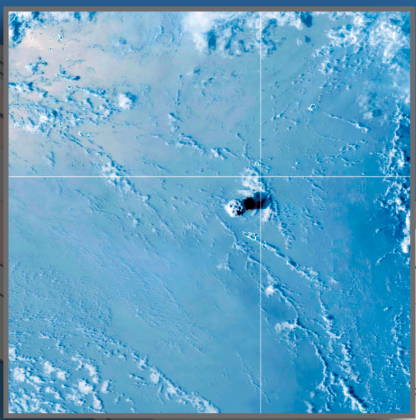
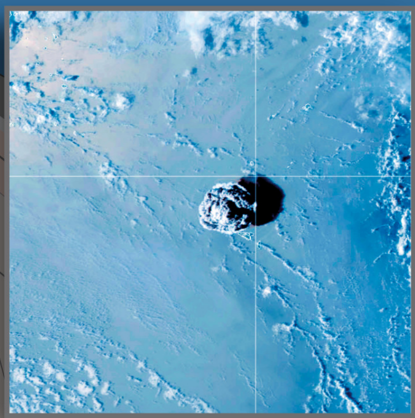
THE HUNGA VOLCANIC ERUPTION

Atmospheric Impacts Report

2025





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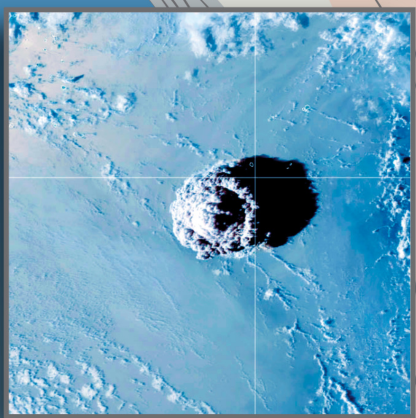

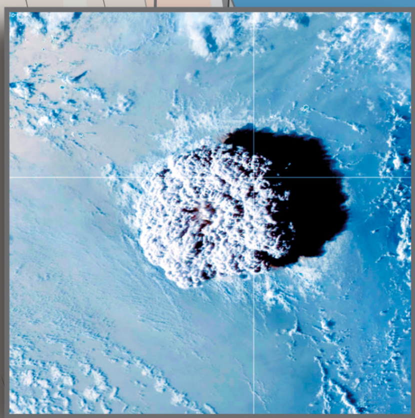

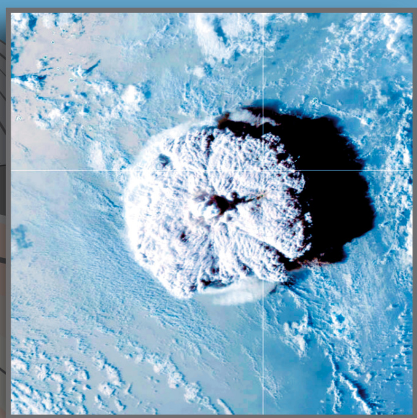

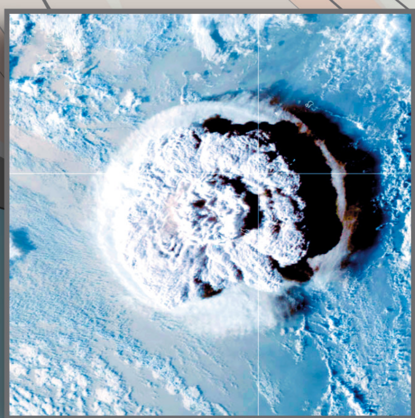

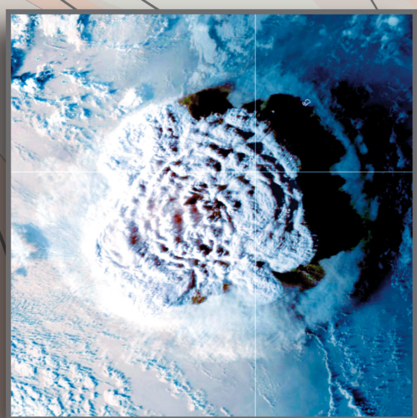

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The Hunga Volcanic Eruption Atmospheric Impacts Report

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Final author meeting
Executive summary and Highlights
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We acknowledge the key role satellite observational programs funded by US, European, Canadian, Japanese, and other atmospheric and space science agencies played, enabling global monitoring of the evolving Hunga volcanic cloud. In particular, the MLS instrument on the Aura satellite, the SAGE-III instrument on the International Space Station, and many others (e.g., ACE-FTS, OMPS, OSIRIS, MISR, MODIS, GPS-RO, DSCOVR/EPIC, N20/NPP NM), provided benchmark measurement datasets for the Hunga-excess water vapour and volcanic aerosol in the stratosphere. We note Hunga is the first time lidar measurements from satellite have monitored a deep-stratosphere injecting volcanic eruption cloud. And we acknowledge the joint public investment from NASA and the French space agency (CNES) that enabled this, to measure the vertical structure of the full extent of the dispersing Hunga volcanic cloud, from the CALIOP lidar on the CALIPSO satellite.

