AGU PUBLICATIONS

Geophysical Research Letters

Supporting Information for

Climate Projections Very Likely Underestimate Future Volcanic Forcing and its Climatic Effects

Man Mei Chim[1], Thomas J. Aubry[2], Nathan Luke Abraham[1,3], Lauren Marshall[4], Jane Mulcahy[5], Jeremy Walton[5], Anja Schmidt[1,6,7]

[1]Centre for Atmospheric Science, Yusuf Hamied Department of Chemistry, University of Cambridge, Cambridge, United Kingdom
[2]Department of Earth and Environmental Sciences, University of Exeter, Penryn, United Kingdom
[3]National Centre for Atmospheric Science, United Kingdom
[4]Department of Earth Sciences, Durham University, Durham, United Kingdom
[5]Met Office, FitzRoy Road, Exeter, EX1 3PB, UK
[6]German Aerospace Center (DLR), Institute of Atmospheric Physics (IPA), Oberpfaffenhofen, Germany
[7]Ludwig-Maximilians University Munich, Meteorological Institute, Munich, Germany

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Introduction

The supplementary information includes details of the resampling of eruption source parameters (Text S1), description of the UKESM-VPLUME framework (Text S2), and the procedures to remove the anthropogenic signal from time series data (Text S3). Data files including the large-magnitude and small-magnitude eruption datasets used in resampling (d01.xslx) and the future eruption scenarios used in model simulation (d02.xslx) are uploaded as additional information.

Text S1. Resampling of eruption source parameters.

In this study, we resample eruption source parameters, including SO_2 mass, eruption location, and mass eruption rate, from the ice-core and satellite-based volcanic SO_2 emission datasets (Sigl et al., 2022; Carn, 2022) and the Smithsonian Global Volcanism Program (Global Volcanism Program, 2022). The following sections provide more details on the resampling of the eruption source parameters.

i. SO_2 mass

We use 3 Tg of SO_2 as the threshold to define "small-magnitude" and "large-magnitude" eruptions and resample small-magnitude eruptions only from the satellite record. Large-magnitude eruptions are resampled from the combined bipolar ice-core array and satellite records. For both datasets, the probability of any specific eruption to occur on a given day is the inverse of the number of days in the dataset, i.e., 2.4×10^{-7} and 6.6×10^{-5} for the large- and small-magnitude eruption input datasets, respectively. To generate stochastic eruption scenarios for 2015-2100, we perform Monte Carlo simulations by generating random numbers between 0 and 1 from a uniform distribution for each day of the 2015-2100 period and each eruption in the input datasets. An eruption in one of the input datasets is triggered if the random number drawn is lower than the probability of that eruption to occur (i.e., 2.4×10^{-7} or 6.6×10^{-5}). We first generate 1000 future large- and small-magnitude eruption scenarios separately and combine both eruption chronologies to obtain 1000 unique future eruption scenarios from 2015 to 2100.

In addition to the details described in the main text, we have the following assumptions:

(1) In the satellite record, we assume that explosive eruptions that occur in the same eruption phase (i.e., with the next eruption occurring within 7 days) are one single eruption event. The SO_2 mass from these combined eruptions is summed and the eruptive plume height is the average plume height weighted by the SO_2 mass of the events.

(2) We assume that sulfate aerosol deposition from all explosive eruptions recorded in Holvol corresponds to stratospheric emissions. We note that a recent study on the isotopic signature of ice-core sulfate from Antarctic ice cores showed that several previously attributed Southern Hemisphere eruption events in the ice-cores record in Sigl et al. (2015) in fact originated from the troposphere (Gautier et al., 2019). Since this sulfate isotopic study is limited to the record in Sigl et al. (2015), we decide to assume that all explosive volcanic SO_2 emissions in Holvol are stratospheric emissions.

