing against data from modelling studies, which prescribed the measured sulfur emission or aerosol distribution[22,24,41–43].

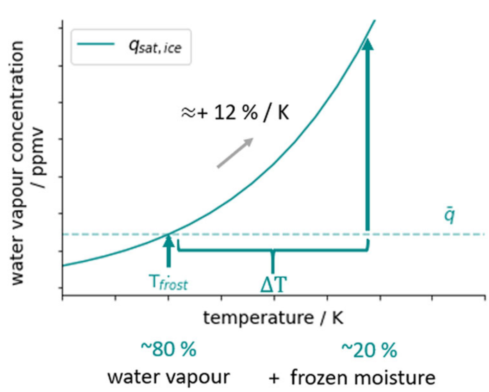

Fig. 1 | Clausius–Clapeyron scaling for vapour and frozen moisture at the cold-point tropopause. The saturation specific humidity at the EFT (T_{frost}) calculated via the Clausius–Clapeyron dependency (solid line) describes the mean specific humidity at the cold-point tropopause ($\bar{q}$, dashed line). The additional frozen moisture can be calculated by considering a constant temperature offset to the EFT.

Here, we present a conceptual framework that allows for a quantitative comparison of direct moisture injections and the more common indirect moisture increases after large-magnitude explosive volcanic eruptions in the tropics. For the corresponding estimate only three constants and the warming of the lowest cold-point temperatures in the TTL, the so-called equivalent frost-point temperature (EFT) have to be known. The EFT is defined here as the temperature that would set the average water vapour amount entering the tropical stratosphere from below when assuming a homogeneous cold-point temperature and water vapour fluxes which are constrained by the Clausius–Clapeyron equation.

Estimation of indirect stratospheric moisture increases via the dependence of saturation-specific humidity on temperature

Water vapour changes via the indirect pathway are temperature-dependent, thus moisture flux changes can be calculated based on two relationships:

1. After explosive volcanic eruptions, the water vapour increase at the cold-point tropopause follows the Clausius–Clapeyron scaling with a 12% rise per degree increase of the EFT[35,44].
2. The moisture partitioning in frozen and non-frozen contribution at the tropical cold-point tropopause remains constant at around 20%:80% even under temperature perturbations, which means that the frozen moisture also follows the Clausius–Clapeyron scaling at the cold-point tropopause[45,46]. The frozen moisture contribution can, therefore, be calculated by a temperature offset to the EFT (see Fig. 1).

Figure 2 shows an exemplary calculation of the moisture flux increase after a hypothetical tropical eruption leading to a 1 K increase in the EFT. The chosen temperature increase lies within the range of warming in the TTL and lower stratosphere after the 1991 Mt. Pinatubo eruption, which ranges between 0.5–1.5 K[37] and 2.0 ± 0.8 K[38] based on observational data. For our calculation, we assume a water vapour flux of 900 Tg per year into the volcanically unperturbed stratosphere[6]. With the 20% contribution of frozen moisture flux this yields a total moisture flux of 1125 Tg. If the EFT is enhanced by 1 K due to the presence of a stratospheric volcanic sulfate aerosol layer, the vapour flux per year will be increased to 1008 Tg following Clausius–Clapeyron scaling. With the additional frozen moisture, a total of 1260 Tg is obtained. This constitutes an increase of 135 Tg per year, which is close to the upper limit of the estimated range for the direct injection of 50–150 Tg during the 2022 Honga eruptions.

Moisture increases via the indirect pathway compared to water vapour directly injected by 2022 Hunga

For most eruptions, the emitted sulfur amount is better documented than the increase in EFT, thus we link both quantities in Table 1. We use EFT increases for four idealized tropical explosive volcanic eruptions emitting between 5 and 40 Tg S based on the model simulations[35]. The corresponding moisture increases are calculated using the presented framework. The respective EFT warming is based on the average EFT warming for the year after reaching the highest EFT, which occurs in the first year after an eruption. For 1991 Pinatubo, maximum temperature increases were observed around 90 days after the eruption itself[23]. The moisture increase after one year ranges between 86 Tg (for 5 Tg S) and 1298 Tg (for 40 Tg S).

Fig. 2 | Exemplary estimation of the stratospheric moisture increases via the indirect pathway. The total yearly moisture flux into the stratosphere is calculated for an unperturbed scenario (Control) and a scenario with a 1 K perturbation of the EFT (Perturbed). The calculation is based on a 12%/K increase in moisture according to Clausius–Clapeyron scaling in the TTL and an 80:20 partitioning of moisture fluxes in non-frozen and frozen contribution.

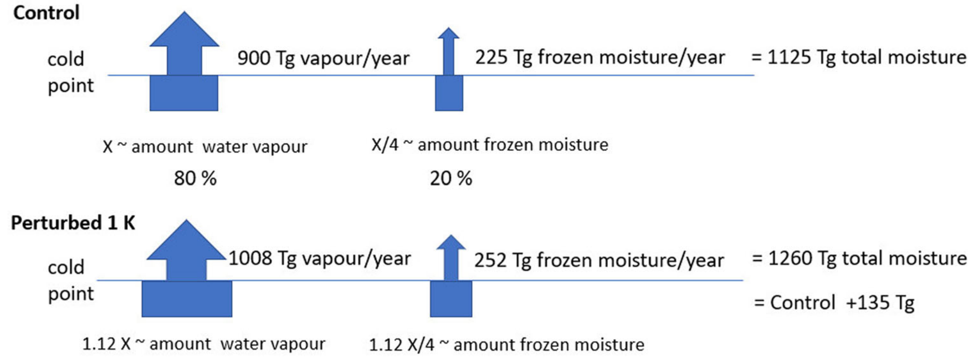

Table 1 | Estimate of the stratospheric moisture increase via the indirect pathway for four idealized explosive volcanic eruptions in the tropics