In the initial hours and days after the Hunga eruption, the geostationary GOES and Himawari satellite instruments measured the atmospheric waves and properties of the umbrella cloud of ice, ash and sulfate aerosol, these capabilities funded by NOAA and NASA, and the Japanese meteorological agency (JMA) respectively. A key element of the early-phase post-eruption satellite monitoring of such an explosive event requires quantifying the sulfur released to the stratosphere, for potential climate and ozone impacts. In this regard, the Aura, Sentinel-5 and MetOp-B satellite hosting the OMI, TROPOMI and IASI instruments, were key to establishing a reliable consensus on the emitted sulfur.

We acknowledge also the value of in-situ measurements and ground-based remote sensing networks (e.g. TAC/BUFR radiosonde, NDACC, NOAA B2SAP, AERONET, WMO GAW, GNSS, and other ground-based balloon and lidar systems hosted by different countries) in providing ground-truth information to validate satellite assessments and to ensure reliable model predictions. We are grateful for the international collaborations that led to two field campaigns specifically to measure the progressing global dispersion of the Hunga cloud: the balloon and lidar monitoring in the TR2Ex rapid response campaign from Reunion Island, and the BraVo field campaigns from Sao Paulo. We recognise also the value of prior co-ordination via the NASA VolRes co-ordination activity to prepare for future major eruption (see Carn et al., 2021).

We acknowledge also the investment leading to the long-term record of air temperatures in the stratosphere from the SSU (1978-2006) and AMSU (2001-present) sounders on the NOAA series of satellites. The long-term records provide important datasets to understand the opposite-sign post-volcanic cooling of the stratosphere after Hunga, compared to the warming after El Chichón and Pinatubo (see Figure ES-3). We also acknowledge other valuable atmospheric data for monitoring the gravity wave propagation into the upper atmosphere, and the atmospheric waves and ionospheric perturbations from the initial Hunga explosions.

This report has aligned closely with two of APARC's activities, the Stratospheric Sulfur and its Role in Climate (SSiRC) and Chemistry Climate Model Initiative (CCMI). We thank the support of University of Leeds and Ecole Normale Superieure, Paris, for hosting the Hunga activity open science workshops in 2022 and 2024, and NSF NCAR Boulder for hosting the Hunga assessment meeting in 2025. Funding from NASA and APARC provided travel support for early career and scientists from the global south to attend the meetings in person.

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Contents

Highlights

- **The 15th January 2022 eruption of Hunga volcano was a high-magnitude (Volcanic Explosivity Index 6) submarine explosive eruption unique in the era of satellite observations.** The shallow underwater setting led to interaction of volcanic magma and seawater, making this event distinct from large subaerial eruptions of recent decades (e.g., Mt. Pinatubo in 1991). The Hunga eruption increased the global stratospheric water burden by ∼10%, and most of this water vapour remains in the stratosphere through 2025. The shallow underwater setting removed most of the volcanic sulfur released, and a modest amount of sulfur dioxide (SO_2, 0.5–1 Tg) was transported into the stratosphere.

- **Hunga water vapour led to a cooling of 0.5–1 K in the global mid-to-upper stratosphere over the first two years after the eruption and >1 K in the mesosphere afterwards.** This contrasts with previous major volcanic eruptions where aerosols led to stratospheric warming.

- **In the months following the eruption, substantial perturbations in stratospheric ozone and related trace gases were observed throughout the Southern Hemisphere.** The changes in 2022, while partly driven by anomalous heterogeneous chemistry on volcanic aerosol, were dominated by transport. The extent to which transport anomalies were causally connected to the eruption is not clear. Low ozone abundances observed in the SH midlatitude lower stratosphere had minor impacts on total column ozone.

- **The Hunga eruption had no significant impact on the Antarctic ozone hole or ozone in the Arctic stratosphere.**

- **The record-high global surface temperatures in 2023/2024 were not due to the Hunga eruption.** The Hunga global-mean tropopause radiative forcing was about $-0.4\ \mathrm{W\,m^{-2}}$ averaged over the first two years; this cooling was mainly caused by aerosol attenuation of solar radiation. The maximum Hunga-induced cooling in global surface air temperature was estimated to be 0.05 K (with about 50% uncertainty), but this cooling is indistinguishable from background variability in the current climate. Surface climate impacts of the eruption—driven either directly by radiation or indirectly by Hunga-induced changes in atmospheric circulation and stratosphere–troposphere coupling—are relatively small and not distinguishable from the background internal variability of the Earth system.

- **After 2024, the Hunga aerosol loading largely disappeared. The remaining Hunga stratospheric water vapour positive radiative forcing is expected to be negligible.**

- **The Hunga eruption and its aftermath provided a unique opportunity to assess the impacts of a water-rich volcanic eruption, where sulfate aerosol formed unusually fast.**

- **Global chemistry–climate models consistently reproduce key aspects of the observed middle-atmospheric transport, temperature change, and mesospheric ozone response after the Hunga eruption.** Models are critical tools to elucidate the detailed chemical, radiative, and dynamical impacts on the Earth system from volcanic events, especially in the context of interannual variability. Models differ in their simulations of Hunga aerosol microphysical properties, indicating that simulating aerosol microphysics remains a challenge for model development.