ii. Eruption location and vent altitude

The majority of volcanic eruptions with volcanic sulfate deposits recorded in ice core records are from unknown sources (represented as triangles in Figure S1). The sulfate signals from the synchronized bipolar ice cores determine the eruption hemisphere of these unknown eruption events, i.e., attributed as extra-tropical Northern Hemisphere event for Arctic-only sulfate signal, Tropical event for bipolar sulfate signals, and extra-tropical Southern Hemisphere event for Antarctic-only sulfate signal. We only know the exact eruption latitudes and longitudes for eruptions recorded by satellite measurements and those with known sources in the bipolar ice-core record. To obtain a realistic distribution of eruption location in the stochastic future eruption scenarios, we randomly resample the eruption location and vent altitude for volcanoes among those that had confirmed explosive eruptions with volcanic explosivity index (VEI) > 3 in the Holocene from the Smithsonian Global Volcanism Program Holocene Eruption database (Global Volcanism Program, 2022) and with a latitude belonging to the latitudinal band of the eruption resampled. We choose latitudinal boundaries at 30 ^{o}N/S to distinguish the eruption hemispheres, which correspond to the edges of the tropical pipes (Butchart et al., 2014). This allows the eruption location distribution in the stochastic scenarios to resemble that in the Holocene record and the eruptions to occur at real locations of volcanoes instead of hypothetical latitudes and longitudes.

ii. Mass eruption rate

Like SO_2 mass, the mass eruption rate is resampled. However, this parameter is absent from the ice-core and satellite datasets, so we need to attribute a mass eruption rate for each eruption in these records. The mass eruption rate for each eruption from the satellite record is inverted using Plumeria (see UKESM-VPLUME section) from the satellite-measured eruptive plume height, vent altitude, and the atmospheric profile from the ERA5 reanalysis dataset (Hersbach et al., 2019) at the eruption date and location. We assume that eruptions recorded in ice-core have an SO_2 injection height of 23 km above sea level, consistent with that observed for the 1991 Mt. Pinatubo eruption (Guo et al., 2004; Fero et al., 2009). We then invert the mass eruption rate from this plume height using Plumeria. We perform this inversion for 9 locations corresponding to 9 known eruptions in the ice-core dataset, with three locations each in the extra-tropical Northern Hemisphere, the Tropics, and the extra-tropical Southern Hemisphere (Table S3). We obtain decadal-averaged atmospheric profiles at each eruption location from the UKESM pre-industrial control run. The average of the 9 mass eruption rates obtained using this procedure is 6.6×10^8 kg/s, and we use this value for all eruptions in the ice-core record.

The resampling datasets for large- and small-magnitude eruptions and the final input eruption scenarios for all VOLC runs (i.e., VOLC2.5, VOLC50-1, VOLC50-2, and VOLC98) with eruption source parameters are available in separate data files in the Supplementary Information.

Text S2. UKESM-VPLUME framework.

UKESM-VPLUME is a plume-aerosol-chemistry-climate modeling framework that couples the 1-D eruptive plume model Plumeria (Mastin, 2007, 2014) with version 1.1 of UK Earth System Model (UKESM1.1; Mulcahy et al., 2023).

UKESM is a state-of-the-art Earth System Model based on the Hadley Centre Global Environment Model version 3 (HadGEM3), a physical global atmosphere ocean climate modelling system, and is coupled with the ocean component model, Nucleus for European

Modelling of the Ocean (NEMO), and atmospheric chemistry component model UK Chemistry and Aerosols (UKCA; Dhomse et al., 2014; Archibald et al., 2020). The UKCA atmospheric chemistry model accounts for the full atmospheric chemistry processes of volcanic sulfate aerosols, volcanic halogen species, and the evolution of aerosol particles with an interactive stratospheric aerosol module, which enables the simulation of the volcanic sulfate aerosol life cycle and radiative effects. The HadGEM3 model coupled with NEMO can simulate long-term atmospheric and ocean dynamical changes in response to climate variations.

Plumeria is a one-dimensional volcanic plume model integrating the conservation equations for mass, momentum, and energy upward through a cylindrical plume (Mastin 2007, 2014). The main model outputs are the maximum plume height defined as the height where the ascent velocity of the plume reaches zero, and the neutral buoyancy height which is defined as the height at which the density of the plume equals the ambient density. The main model inputs are (i) the eruption source conditions including the temperature, gas content, specific heat and density of the magma, vent diameter, vent altitude, and the initial exit velocity; and (ii) the atmospheric condition at the eruption location, i.e., the vertical profile of the temperature, pressure levels, wind speed, wind direction, and relative humidity.

The mass eruption rate (M_0) of the eruption is a key input in Plumeria, which is calculated from the eruption source parameters:

$$M_0 = \pi \rho_0 R_0^2 U_0$$

where ρ_0 is the density of the ash-gas jet (in kg/m^3), which is dependent on the temperature and gas content of the magma, R_0 is the vent radius (in m), and U_0 is the exit velocity of the jet (in m/s).

