S4 Other chapter supplementaries

Authors (Section S4.1)	Xinyue Wang Lawrence Coy
Authors (Section S4.2)	Freja F. Østerstrøm Michelle L. Santee
Contributing authors (Section S4.1)	Masatomo Fujiwara Pu Lin Alison Ming Feng Li Ewa Bednarz Zhihong Zhuo Kirstin Krüger
Contributing authors (Section S4.2)	Martyn P. Chipperfield Stephanie Evan Dan Smale Krzysztof Wargan David M. Wilmouth Ingo Wohltmann

S4.1 Stratospheric anomalies following the Hunga eruption for Chapter 4

This section provides additional figures on stratospheric anomalies following the Hunga eruption that were not included in Chapter 4.

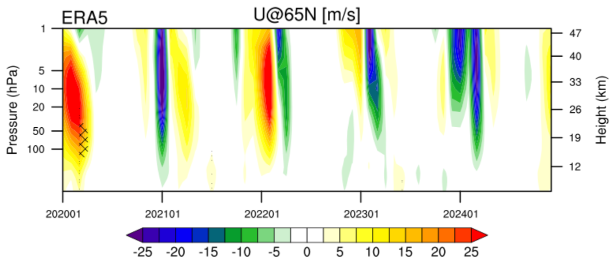

Figure S4.1: *Time series of Northern Hemisphere zonal mean zonal wind anomalies at 65°N [m/s] from ERA5, with the 2005–2021 mean removed. Hatched regions indicate anomalies that fall outside two standard deviations of internal variability.*

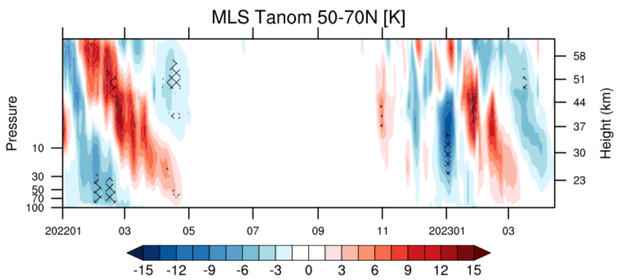

Figure S4.2: *Time series of Northern Hemisphere temperature anomalies averaged over 50°-70°N [K] from MLS, with the 2005–2021 mean removed. Hatched regions indicate anomalies that are outside the range of all variability during 2005-2021.*

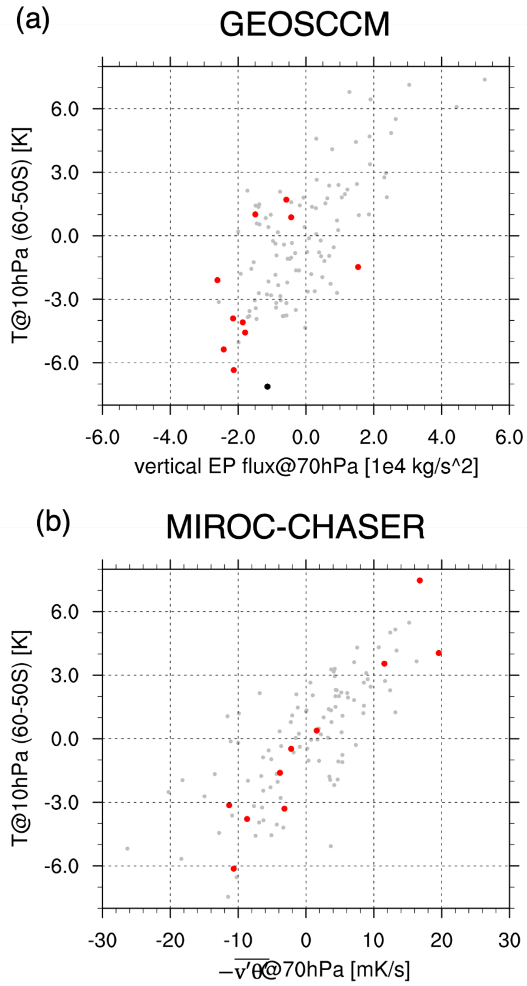

Figure S4.3: *Relationship between July–August average temperatures at 10 hPa and wave activity at 70 hPa over 55°S–65°S. Red dots show the differences between Hunga-forced and control simulations for July–August 2022, based on 10 ensemble members from (a) GEOSCCM and (b) MIROC-CHASER. Gray dots represent deviations from the control ensemble mean for July–August averages across 2022–2031 (10 ensemble members × 10 years for each model). The black dot in (a) marks the July–August 2022 value from ERA5. Note that in (b), is used as a proxy for wave activity, as it is positively correlated with upward EP flux.*

S4.2 Models used in Chapter 5 but not included in HTHH-MOC or Tonga-MIP

S4.2.1 ATLAS

Alfred Wegener InsTitute LAgrangian Chemistry/Transport System.