- **Comprehensive observations of the Hunga eruption and its aftermath were produced by satellites, balloons, and ground observation networks developed over the last few decades by many countries.** These observations were critical for understanding the Hunga atmospheric impacts. Geostationary satellite measurements yielded minute-by-minute observations of the eruption cloud evolution and spread. The NASA Aura Microwave Limb Sounder (MLS) provided global observations of the high water vapour from Hunga. Additional observations from MLS and NASA/NOAA ozone instruments characterised stratospheric chemistry changes following the eruption. Observations from the Stratospheric Aerosol and Gas Experiment III on the International Space Station, the joint NASA/CNES Cloud-Aerosol Lidar with Orthogonal Polarization, and NOAA/NASA Ozone Mapping and Profiler Suite documented the evolution of the sulfate aerosol layer. The rapid-response balloon deployment to La Réunion in the Indian Ocean within the first week after the Hunga eruption quantified early development of aerosols and sulfur dioxide in the Hunga stratospheric plume. The Network for the Detection of Atmospheric Composition Change and the AErosol RObotic NETwork of ground-based instruments provided observations of composition and aerosol spread. Other satellites and instruments, unnamed here, contributed to understanding of the Hunga impacts.

- **Loss of observational capabilities will severely hinder our ability to observe future volcanic eruptions and other stratospheric aerosol injections and to understand their impacts.** Hunga research illustrates the importance of global satellite measurements of chemical constituents, temperature, and aerosols. Gaps due to asset cancellation and lack of new instrument deployments will result in far fewer key observations (in particular, vertically resolved water vapour measurements) that were critical for understanding the Hunga impacts. Gaps could be covered with high-altitude aircraft missions to sample stratospheric plumes, expanded research-quality balloon sampling, and additional ground-based network observations.

Executive summary

Introduction

On 15 January 2022 a highly explosive eruption of the Hunga volcano occurred in the Kingdom of Tonga in the South Pacific Ocean (175°24' W, 20°33' S). The Volcanic Explosivity Index (VEI) 6 eruption originated from a shallow submarine vent, making it distinct from large subaerial eruptions of recent decades (e.g., 1982 El Chichón, 1991 Mt. Pinatubo). In particular, seawater enhanced explosivity and dampened sulfur dioxide (SO_2) emissions. The eruption was the culmination of ~1 month of precursory activity; however, the timing and size of the eruption were unexpected, partly due to the challenges of monitoring submarine volcanoes. The stratospheric hydration caused by the eruption was unprecedented in magnitude, altitude, and duration in the satellite record.

This Executive Summary reflects the current assessment of the Hunga eruption and its impact on the climate system. We report key observations of the eruption and its aftermath, as well as simulations of its impact by global chemistry-climate models. The Hunga eruption had an unprecedented impact on the stratosphere and mesosphere due to the plume height and large water content, which increased the global stratospheric water vapour burden by 10%. Most of this water has remained in the atmosphere into 2025. However, Hunga's net impact on surface climate was small compared to that of earlier large-magnitude volcanic eruptions, due to limited sulfate aerosol loading in the stratosphere and the high altitude of the water vapour injection.

The eruption and its emissions

- The paroxysmal plume appeared at around 04 UTC on 15 January 2022, with geophysical signals subsiding by approximately 15 UTC.
- Post-eruption bathymetric observations suggest that the Hunga eruption, with a VEI of 6, was similar in magnitude to the 1991 Mt. Pinatubo eruption.
- The highest plume overshoot reached 58 km altitude in the lower mesosphere. The main volcanic plume detrained at 30-35 km, with rapid descent over a few days to a layer at 26-30 km altitude.
- The umbrella cloud expanded to a diameter of 400 km within an hour and was blown westward by stratospheric winds. The Hunga ash cloud disappeared within 15 hours of forming, probably washed out by massive precipitation of ice and water, scavenging the ash.
- The Hunga eruption is estimated to have emitted ~20 Tg of SO_2, but ~95% was removed in the seawater, such that only ~0.5-1 Tg reached the stratosphere. This is at least an order of magnitude less than Mt. Pinatubo's stratospheric injection of SO_2.
- Hunga injected an exceptional amount of water into the stratosphere, causing a ~10% (~150 Tg) increase in the global stratospheric water vapour burden.
- The eruption injected very minor amounts of halogens into the stratosphere.
- The stratospheric injection of salt from seawater is subject to ongoing research. Based on all available measurements the presence of salt in the Hunga aerosol that remained in the atmosphere was likely minor.
- Hunga generated the most intense lightning (peak intensity >2,615 flashes min^{-1}) ever observed in Earth's atmosphere. However, the lightning-generated perturbations in nitrogen oxides (NO_x) and related stratospheric chemistry were not observed.