We assume that the eruption source parameters related to magma properties are the same across all eruptions in our future eruption scenarios (see Table S4 for the values used in this study). We fix the ratio of the vent radius to the square of exit velocity at 0.02 to ensure that the eruptive plume is a buoyant plume in the model. This ratio is proportional to the Richardson number, which is a parameter governing the stability of the eruptive column (e.g., Aubry and Jellinek, 2018).

Last, the main model parameters are the radial (α) and wind (β) entrainment coefficients which govern the rate of turbulent entrainment of atmosphere into the rising volcanic plume. We use values of $\alpha = 0.1$ and $\beta = 0.25$ which result in the best agreement between a similar one-dimensional plume model and a dataset of well-observed eruptions (Aubry and Jellinek, 2018).

In the UKESM-VPLUME framework, we couple Plumeria with version 11.7 of the UKCA atmospheric chemistry model in UKESM version 1.1 to calculate the eruptive plume height during eruption at every model timestep. The SO_2 injection lasts for 24 hours for each eruption. During the eruption and at every timestep of the atmospheric model used in UKESM (i.e., every 20 minutes), the vertical profiles of atmospheric conditions simulated by UKESM are passed interactively to Plumeria. Plumeria then calculates the eruptive plume height with the prescribed eruption source parameters and the instantaneous atmospheric conditions. The calculated plume height is then passed to the UKCA model to inject volcanic SO_2 mass at the eruption location. In this study, the volcanic SO_2 for all eruptions is assumed to be injected at the neutral buoyancy level in the calculation of mass eruption rate and the UKESM-VPLUME framework (injected using a Gaussian profile). The eruptive plume heights of eruptions are thus consistent with the climate conditions simulated by UKESM (Figure S6), which allows us to account for the impacts of global warming on eruptive plume height.

Text S3. Removal of anthropogenic trend in time series data

In this study, we remove the anthropogenic signal in the time series data of all VOLC runs in order to compare the annual mean or decadal mean volcanic impacts on large-scale climate indicators (see probability density functions in Figure 3 and 4). For each large-scale climate indicators, we first calculate the anthropogenic signal from 2015 to 2100 by fitting a third-order polynomial function to the annual mean ensemble mean of the NOVOLC run. We then subtract the anthropogenic signal from all the annual mean time series in VOLC and NOVOLC runs to obtain detrended annual mean time series data (as in Figure 3b). In the calculation of detrended decadal mean time series, we subtract the annual mean anthropogenic signal from each ensemble member of the VOLC and NOVOLC runs before calculating the decadal mean. We then plot the detrended decadal mean for all the ensemble members as one probability density function (as in Figure 4).

