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Tonga eruption increases chance of temporary surface temperature anomaly above 1.5°C

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On 15th January 2022, the Hunga Tonga-Hunga Ha'apai (HTHH) eruption injected 146 MtH2O and 0.42 MtSO2 into the stratosphere. This large water vapour perturbation means HTHH's will likely increase the net radiative forcing, unusual for a large volcanic eruption, increasing the chance of the global surface temperature anomaly temporary exceeding 1.5°C over the coming decade. Here, we estimate the radiative response to the HTHH eruption, and derive the increased risk that the global mean surface temperature anomaly shortly exceeds 1.5°C following the eruption. We show that HTHH has a tangible impact of the chance of imminent 1.5°C exceedance (increasing the chance of at least one of the next five years exceeding 1.5°C by 7%), but the level of climate policy ambition, particularly the mitigation of short-lived climate pollutants, dominates the 1.5°C exceedance outlook over decadal timescales.

The eruption of Hunga Tonga-Hunga Ha'apai (HTHH) on 15th January 2022 was one of the most well-observed in human history[1–4]. Ranked with a Volcanic Explosivity Index of 5[3], this was the most explosive eruption since Pinatubo in 1991, producing perturbations in surface pressure which reverberated around the globe for days after the climactic eruption event itself[1]. But perhaps more significant than this, the eruption was notable because of the composition of its stratospheric perturbation – an estimated 0.42 MtSO_2 sulphur dioxide injection[2,3] and 146 MtH_2O water vapour injection[5]. The HTHH eruption resulted in the largest stratospheric water vapour perturbation observed in the satellite era (a 10-15% increase in the water vapour content of the stratosphere), with a modest accompanying SO_2 injection (approximately 1/50th the size of the Pinatubo eruption[6]).

Most large volcanic eruptions are notable for their negative perturbation on global surface temperatures, since they emit large quantities of SO_2, an aerosol particulate which scatters incoming solar radiation. However, it is possible that over a multi-year period HTHH will cause a temporary increase in global surface temperatures due to this large water vapour increase and lack of a large counterbalancing sulphate aerosol perturbation[7]. Some groups have separately calculated the radiative impact of the SO_2 injection[8], ignoring the impact of the large water vapour perturbation, while others have included the water vapour[9], but focus on the negative radiative perturbation caused by an increased rate of hydrolysis of SO_2 to H_2SO_4, and not the impact of the water vapour itself. Estimates of the combined radiative perturbation resulting from the HTHH eruption are dominated by the water vapour contribution, resulting in a positive net radiative forcing perturbation despite the increased rate of SO_2 hydrolysis[7], and meaning the multi-year climate response to HTHH is determined by the evolution of the stratospheric water vapour perturbation. If a large fraction of the injected stratospheric water vapour plume remains over several years, the HTHH eruption could measurably, albeit temporarily, change the likelihood of the global mean surface temperature (GMST) anomaly exceeding 1.5°C. This is not identical to 1.5°C-exceedance in the context of the Paris Agreement, which relies on GMST averaged over a multidecade interval, isolating the long-term trend. Despite this, the first year which exceeds 1.5°C will garner significant media attention, even if a portion of this results from HTHH. Here, we look to place the likelihood of 1.5°C-exceedance into context by understanding the contribution from the HTHH eruption.

In May 2022 the World Meteorological Organisation published its assessment of the probability of the annual-average GMST anomaly exceeding 1.5°C in at least one of the next five years, determining a 50:50 chance that a 1.5°C year (GMST relative to 1850-1900 baseline) would be recorded between 2022-2026[10,11]. This analysis used several full-complexity general circulation models forced with prescribed historical concentration timeseries until present day and the SSP2-45[12] scenario thereafter (following the Decadal Climate Prediction Project protocol[13]), but did not include the impact of the recent HTHH eruption. To consider the impact of this eruption on this statement, we first require an estimate the additional instantaneous radiative forcing (IRF) resulting from a well-mixed (±60°N/S, 7.5hPa-40hPa) 146 MtH_2O stratospheric water vapour injection.