Transport of the volcanic water and aerosol cloud

- The infrared cooling due to Hunga water vapour caused the initial cloud to descend to around 23-27 km altitude by the middle of February 2022, where it resided for the following few months. (See A on Figures ES-1c and ES-1d)
- Easterly stratospheric winds moved the volcanic cloud westward; several downwind ground-based observations and a rapid response campaign successfully measured the fresh volcanic cloud in the weeks following the eruption.
- Within a month after the eruption, the volcanic cloud had spread across the tropics between 30°S and 10°N latitude. (See B on Figures ES-1a and ES-1b)
- The Hunga water vapour and aerosol were initially co-located but began to separate in altitude in the first months after the eruption as the aerosol particles grew and sedimented toward the lower stratosphere. This separation resulted in different long-term transport of the water vapour and aerosol. (compare C between Figures ES-1c and ES-1d)
- After initially covering the lower-stratospheric tropics in February 2022, both water vapour and aerosol spread into the southern midlatitudes during the austral fall (April-June 2022) as the stratospheric flow reversed from westward to eastward (See D on Figures ES-1a and ES-1b).
- Hunga water vapour had spread to the Northern Hemisphere (NH) midlatitudes about one year after the eruption in January-March 2023. (see E on Figures ES-1a and ES-1b)
- The excess water vapour remained at 20-32 km altitude until October 2022. After November 2022, the Hunga water vapour was carried upward by the tropical stratospheric circulation and reached the mesosphere by early 2023 (see F on Figure ES-1c). By mid-2023, the Hunga water vapour was meridionally well mixed across both hemispheres in the mesosphere (50-80 km).
- The water vapour reached both polar regions after the breakdown of the Southern Hemisphere (SH) and NH polar vortices in December 2022 and April 2023, respectively. Enhanced water vapour from Hunga was also observed in subsequent years and continues to persist in the stratosphere up through the present (mid-2025). See G in both hemispheres on Figure ES-1a.
- Volcanic aerosol remained mostly in the tropics and SH lower stratosphere through 2024. While the bulk of the aerosol and water vapour did not penetrate the Antarctic vortex in 2022, observations suggest that there was some aerosol transport to high southern latitudes in the lowermost stratosphere in June 2022.
- Global chemistry-climate models simulate key aspects of the southward transport and vertical separation of the volcanic aerosol from the water vapour, indicating satisfactory representation of the large-scale circulation and particle sedimentation. The cross-equatorial transport of the aerosol from the SH to the NH is underestimated. (Figure ES-2)
- Aura Microwave Limb Sounder (MLS) measurements and model simulations suggest that the excess Hunga stratospheric water vapour will persist through the end of this decade. (Figure ES-2)

Aerosol cloud evolution

- Hunga produced the largest global stratospheric aerosol optical depth (SAOD) since Mt. Pinatubo in 1991. (Figures ES-1b and ES-1d)
- The aerosol particles grew to an effective radius of 0.4 μm in the densest part of the volcanic cloud within a couple of weeks, and the size was roughly maintained through the first two years. The rapid growth occurred through fast conversion of the SO_2 to sulfate aerosol due to the high water vapour providing abundant OH for SO_2 oxidation. The aerosol sedimented gradually toward the tropopause.
- Models simulate a rapid growth in aerosol effective radius, up to 0.3-0.5 um (depending on the model), then the simulated effective radius decreases faster than is observed.
- The first significant post-Hunga SAOD perturbation, caused by the Ruang volcanic eruption in April 2024, ended the period of Hunga-driven stratospheric aerosol perturbation. (see R in Figures ES-1b and ES-1d)
- The Hunga eruption highlighted challenges in limb scattering satellite aerosol retrieval algorithms. Solar occultation measurements provide an accurate measurement, but with sparse sampling.

Impacts on stratospheric and mesospheric ozone and related constituents

- The Hunga eruption initially caused a rapid 5% reduction in ozone in the 25–29 km layer over the tropical southwestern Pacific and Indian Ocean region within the first two weeks after the eruption. The ozone loss was driven by the Hunga excess water vapour intensifying both gas-phase and heterogeneous chemistry on aerosol.
- Starting in mid-2022, heterogeneous chemical processing led to widespread perturbations in stratospheric chlorine and nitrogen partitioning of unprecedented magnitude and duration in the southern tropics and midlatitudes. Although the observed chlorine activation was exceptional for those latitudes, the chlorine radical concentration was still an order of magnitude less than that observed in a typical polar winter.
- Record-low abundances of stratospheric ozone were observed in the southern midlatitudes in the months following the eruption. However, the degree of ozone destruction due to heterogeneous chemistry on volcanic sulfate aerosol was relatively minor, and the observed ozone changes in the tropics and southern midlatitudes were largely produced by transport.
- Hunga has not substantially perturbed the Antarctic ozone hole.
  - In 2022 the Hunga water vapour was excluded from the Antarctic polar vortex by the strong transport barrier at the vortex edge, and consequently the heterogeneous chemical processing and springtime ozone loss that took place within it were unremarkable.
  - In 2023 the enhanced water vapour prompted unusually early and vertically extensive polar stratospheric cloud (PSC) formation and chlorine activation. Dehydration subsequently removed the enhanced water vapour. By August, lower stratospheric chemical processing had essentially run to completion, as is typical in the Antarctic, preventing an exceptionally severe ozone hole.
  - In 2024 the Antarctic vortex also had enhanced water vapour from Hunga, but warm and dynamically disturbed conditions led to near- or slightly above-average ozone amounts.
- Hunga has not substantially perturbed Arctic ozone abundances. The Hunga water vapour reached the Arctic in spring 2023 after the ozone loss season. Although high water vapour abundances were present inside the 2023/2024 vortex, warm and dynamically disturbed conditions were unfavorable for substantial chemical ozone loss.
- Mesospheric water vapour increased by ~3-4 Tg in 2023 via upward transport from the stratosphere. (Figsures ES-1a and ES-1c) The water vapour increases led to ~5% loss of mesospheric ozone, because of enhanced HO_x chemistry.
- Global chemistry-climate models reproduce the water vapour transport (Figures ES-2a and ES-2b) and ozone anomalies in the stratosphere and mesosphere observed by MLS. The models predict that perturbations to mesospheric water vapour will persist until at least 2026.