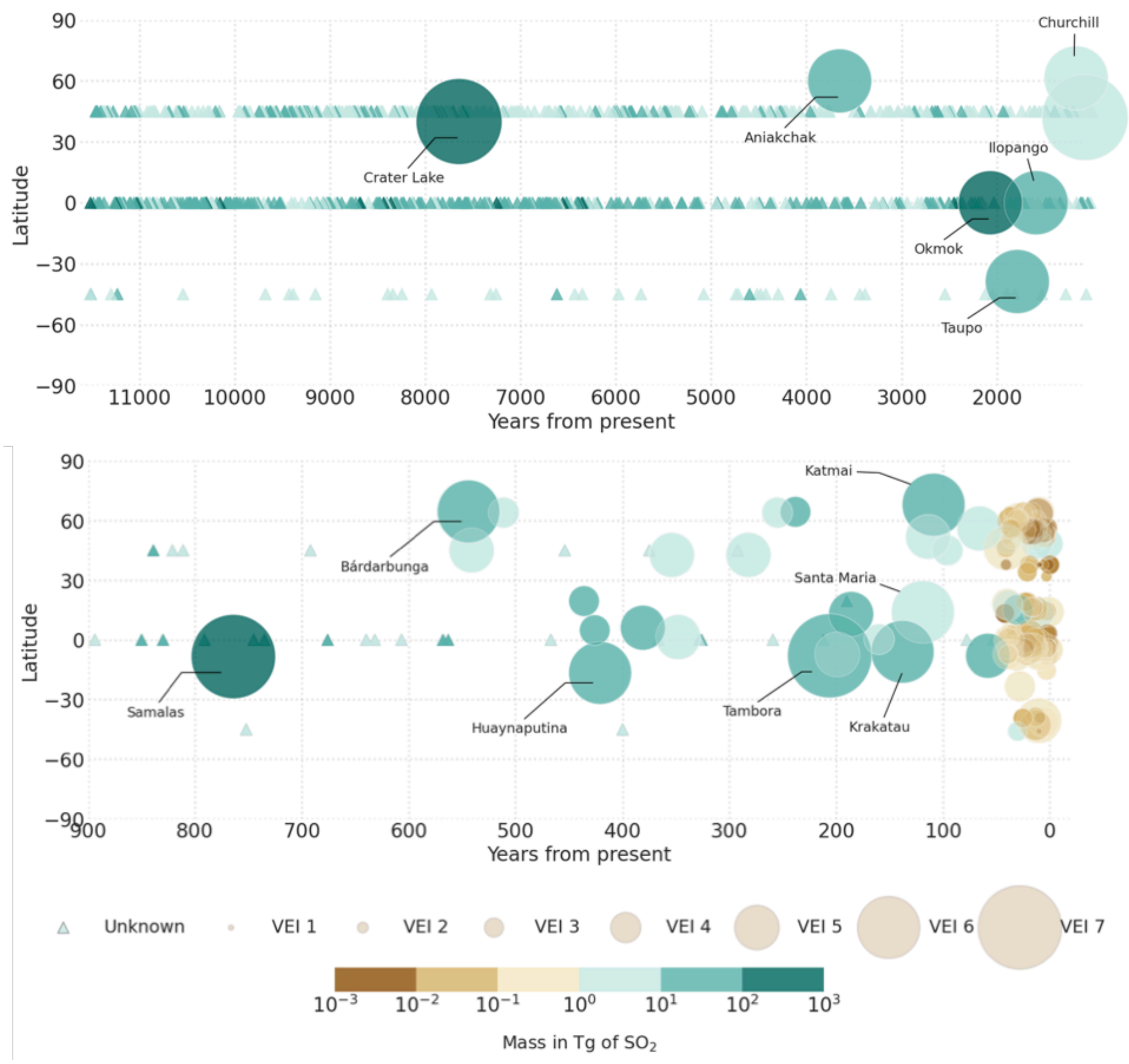

Figure S1. Historical explosive eruptions from ice core and satellite records in the past 11,500 years from Holvol ice-core dataset and satellite datasets after data filtering. Unknown eruptions with hemispheric information only are assigned with fixed latitudes (i.e., at 0º and 45ºN/S). The Volcanic Explosivity Index (VEI) of the eruptions is obtained from the Smithsonian Global Volcanism Program database (Global Volcanism Program, 2022).