We estimate this using the SOCRATES Radiative Transfer Model[14,15] using a representative near-present day ERA5 reanalysis atmospheric profile[16] (the full protocol used to determine the water vapour's IRF contribution is described in the methods). In January 2022, a water vapour perturbation of 1 ppm mass mixing ratio (MMR) of H_2O is added to the background climatology state between 40 and 7.5 hPa, and 60°S and 60°N. Over this domain a 1 ppm MMR increase is very close to the 146 Tg H_2O mass of water vapour increase estimated by retrievals from the Microwave Limb Sounder on board NASA's Aura satellite[5]. This results in a +0.12 (±0.04) W/m^2 IRF perturbation directly following the eruption event, which subsequently decays as the stratospheric water vapour perturbation is removed over the following decade. The uncertainty range on this IRF estimate is calculated using various alternative domains for the vertical and horizontal spread of the water vapour, as described in methods. We ignore the negative IRF contribution from the accompanying SO_2 deposit since the SO_2 deposit is significantly smaller than the accompanying water vapour deposit[7], and it is unclear that the SO_2's cooling response would be measurable following a HTHH-sized stratospheric SO_2 injection[17]. Some studies[9] which include the SO_2 injection and find a net-negative IRF in the initial months following the eruption, however the size of this negative IRF appears inconsistent with the context of other similarly sized tropical eruptions in the observational record[17], and with observations of tropical stratospheric temperatures which are consistent with a large radiative perturbation due to the water vapour injection[18]. Despite this simplification, our IRF perturbation is consistent with other groups' estimates of the combined radiative forcing perturbation from HTHH[7].

These are used to construct perturbed effective radiative forcing (ERF) scenarios by adding the HTHH IRF timeseries to the background ERF scenario (*historical*+SSP2-4.5[19]; see figure S1 in the SI), assuming stratospheric water vapour's IRF is approximately equal to its ERF. The warming response are computed using the FaIRv2.0 simple climate model[20] (see methods). We also include two further scenarios assuming that a 1.5°C-consistent mitigation pathway is followed beyond present day (i.e. following a *historical*+SSP1-1.9[19] ERF timeseries, with and without HTHH), to assess the relative impact of the HTHH eruption compared to global mitigation decisions over the next decade.

The resulting GMST anomaly for each scenario is shown in figure 1a. The *historical*+SSP2-4.5 ERF scenario including HTHH is shown in green, and excluding HTHH in light grey (best-estimate shown with solid lines, dotted lines denote a plume showing 5-95th percentile range). The two SSP1-1.9 scenarios are also shown on panel a (blue including HTHH, dark grey excluding HTHH). For all scenarios the GMST anomaly lies around 1.1°C between 2010-2019 compared to 1850-1900 preindustrial reference period, consistent with estimates from the IPCC's Sixth Assessment Report[21]. Solid lines in panel b show the increasing risk of 1.5°C-exceedence for each scenario between 2015-2035, calculated as the fraction of a 50,000 member GMST ensemble which exceeds 1.5°C in each year. Following the HTHH eruption, the GMST anomaly increases (green and blue lines), meaning the chance of 1.5°C-exceedence in any year in the decade following HTHH is elevated compared to the baseline cases (grey lines). The cumulative probability of remaining below 1.5°C (dashed lines in panel b) decreases rapidly from 2022 in all scenarios, but faster for scenarios including HTHH, since these include an additional positive radiative forcing from HTHH. Over the five-year period 2022-2026, the light grey *historical*+SSP2-45 scenario has a 50% probability of 1.5°C-exceedence, which increases to 57% once the HTHH eruption is included (green).

While this increase in 1.5°C-exceedence risk is important, over multi-year timescales the changing risk profile for 1.5°C-exceedence is still dominated by human choices. Following a 1.5°C-consistent mitigation pathway beyond present day (dark grey) results in a similar 2022-2026 1.5°C-exceedence risk (60%) without including the impact of the HTHH eruption. This is because the rapid mitigation of short-lived climate pollutants (principally aerosols and methane) in a highly ambitious mitigation pathway results in a temporary increase in the ERF over the next decade, and therefore a temporary increase in the rate of anthropogenic warming. Additionally including the HTHH eruption in this *historical*+SSP1-1.9 scenario (blue) results in a two-thirds probability of 1.5°C-exceedence between 2022-2026 (67%).

While the HTHH eruption produces a measurable change in the probability of imminent 1.5°C-exceedence for any given scenario, human choices still dominate the decadal risk outlook. Further, crossing 1.5°C in a single year does not mean the Paris Agreement has failed. Although exposure to climate risk increases with elevated GMST regardless of cause, exceedance of temperature thresholds in the Paris Agreement are based strictly on the anthropogenic contribution to GMST; natural forcing and the climate system's internal variability does not play a role in dictating whether these thresholds have been crossed. Despite this, the HTHH eruption temporarily does increase the GMST anomaly over the next five years, while stratospheric water vapour concentrations are perturbed[5]. Over this period HTHH increases the likelihood we observe our first 1.5°C year by around 7%.

Data Availability Statement

The ERA5 data required to estimate the radiative perturbation caused by the HTHH eruption are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=overview[22], including atmospheric temperature, specific humidity (water vapour mass mixing ratio), ozone mass mixing ratio, cloud fraction, cloud liquid and ice water content, evaluated on pressure levels. ERA5 surface albedo and surface temperature variables are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form[23]. The Shared Socioeconomic Pathways Effective Radiative Forcing timeseries used to estimate the global temperature response are available at https://doi.org/10.5281/zenodo.5705391[24].