Middle and upper atmospheric radiative and dynamical impacts

- The Hunga eruption produced short-term gravity wave and Lamb wave responses that were unprecedented in the observational record; these perturbations traversed the globe several times and extended up to the top of the atmosphere (including the thermosphere and ionosphere).
- The Hunga water vapour led to a cooling of 0.5-1 K in the global stratosphere (50-1 hPa) through the first two years, and a 1-2 K cooling in the mesosphere after 2023. The stratospheric cooling is in contrast to the warming associated with large amounts of volcanic aerosol in other previous major volcanic eruptions. (Figure ES-3)
- Global chemistry-climate models reproduce the observed Hunga global-mean temperature perturbations throughout the middle atmosphere.
- The 2022 SH winter stratosphere was characterized by extremely low midlatitude temperatures, an unusually strengthened and equatorward-shifted upper stratospheric polar vortex, a weakened mean meridional circulation, and reduced planetary wave forcing. Model simulations suggest some aspects of these circulation anomalies may have been forced by Hunga.
- In the NH, observed stratospheric meteorological conditions following the Hunga eruption were within the range of interannual variability, and model simulations show no consistent circulation response.

- Current evidence is insufficient to say whether the Hunga eruption affected the quasi-biennial oscillation, the major source of interannual tropical stratospheric variability.

Radiative forcing and surface climate effects

- The net globally averaged top-of-atmosphere radiative forcing (TOA RF) due to the Hunga eruption is estimated to be around -0.4 Wm^{-2} over 2022-2023.
- The TOA RF due to the Hunga eruption is the result of a negative radiative forcing from the increased stratospheric aerosol loading, which is slightly offset by a small positive radiative forcing from the increased stratospheric water vapour. Changes in stratospheric ozone and mesospheric composition due to the eruption did not significantly modify the TOA RF.
- As a consequence of the negative TOA RF, the Hunga eruption is estimated to have decreased global surface air temperature by about 0.05 K during 2022-2023; due to larger interannual variability, this temperature change cannot be observed.
- The climatic influence of the Hunga eruption cannot explain the record global average surface temperature increase in 2023-2024.
- After 2024, the TOA RF due to the remaining water vapour is estimated to be negligible (TOA RF < 0.005 Wm^{-2}) and is too small to cause a significant long-term climate response.
- The Hunga-induced stratospheric temperature changes due to aerosol, water vapour, and ozone could have impacted regional surface climate through stratosphere-troposphere dynamic coupling. However, global chemistry-climate model results suggest that the impact is likely smaller than interannual variability.

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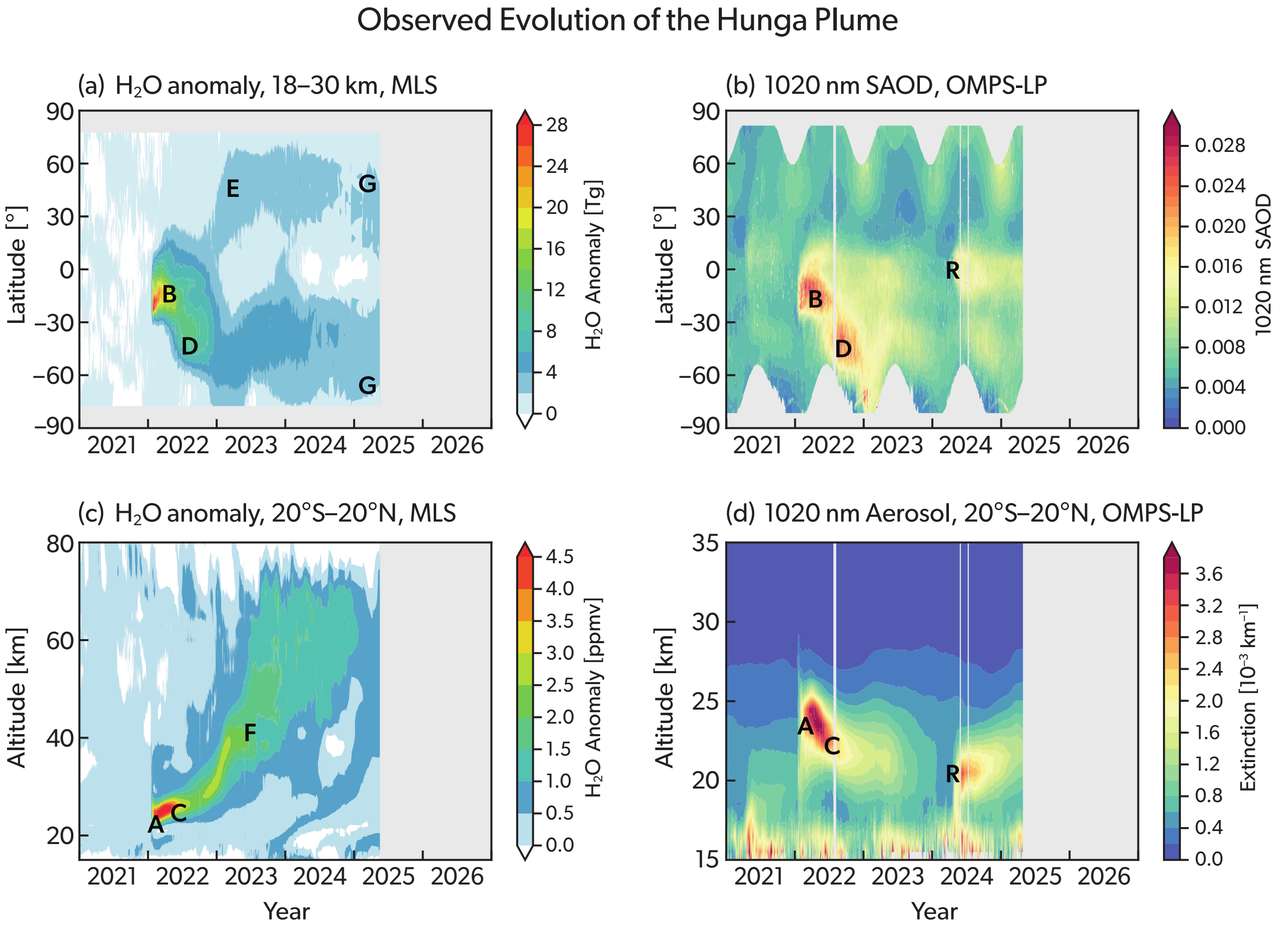