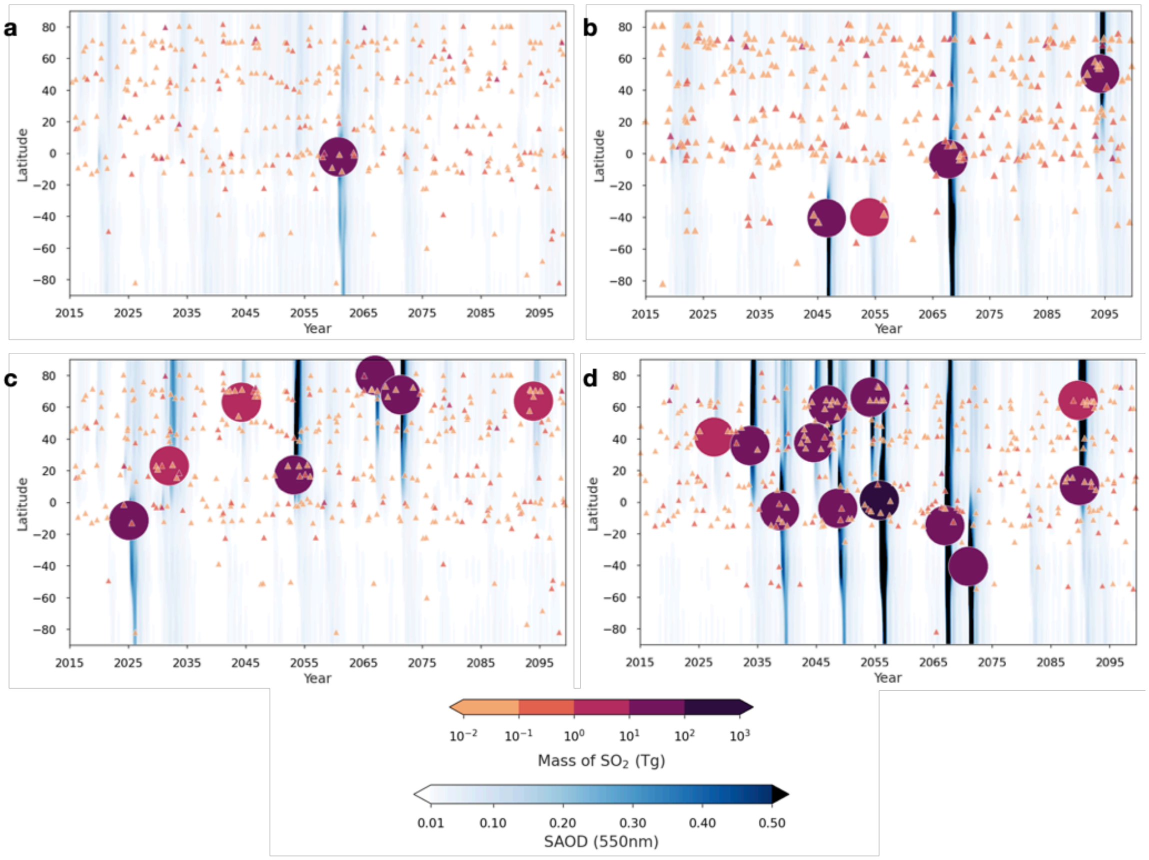

Figure S2. Zonal mean stratospheric aerosol optical depth (SAOD) in 550 nm (blue shading) and eruption time series (markers) with mass of SO_2 from 2015 to 2100 for (a) VOLC2.5, (b) VOLC50-1, (c) VOLC50-2, (d) VOLC98. Large-magnitude (> 3 Tg of SO_2) and small-magnitude (< 3 Tg of SO_2) eruptions are represented in circles and triangles respectively.