ATLAS is a global Lagrangian 3-D chemical transport model (Wohltmann and Rex, 2009; Wohltmann et al., 2010; Wohltmann et al., 2017). The model includes a comprehensive gas-phase stratospheric chemistry module, heterogeneous chemistry on polar stratospheric clouds (PSCs), a particle-based Lagrangian denitrification module, and a dehydration parameterisation. In addition to the binary background aerosol, the model simulates three types of PSCs, that is, supercooled ternary solutions (STS), clouds composed of solid nitric acid trihydrate (NAT) particles, and ice particles. Model runs are driven by meteorological data from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA5 reanalysis (provided on a 1.125° × 1.125° horizontal grid, 3 hr temporal resolution, and 137 model levels; Hersbach et al., 2017; Hersbach et al., 2020). The horizontal resolution is ~150 km. The vertical range of the model domain is 13−50 km (~350−1900 K potential temperature). The simulations for the Antarctic winter 2023 referred to in this report (Chapter 5) are based on a reference model run initialised with MLS data from 1 May 2023 and a sensitivity run that uses exactly the same setup, with the exception of the initialisation of MLS water vapour, which is taken from the preceding year on 1 May 2022 (i.e., without the effect of Hunga on water vapour).

S4.2.2 SOCOL-AERv2-Volc

SOCOL = modeling tools for studies of SOlar Climate Ozone Links, AER = 2-D aerosol model, Volc = heat flux, mixed-layer ocean, and SSP implementation.

SOCOL-AERv2 is a fully coupled 3-D global aerosol-chemistry-climate model. Version 2 is a coupling of SOCOLv3 (Stenke et al., 2013) and the AER 2-D sectional aerosol model (Weisenstein et al., 1997; Weisenstein et al., 2007). The SOCOLv3 model is based on the general circulation model European Centre/Hamburg 5 (ECHAM5; Roeckner et al., 2003; Giorgetta et al., 2006) and the chemistry model MEZON focused on stratospheric chemistry (Rozanov et al., 1999; Egorova et al., 2003). The spatial and temporal resolution is variable; the version of the model presented in this report (Chapter 5) has T42 spectral Gaussian grid resolution (2.8° × 2.8° at the equator) and 39 hybrid sigma-pressure levels spanning the surface to 0.01 hPa (~80 km). The model version (Volc) included in the discussion in Chapter 5 (Wilmouth et al., 2023), described by Østerstrøm et al. (2023), is based on Feinberg et al. (2019) and references therein, with the following two main modifications: (1) The chemical boundary conditions were integrated with those of the Shared Socioeconomic Pathways (SSP) scenarios, and (2) heat fluxes needed to implement an interactive mixed-layer ocean in the model were generated from a 10-member perturbed initial conditions model ensemble running from 2015 to 2100 following model spin-up of 20 years at 2015 conditions. Sea surface temperatures and sea ice thickness used in the ensemble were set to MIROC6 values obtained from the CMIP6 database (Tatebe et al., 2019). The ensemble simulations included in Wilmouth et al. (2023) were initialised from spun-up atmospheric states and include large ensembles of 30 model members in both a background ensemble simulation and a volcanic perturbation ensemble simulation injecting both SO_2 and H_2O at the time of the Hunga eruption. The climatology used in both model scenarios is SSP370 and has the quasi-biennial oscillation (QBO) forced at 2000/2001 conditions.

S4.2.3 TOMCAT

University of Leeds 3-D chemical transport model.

TOMCAT is a global off-line chemical transport model (e.g. Chipperfield, 1999; Chipperfield, 2006). The resolution is variable; the simulations presented here (Chapter 5, and in, e.g., Zhou et al., 2024) used a horizontal resolution of 2.8° × 2.8° (T42 Gaussian grid) and 32 hybrid sigma-pressure levels from the surface to ~60 km. The simulations were forced with ERA5 meteorology (Hersbach et al., 2020), and the vertical motion was diagnosed within the model from the ERA5 divergence. The model has a detailed gas-phase stratospheric chemistry scheme of source gases, reservoirs, and radical species of the major chemical families. The model has a simplified aerosol and PSC scheme for the simulation of heterogeneous chemistry based on the assumption of thermodynamic equilibrium between PSC particles, including liquid aerosol, solid nitric acid trihydrate, and/or solid ice particles (Grooß et al., 2018), and the gas phase (e.g. Feng et al., 2011; Feng et al., 2021). The global abundance of binary liquid aerosols is constrained by reading files of latitude-height monthly mean aerosol surface area density. The model simulations are spun up from a control simulation which started in

1955 constrained by global mean surface observations of source gases (World Meteorological Organization (WMO), 2022). The distribution of all chemical tracers, including long-lived source gases, is thus determined by the model chemistry and transport.

For studies of future evolution, the CTM is run with repeating meteorology. Zhou et al. (2024) simulated the impact of Hunga through 2030 by using repeating winds and temperatures from 2022. While this allows the model to simulate long-term trends in composition, it removes any year-to-year dynamical variability and means that polar ozone loss, for example, is calculated for the same vortex conditions every year.

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