Figure ES-1: Observed evolution of the Hunga water vapour and aerosol perturbations through early 2025. *(Panel a) Water vapour anomalies (terragrams compared to background) in the lower-middle stratosphere as a function of latitude, and (Panel c) water vapour anomalies (parts per million by volume) over 20° N-S as a function of altitude. (Panel b) Stratospheric aerosol optical depth (SAOD) at 1020 nm as a function of latitude, and (Panel d) 1020 nm aerosol extinction over 20° N-S as a function of altitude; note the vertical axis only covers 15-35 km, as the aerosols did not extend above the lower stratosphere. Capital letters on the individual panels refer to specific features discussed in the Executive Summary: A = initial Hunga cloud, B = latitudinal spread over 30° S to 10° N, C = separation of water and aerosol clouds, D = transport to southern hemisphere mid-latitudes, E = water vapour transport to northern hemisphere, F = water vapour transport to mesosphere, G = persistence of water vapour anomalies in both hemispheres, R = eruption of Ruang volcano in April 2024.*

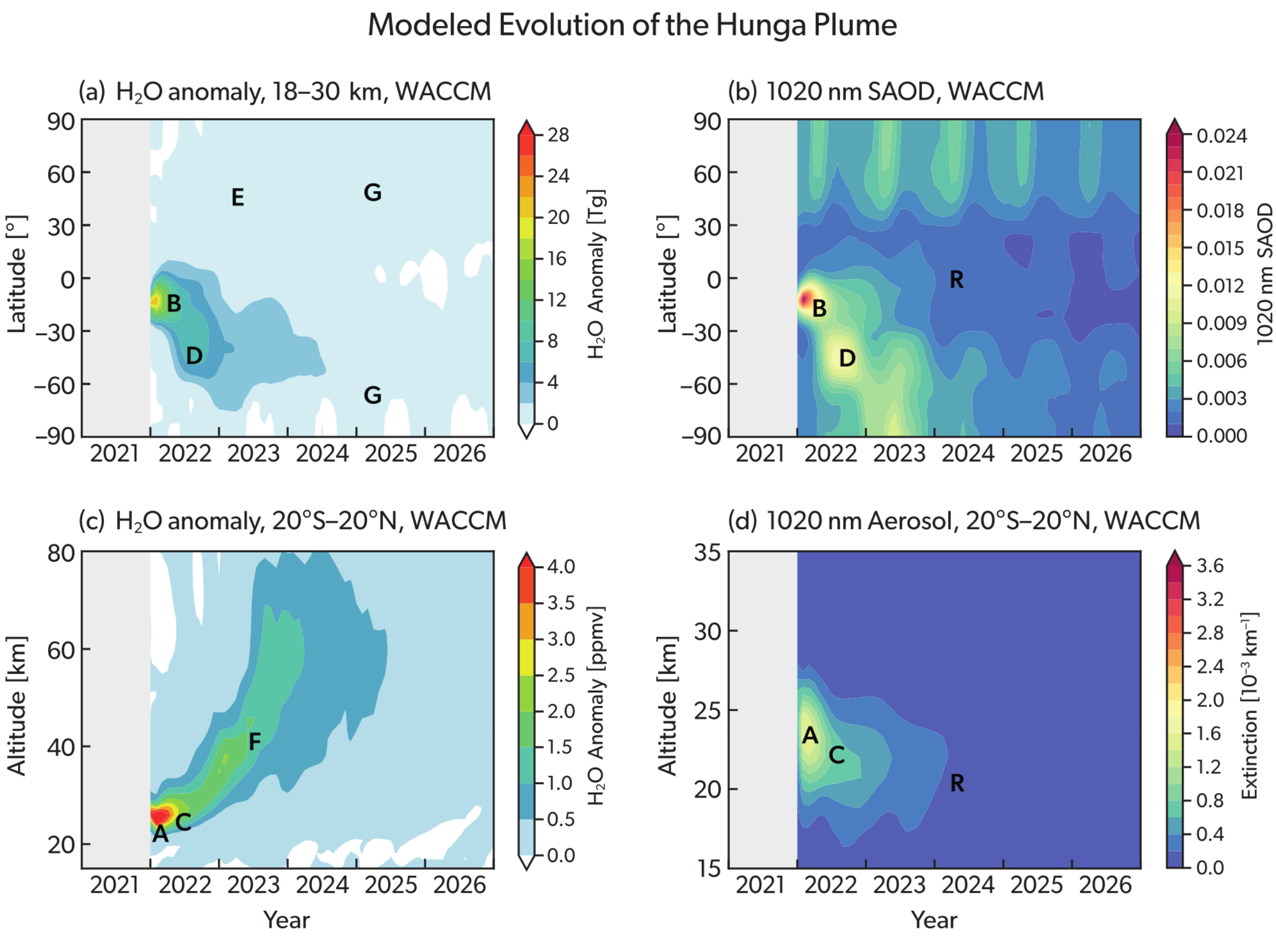

Figure ES-2: Evolution of the Hunga water vapour and aerosol perturbations simulated in a chemistry-climate model. *Panels show modeled evolution of Hunga water vapour and aerosol using the same diagnostics as the observations in Figure ES-1. Results are from the Whole Atmosphere Chemistry-Climate Model, but similar evolution is found in other global model simulations. The 2024 Ruang eruption (see R in Figure ES-1 panels b and d) is not included in the model simulations. Capital