Code Availability Statement

The FaIRv2.0 simple climate model used to estimate the global temperature response is available at https://doi.org/10.5281/zenodo.4683173[20]. The SOCRATES radiative transfer model is available at https://code.metoffice.gov.uk/trac/socrates/wiki[15], with instructions on how to access in https://homepages.see.leeds.ac.uk/~lecsjed/winscpuse/socrates_userguide.pdf. Figure production code is available from https://doi.org/10.5281/zenodo.7319240[24].

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Author Contributions Statement

SJ, MA and RG designed the study. CS ran the SOCRATES offline radiative transfer calculations. SJ computed the temperature response with FaIRv2.0, analysed the results and produced the figure. All authors contributed to writing the manuscript.

Competing Interests Statement

The authors declare no competing interests.

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Methods

Estimating the radiative perturbation from HTHH

To calculate the radiative perturbation in response to the HTHH eruption, we started with a monthly background climatology for the year 2014 from ERA5[1-3]. The base year does not make a large difference for instantaneous radiative forcing (IRF) calculations[4]. ERA5 climatological data comprises atmospheric temperature, specific humidity (water vapour mass mixing ratio), ozone mass mixing ratio, cloud fraction, cloud liquid and ice water content, surface albedo and surface temperature. The variables with three spatial dimensions are retrieved on the CMIP6 pressure layers (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10, 5, 1 hPa). For running the SOCRATES radiative transfer code, layer boundaries need to be defined so we chose the linear midpoint of layers as the boundaries with 1013.25 hPa as the surface pressure and 0 hPa at the top of atmosphere.

Simulations were run from January 2022 to December 2028. In January 2022, a water vapour perturbation of 1 ppm mass mixing ratio (MMR) of H_2O was added to the 30 hPa, 20 hPa and 10 hPa layers in the background climatology (i.e. bounded by 40 and 7.5 hPa) between 60°S and 60°N. Over that domain a 1 ppm MMR increase is very close to the 146 Tg H_2O mass of water vapour increase estimated by retrievals from the Microwave Limb Sounder on board NASA's Aura satellite[5]. The amount of water vapour that we added to this stratospheric domain in addition to the ERA5 baseline climatology decreases linearly every month over 7 years from 1 ppm MMR in January 2022 to zero in January 2029 (based on an estimate of a 5-10 year decay timescale in Millán et al. (2022)[5]). We calculated the net (longwave plus shortwave) IRF for each month as the difference of a pair of radiative transfer simulations using the SOCRATES broad-band radiation code[6,7], taking the flux differences (downwelling minus upwelling) at a latitude-dependent tropopause height[8]. Shortwave radiative forcing was calculated as the weighted sum of 5 representative solar zenith angles at each latitude in each month using Gaussian quadrature. The net IRF for January 2022 with the largest water vapour perturbation is +0.12 Wm^{-2}, comparable to the +0.15 Wm^{-2} estimated in Millán et al. (2022)[5]. IRF at the tropopause is assumed to be similar to effective radiative forcing (ERF) at the top of atmosphere in the absence of any specific literature evidence to the contrary, for which ERF has a closer correspondence to global mean surface temperature than IRF where they differ[9]. The stratospheric water vapour IRF calculated each month was averaged over each year.

Sensitivity analysis

As a sensitivity study we recalculated the IRF with several alternative assumptions for the vertical and horizontal spread of the water vapour plume, conserving the 146 Tg H_2O mass water vapour perturbation throughout. These include: 1) 60S-60N, 4 hPa - 25 hPa, 1.5 ppb (one model level higher), 2) 60S-60N, 15 hPa - 60 hPa, 0.7 ppb (one model level lower), 3) 60S-60N, 4 hPa - 60 hPa, 0.6 ppb (more vertical spread), 4) 90S-90N, 7.5 hPa - 40 hPa, 0.9 ppb (plume spreads globally), 5) 30S-30N, 7.5 hPa - 40 hPa, 1.7 ppb (plume confined to tropics). The experiments which varied the height of the plume show little influence on the globally averaged IRF response (see SI figure S2). Assuming wide or narrow horizontal plume spreads following the water vapour injection scaled the initial IRF response by a factor of two (+0.08 Wm^{-2} for the narrow plume vs. +0.16 Wm^{-2} for the wide plume). In all experiments cases we ignored the impact of the SO_2 injection. While in theory this biased our calculated IRF responses high, in practise the SOCRATES offline radiative transfer calculation was unlikely to change significantly with the SO_2 injection included, since it is so small for the HTHH eruption. Zuo et al. (2022) estimated the GMST response to HTHH to be -0.004°C in the year following the eruption, based on linearly scaling the surface temperature anomaly after large southern volcanic eruptions to the intensity of HTHH's 0.42 $MtSO_2$ injection[10] (substantially smaller than the +0.035°C peak temperature anomaly response to HTHH water vapour plume we calculated here).