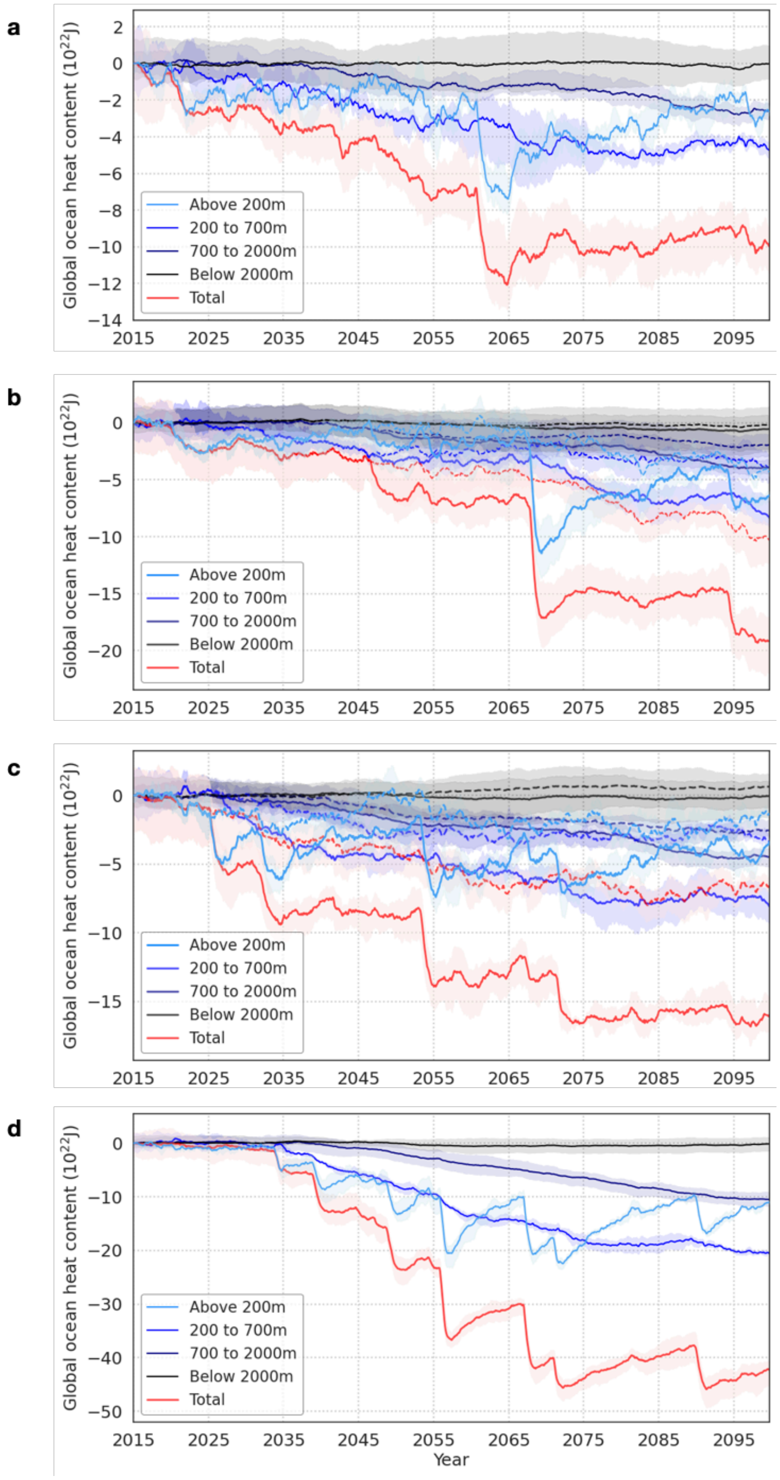

Figure S3. Global monthly-mean ocean heat content anomaly relative to NOVOLC for (a) VOLC2.5, (b) VOLC50-1 (solid lines) and VOLC50-1S (dotted lines), (c) VOLC50-2 (solid lines) and VOLC50-2S (dotted lines), and (d) VOLC98.

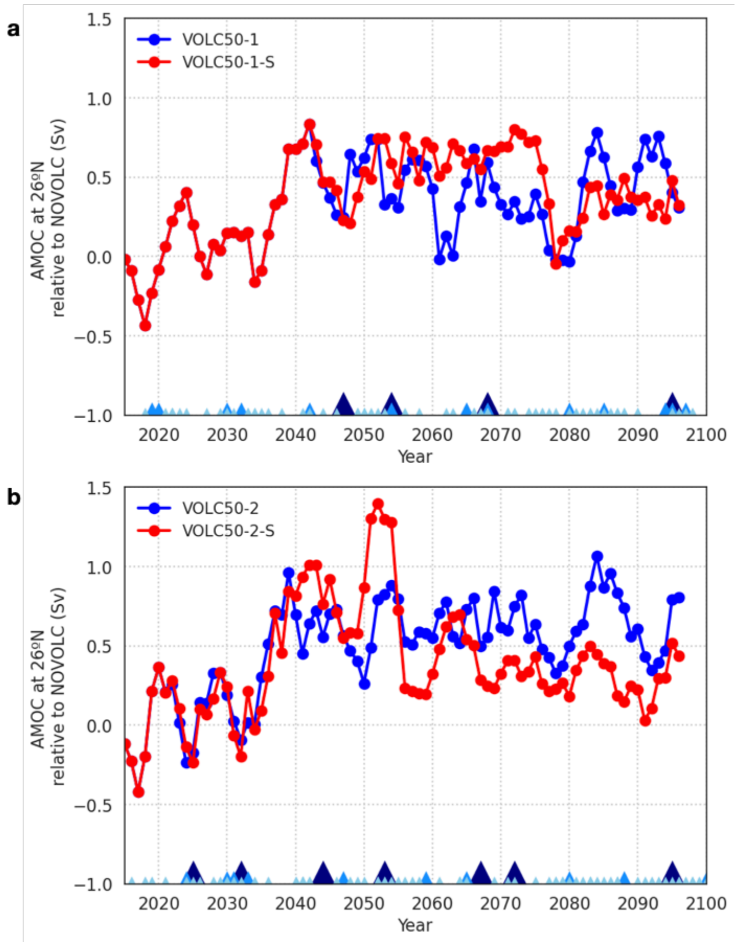

Figure S4. 5-year moving mean of Atlantic meridional overturning circulation (AMOC) at 26ºN relative to NOVOLC for (a) VOLC50-1 and VOLC50-1S, and (b) VOLC50-2 and VOLC50-2S. The triangles represent the eruptions with > 3 Tg of SO_2 (dark blue), between 1 to 3 Tg of SO_2 (blue) and < 1 Tg of SO_2 (light blue) of the scenarios.