letters on the individual panels refer to specific features discussed in the Executive Summary: A = initial Hunga cloud, B = latitudinal spread over 30° S to 10° N, C = separation of water and aerosol clouds, D = transport to southern hemisphere mid-latitudes, E = water vapour transport to northern hemisphere, F = water vapour transport to mesosphere, G = persistence of water vapour anomalies in both hemispheres, R = eruption of Ruang volcano in April 2024.*

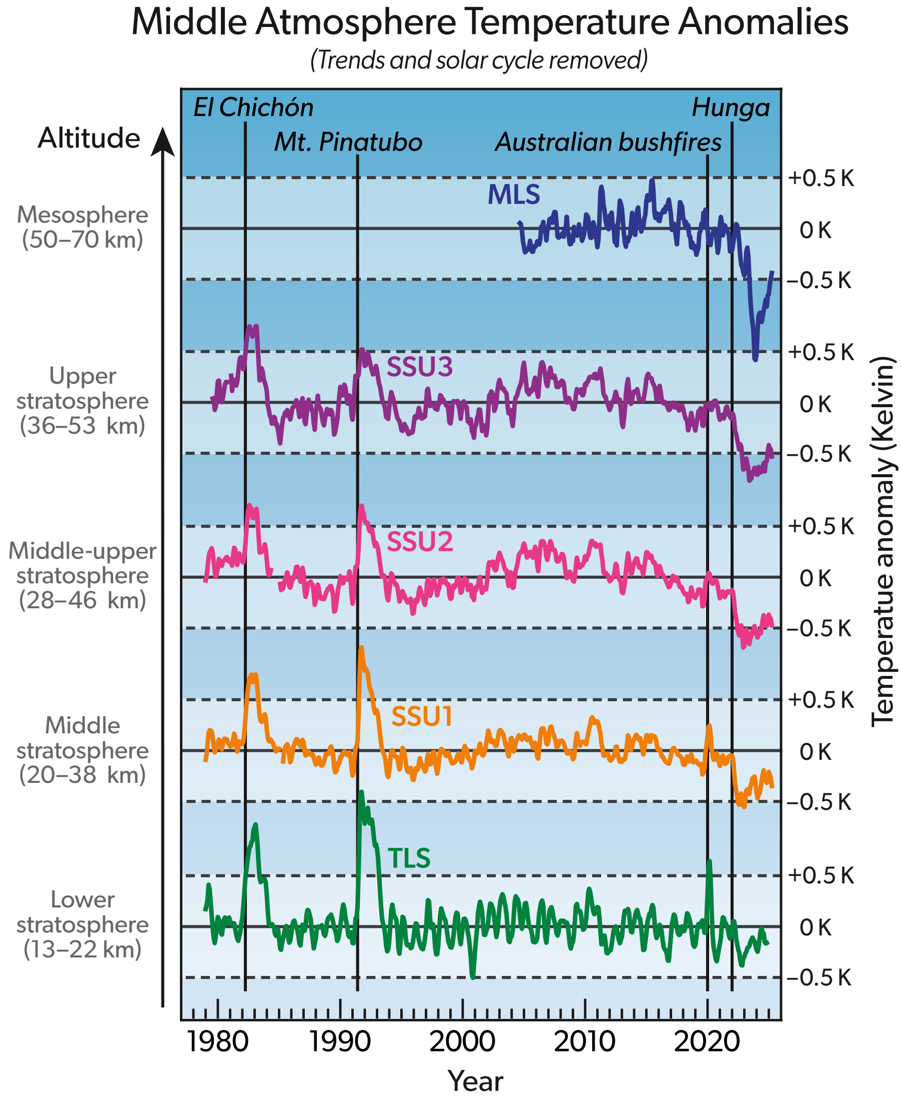

Figure ES-3: Anomalous cooling of the middle atmosphere due to Hunga. *Time series of monthly global average temperature anomalies for thick-layer average satellite measurements spanning the lower to upper stratosphere and mesosphere (bottom to top). Data for each level have been deseasonalized, and linear trends and solar cycle fits have been subtracted. These data are described in Chapter 4 (Figure 4.2). The four black vertical lines mark the timing of major events linked to stratospheric temperature anomalies: the eruptions of El Chichón (1982) and Mount Pinatubo (1991), the 2019–2020 Australian wildfires, and the 2022 Hunga eruption.*

Preface

The 15 January 2022 eruption of the Hunga volcano was the most explosive eruption in the satellite era, and within hours of the eruption information on the unprecedented altitude of the initial plume burst across the scientific community and social media. Scientists immediately began organising observational campaigns and analysing satellite information and ground observations to measure and understand the deep impact that the eruption would cause.