Estimating the temperature response

A perturbed effective radiative forcing (ERF) scenario was then produced by adding the HTHH IRF timeseries to the background ERF scenario (*historical*+SSP2-4.5 or *historical*+SSP1-19[11]; shown in figure S1 of the SI), assuming stratospheric water vapour's IRF was approximately equal to its ERF. The warming response to the HTHH-perturbed and unperturbed scenarios were computed with the FaIRv2.0 simple climate model[12], using best-estimate observationally-constrained physical response parameters. Having determined the warming response to these drivers, additional uncorrelated 'internal variability' noise (normally distributed; σ=0.2°C, n=50,000-member ensemble) was added to the temperature anomaly to produce GMST-like temperature anomaly realisations covering the entire historical and near-future period. The standard deviation of the internal variability distribution is chosen to reproduce the WMO's result that the probability of 1.5°C-exceedence between 2022-2026 in the unperturbed *historical*+SSP2-4.5 scenario is 50%[13].

All code to reproduce the figures is available at https://doi.org/10.5281/zenodo.7319240[14].

Methods References

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Figure captions

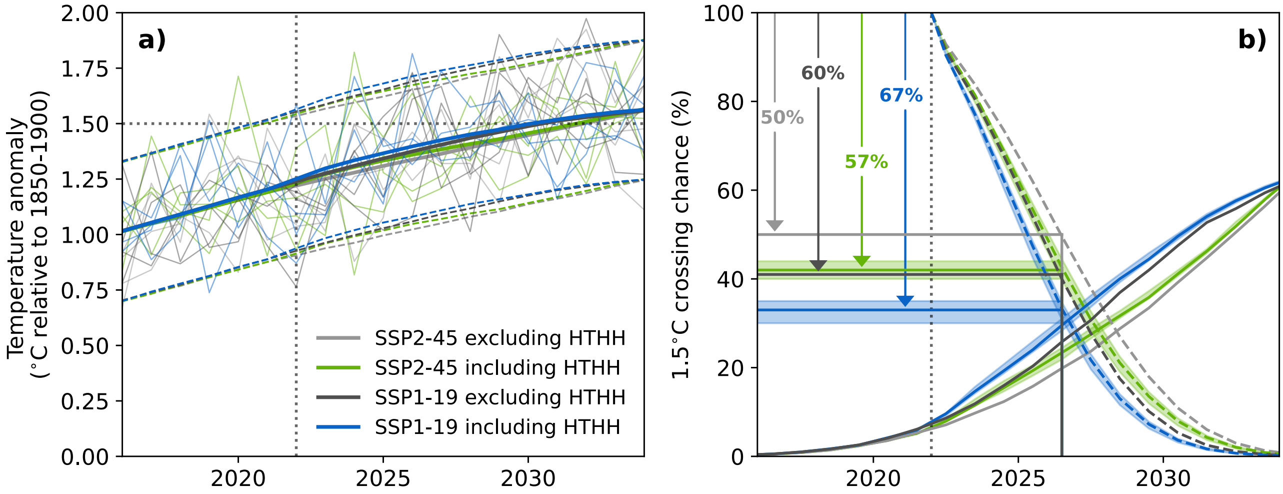

Figure 1: Impact of the 2022 HTHH eruption on projected global average surface temperature anomaly between 2015 and 2035. HTHH eruption occurs in 2022 (vertical dotted lines). Panel a plots the temperature anomaly relative to 1850-1900 calculated with FaIRv2.0 and best-estimate climate response parameters for two SSP scenarios (SSP2-45, current policy trajectory; and SSP1-19, ambitious mitigation pathway), both including (green/blue for SSP2-45/SSP1-19) and excluding (light/dark grey for SSP2-45/SSP1-19) the estimated forcing response to the HTHH eruption. Dashed lines show the 5-95th percentile range; best-estimate responses are shown with thick coloured lines; thin lines show interannual variability. Panel b shows the likelihood of global surface temperature anomaly exceeding 1.5°C between 2015-2035 (solid lines) and the cumulative probability that no year has yet exceeded 1.5°C (dashed lines). Cumulative risk of 1.5°C-exceedance for the five years 2022-2026 are marked with arrows in the top left corner of panel b. The shaded ranges show the uncertainty in the 2022-2026 1.5°C-exceedance risk.