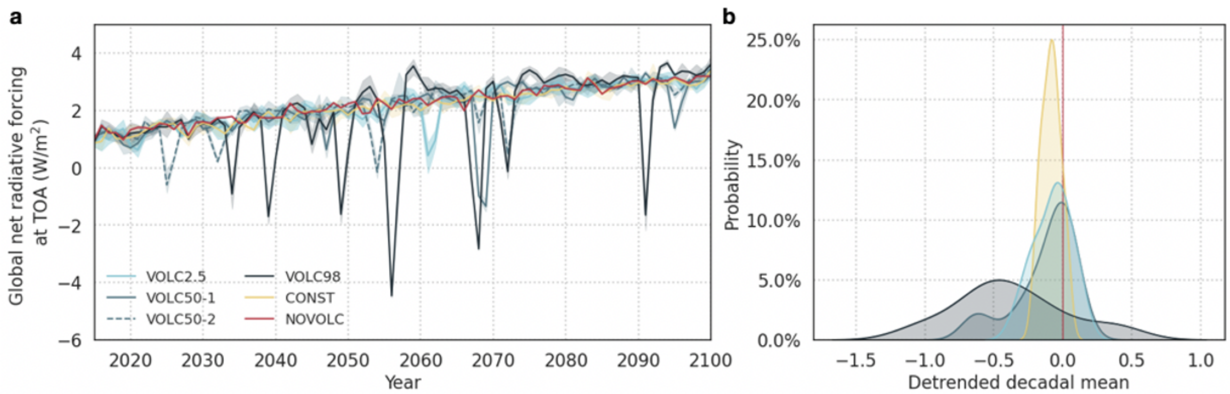

Figure S5. (a) Global annual-mean net radiative forcing at the top-of-the-atmosphere (TOA) (in W/m^2) from 2015 to 2100, and (b) the respective probability density function of the detrended decadal mean.

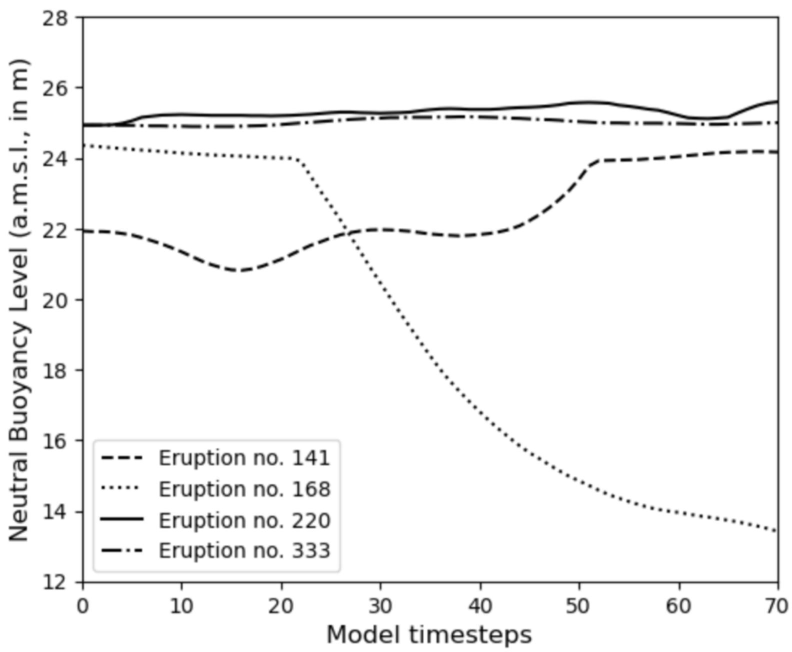

Figure S6. The time series of plume height in neutral buoyancy level above mean sea level (in m) for four large-magnitude eruptions during SO_2 mass injection in the UKESM-VPLUME framework. The data is extracted from one of the ensemble members for the VOLC50-1 run.