Activity towards a Hunga assessment report began in October 2022 at the General Assembly for the Stratosphere-troposphere Processes And their Role in Climate (SPARC) (SPARC is now the Atmospheric Processes And their Role in Climate, APARC). The Assembly included many presentations related to the Hunga eruption, and final-day discussions precipitated an effort to scope a potential community assessment of the eruption and its impacts. Key scientists were then invited to join a special meeting to discuss the idea, at which Drs. Yunqian Zhu (CIRES/NOAA CSL), William Randel (NCAR), Graham Mann (U. Leeds), and Paul A. Newman (NASA) volunteered to co-ordinate a potential outline for the report.

This initial Hunga report team co-wrote a proposal to APARC outlining a "Hunga Impacts" activity, and guidance from the APARC leadership saw a proposal submitted in January 2023 for a 3-year activity to co-ordinate an assessment report for publication in December 2025. The proposal outlined a 7-chapter document that both described the eruption, analysed the eruption's impacts and modelled its atmospheric effects. APARC leadership approved this proposal in late-January 2023 as a formal APARC "limited-term cross-activity focus" project defined to run from February 2023 to January 2026.

The new APARC activity enabled co-ordination across the inherently cross-cutting nature of the eruption's impacts, but an overarching focus of the report was to provide a definitive source ahead of the upcoming 2026 UNEP/WMO Scientific Assessment of Ozone Depletion Report. In addition to the report providing a comprehensive synthesis of observational studies on the volcanic cloud evolution and impacts, the Activity was also given a remit to co-ordinate multi-model activities building upon initial studies which predicted significant impacts on climate and the ozone layer.

On 2 February 2023 an email announcing the Activity was sent to over 100 members of the atmospheric sciences community, seeking feedback on the proposed structure and volunteer report contributors (lead authors, co-authors, reviewer). The community's responses revised the initial report structure, and provided a traceable basis for the subsequent recruitment of chapter co-author teams and review editors.

Announcements of the APARC Hunga activity were also sent to community mailing lists including SSiRC, S-RIP, CCMI, VolRes and CMIP-VolMIP activities. The timeline for the report's formal peer-review stages was devised, and also included two open science workshops, for further input from the scientific community, with 160 scientists attending the May 2023 online workshop and 56 abstracts presenting at the in-person May 2024 workshop. In September 2023, the report's lead authors were selected, and review editors for each chapter were also selected.

Multi-modelling activity began April 2023, and was termed the Hunga Tonga–Hunga Ha'apai Model Observation Comparison (HTHH-MOC), to emphasise a focus on simulations of the eruption's impacts. More than 50 scientists participated in writing the HTHH-MOC protocols (see Supplementary S1), over 10 global model groups signed up to run the simulations, and a data analysis team volunteered to perform multi-model analysis on different sub-topics.

Monthly online HTHH-MOC meetings involved discussion of emerging findings and also helped provide support and feedback to participating modelling groups. For the multi-model analysis, a group workspace area was set-up on the JASMIN (Joint Analysis System Meeting Infrastructure Needs) data analysis facility. This allowed the data analysis team to conduct initial data inspection and evaluation ahead of the initial multi-model papers being written (see Supplementary S3). The model simulations fed into the second, third, and the final drafts of the assessment. In autumn 2025, the datasets will be migrated from JASMIN to Centre for Environmental Data Analysis (CEDA) as a public release of the HTHH-MOC datasets.

Details of the various observational data sets (satellites, ground-based and balloon) used throughout the report are included in the Observational Data Supplement. These were compiled with input from recruited data experts and teams with extensive knowledge of the different data sets. At the December 2023 and December 2025 AGU fall meetings, the author team convened dedicated sessions, the former focused on observations and the latter on model findings from HTHH-MOC and other studies. In addition to the event meetings, the co-chairs held weekly meetings and hosted monthly "lead-author meetings" to facilitate team communications.

The report underwent three review cycles. The first report draft was completed by 15 September 2024 and was sent to anonymous reviewers by the Review Editors. Reviews were returned by 31 October 2024 and authors began chapter revisions in conjunction with the Review Editors. The 2nd draft was completed by 10 March 2025 and sent out for a 2nd review. Reviews were returned by April 10, and the 3rd report draft was completed by 10 May 2025. This 3rd draft was sent out to reviewers for final comments.

The final meeting of the report team was held in Boulder, CO, USA 10-12 June 2025. At this meeting the individual final chapter drafts were discussed in an open review forum as moderated by the Review Editors. Meeting attendees included the Co-chairs, Lead Authors, 1-2 selected co-authors from each chapter, the Review Editors, and a few specific reviewers selected by the Review Editors. Final chapter changes were discussed in an open plenary session and agreed upon. The final chapter revisions and write-ups were approved by the Review Editors in July 2025.

This final 10-12 June 2025 report team meeting was also set-up for the writing of the Executive Summary (ES). This ES was initially drafted by the report co-chairs from the detailed chapter bullets. The ES was edited and adjusted during the meeting by the attendees. The ES text was line-by-line agreed to in plenary session by all participants (both in-person and virtually on-line).

The 4th and final chapters drafts were submitted for detailed technical editing in August 2025, and this report was released in December 2025.