Emitted (S/Tg)	EFT warming (K)	$\Delta q_{80:20}$ (Tg/year)	comparable eruption with (year/Tg S)
5	0.65	86	1963 Mt. Agung 2.5–5 (3)
			1982 El Chichón 2.5–5 (3)
			1991 Mt. Pinatubo 5–10 (7)
10	2.08	299	1991 Mt. Pinatubo 5–10 (7)
20	4.30	706	1815 Mt. Tambora 14–30 (30)
40	6.77	1298	1815 Mt. Tambora 15–40 (30)

Emitted sulfur for four idealized volcanic eruptions in Tg of sulfur, and associated EFT warming given Kelvin[35]. $\Delta q_{80:20}$ (Tg/yr) denotes the increase in moisture flux due to the indirect pathway based on the presented conceptual calculation. Comparable eruptions with a range of emitted sulfur and best estimate (in parenthesis) are listed for reference.

The 1991 Mt. Pinatubo eruption emitted around 7 Tg S into the tropical stratosphere[47], which lies between our 5 and 10 Tg S scenarios. The moisture increase for the latter two scenarios via the indirect pathway is 86 and 299 Tg, respectively. This is slightly higher than the lowest estimate and double the highest estimate for 2022 Hunga.

Our result highlights the importance of considering the disparate durations over which the direct and indirect pathways operate. The direct pathway manifests peak water vapour anomalies almost instantly, whereas stratospheric water vapour concentrations increase continuously over the course of several months via the indirect pathway. It is, therefore, crucial to consider the long-term moisture transport into the stratosphere via the indirect pathway. Following the 2022 Hunga eruptions, Microwave Limb Sounder data revealed a height-dependent peak water vapour anomaly of 8 ppmv between [−30,0]°N within the first three months, contrasting with an initial highly localized water vapour anomaly of 1500 ppmv[17,48]. In contrast, analysis of the 1991 Mt. Pinatubo eruption indicated a stratospheric water vapour increase of up to 0.8 ppmv, based on trajectory calculations using MERRA-2 and JRA-55 reanalysis data between [−20,20]°N at $\theta = 400$ K. The corresponding one-year-average increase in water vapour concentrations via transport into the stratosphere amounted to 0.6 ppmv over a one-year-average background transport value of 4.2 ppmv[27]. Considering these boundary conditions, the net influx of 1125 Tg into the stratosphere and unchanged relative importance of moisture transport pathways, which were demonstrated even under cold-point temperature perturbation of more than 9 K[49], the stratospheric water vapour increase after 1991 Mt. Pinatubo, amounts up to 160 Tg over the course of 12 months compared to 50–150 Tg for the 2022 Hunga eruptions. The value of 160 Tg is calculated based on Eq. (1):

$$\delta q_{\text{entry}} = 1125\text{Tg} \cdot \frac{(0.6\,\text{ppmv} + 4.2\,\text{ppmv})}{4.2\,\text{ppmv}} - 1125\,\text{Tg} = 160.7\,\text{Tg}. \quad (1)$$

This estimate assumes a constant upwelling term. Some modelling studies have shown aerosol heating induced increases in upwelling after volcanic eruptions, especially near the atmospheric levels with highest aerosol concentrations[50,51], however observational studies have found little effect in the TTL region[52].

Conclusion

We conclude, that the magnitude of the moisture increase after the 2022 Hunga eruptions is not what makes Hunga so exceptional. Similar-magnitude moisture increases can be obtained via the indirect pathway, for Pinatubo-magnitude explosive eruptions in the tropics albeit on a different timescale than observed for 2022 Hunga.

What makes 2022 Hunga unprecedented, however, is the injection altitude, the observational coverage of a direct injection of this magnitude, and the radiatively-driven plume descent shortly after the eruption due to the highly localized moist volcanic cloud. Of additional interest is the comparatively low observed amount of sulfur emitted along with the moisture—a similar ratio would never be obtainable for the indirect pathway as the moisture increase is always a function of the heating in the TTL induced by the sulfate aerosol formed from the emitted sulfur. The directly injected moisture is, however, independent of the sulfur mass and aerosol altitude. This decoupling led to the possibility of a net positive total forcing after the Hunga eruptions, with the positive forcing of the emitted water vapour counterbalancing the negative forcing by the volcanic sulfate aerosol, although the sign of the long-term net radiative forcing is still being discussed. In model simulations, the estimated net forcing after 2022 Hunga ranges between a negative forcing of -0.2 W m^2 [48] and a positive forcing of up to 0.2 W m^2[17]. Some model studies conclude that the potential net positive forcing increased the likelihood of temporarily exceeding a global surface temperature anomaly of 1.5 K by 7%[53]. In contrast, the forcing due to indirect increases in stratospheric water vapour from a Pinatubo-magnitude eruption emitting 10 Tg S compensates around 4% of the negative sulfate aerosol forcing[35], whereby the combined tropospheric and stratospheric water vapour feedback amplifies the cooling[54] with a net negative forcing overall.

The next large-magnitude explosive eruption in the tropics might provide an opportunity to assess the strength of the indirect pathway using more comprehensive measurements than in the past. This would yield an estimate for the volcanically induced stratospheric water vapour increase that can be compared to that simulated in current-generation climate models.

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Author contributions

The idea to write this comment arose during a discussion between A.S. and C.A.K., following the C.A.K.'s talk on the indirect pathway. Using her quantification of stratospheric moisture increases after volcanic eruptions as a basis, C.A.K. wrote the first draft of the manuscript. Both A.S. and C.A.K. refined it.

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