Climate indicators	VOLC50-1	VOLC50-1S	VOLC50-2	VOLC50-2S	CONST	VOLC-98	VOLC-2.5
Global mean surface air temperature (^oC)	-0.20 (-4.0%)	-0.11 (-2.1%)	-0.24 (-4.8%)	-0.09 (-1.8%)	-0.12 (-2.4%)	-0.56 (-11.1%)	-0.16 (-3.1%)
Global ocean heat content ($\times 10^{22}$ J)	-8.34 (-3.1%)	-4.63 (-1.7%)	-10.70 (-3.9%)	-4.63 (-1.7%)	-6.52 (-2.4%)	-24.20 (-8.9%)	-6.64 (-2.4%)
Global thermosteric sea level rise (m)	-0.012 (-3.3%)	-0.006 (-1.8%)	-0.015 (-4.2%)	-0.007 (-1.9%)	-0.009 (-2.5%)	-0.033 (-9.6%)	-0.009 (-2.6%)
Global precipitation flux (mm/day)	-0.018 (-6.3%)	-0.009 (-3.3%)	-0.020 (-7.1%)	-0.008 (-2.7%)	-0.010 (-3.6%)	-0.052 (-18.2%)	-0.014 (-4.8%)
Global net radiative forcing at top-of-the-atmosphere (W/m^2)	-0.15 (-6.8%)	-0.08 (-3.6%)	-0.13 (-5.7%)	-0.05 (-2.4%)	-0.08 (-3.8%)	-0.34 (-15.0%)	-0.08 (-3.5%)
Atlantic Meridional Overturning Circulation at 26^{o}N (Sv)	+0.31 (+5.5%)	+0.36 (+6.5%)	+0.49 (+8.7%)	+0.38 (+6.7%)	+0.28 (+4.9%)	+0.93 (+16.6%)	+0.26 (+4.6%)
Global sea ice extent (million km^2)	+0.52 (+3.4%)	+0.21 (+1.4%)	+0.68 (+4.4%)	+0.22 (+1.4%)	+0.20 (+1.3%)	+1.53 (+9.9%)	+0.43 (+2.8%)
Arctic sea ice extent (million km^2)	+0.31 (+3.4%)	+0.17 (+1.9%)	+0.48 (+5.4%)	+0.16 (+1.8%)	+0.16 (+1.7%)	+0.81 (+9.1%)	+0.18 (+2.1%)
Antarctic sea ice extent (million km^2)	+0.22 (+3.3%)	+0.04 (+0.6%)	+0.20 (+3.0%)	+0.06 (+0.9%)	+0.04 (+0.6%)	+0.72 (+11.1%)	+0.25 (+3.9%)

Table S1. Time-averaged volcanic effects relative to the magnitude of anthropogenic contribution on large-scale climate indicators over the period of 2015 to 2100. Data for Figure 5 in the main text.

Model scenarios	Year of crossing		
	1.5 °C	2 °C	3 °C
NOVOLC	2019.40 (2018.87 - 2019.75)	2029.00 (2028.03 - 2029.75)	2047.77 (2046.40 - 2048.57)
CONST	2020.76 (2019.77 - 2021.40)	2031.06 (2029.79 - 2032.20)	2049.38 (2047.96 - 2050.73)
VOLC2.5	2021.20 (2021.09 - 2021.27)	2031.45 (2031.22 - 2031.78)	2050.53 (2049.73 - 2051.14)
VOLC50-1	2021.04 (2020.02 - 2022.60)	2031.13 (2029.99 - 2033.15)	2049.01 (2047.87 - 2051.17)
VOLC50-2	2022.59 (2022.10 - 2023.21)	2033.29 (2032.30 - 2034.09)	2051.89 (2050.45 - 2053.06)
VOLC98	2021.69 (2021.27 - 2022.67)	2036.19 (2034.17 - 2038.25)	2062.13 (2061.16 - 2063.37)

Table S2. Year range of crossing 1.5 °C, 2 °C, and 3 °C for all the model scenarios. The numbers in the bracket refer to the uncertainty range of the maximum and minimum ensemble members.

Volcano	Latitude	Longitude	Vent altitude (m)
Mount Churchill	61.25	-141.750	5005
Mount Katmai	58.75	-154.963	2047
Changbaishan	42.50	128.080	2744
El Chichón	17.50	93.230	1205
Mount Pinatubo	15.00	120.350	1486
Mount Tambora	-8.75	118.000	2850
Taupō	-38.75	176.000	760
Calbuco	-41.25	-72.618	1974
Mount Hudson	-46.25	-72.970	1905

Table S3. List of volcanoes used in deriving the mass eruption rate for large-magnitude eruptions. The latitudes, longitudes and vent altitudes are obtained from the Smithsonian Global Volcanism Program database (Global Volcanism Program, 2022).

Input parameters	Values used
Magma temperature	1100 °C
Mass fraction of gas in magma	5 wt.%
Specific heat of magma	1280 J/kg K
Magma density	2350 kg/m^3

Table S4. Values of input parameters related to magma properties in Plumeria.

Data Set S1. The input datasets for large-magnitude (> 3 Tg of SO_2) and small-magnitude (< 3 Tg of SO_2) historical eruptions from the ice-core and satellite datasets used for resampling.

Data Set S2. The eruption time series and information of the future stochastic scenarios VOLC2.5, VOLC50-1, VOLC50-2 and VOLC98.