# 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, United Kingdom
[6] German Aerospace Center (DLR), Institute of Atmospheric Physics (IPA), Oberpfaffenhofen, Germany
[7] Ludwig-Maximilians University Munich, Meteorological Institute, Munich, Germany

Corresponding author: Man Mei Chim (mmc70@cam.ac.uk)

**Key Points:**

- There is a 95% chance that the time-averaged 2015-2100 volcanic $SO_2$ flux from explosive eruptions exceeds the time-averaged 1850-2014 flux
- Standard climate projections very likely underestimate the 2015-2100 stratospheric aerosol optical depth and volcanic climate effects
- Small-magnitude eruptions (< 3 Tg $SO_2$) contribute 30% to 50% of the volcanic climate effects in a median future eruption scenario

## Abstract

Standard climate projections represent future volcanic eruptions by a constant forcing inferred from 1850-2014 volcanic forcing. Using the latest ice-core and satellite records to design stochastic eruption scenarios, we show that there is a 95% probability that explosive eruptions could emit more sulfur dioxide ($SO_2$) into the stratosphere over 2015-2100 than current standard climate projections (i.e., ScenarioMIP). Our simulations using the UK Earth System Model with interactive stratospheric aerosols show that for a median future eruption scenario, the 2015-2100 average global-mean stratospheric aerosol optical depth (SAOD) is double that used in ScenarioMIP, with small-magnitude eruptions (< 3 Tg of $SO_2$) contributing 50% to SAOD perturbations. We show that volcanic effects on large-scale climate indicators, including global surface temperature, sea level and sea ice extent, are underestimated in ScenarioMIP because current climate projections do not fully account for the recurrent frequency of volcanic eruptions of different magnitudes.



## Plain Language Summary

Climate projections are the simulations of Earth's climate in the future using complex climate models. Standard climate projections, as in Intergovernmental Panel on Climate Change Sixth Assessment Report, assume that explosive volcanic activity over 2015-2100 are of the same level as the 1850-2014 period. Using the latest ice-core and satellite records, we find that explosive eruptions could emit more sulfur dioxide into the upper atmosphere for the period of 2015-2100 than standard climate projections. Our climate model simulations show that the impacts of volcanic eruptions on climate, including global surface temperature, sea level and sea ice extent, are underestimated because current climate projections do not fully account for the recurrent frequency of volcanic eruptions. We also find that small-magnitude eruptions occur frequently and can contribute a significant effect on future climate.


## 1. Introduction

Large explosive volcanic eruptions can inject sulfur dioxide ($SO_2$) forming volcanic sulfate aerosols in the stratosphere that scatter incoming solar radiation, resulting in negative radiative forcing and global surface cooling for 1-3 years (McCormick et al., 1995). Stratospheric volcanic sulfate aerosols also heat the stratosphere by absorbing infrared and near-infrared radiation, which can further induce complex climate responses on seasonal to multi-decadal timescales (see Marshall et al. (2022) for a review).

As we cannot predict future volcanic eruptions, a constant volcanic forcing is commonly used in climate projections, e.g., as done in Phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016), which informs the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report. In the CMIP6 Scenario MIP (ScenarioMIP; O'Neill et al., 2016), the constant volcanic forcing is inferred from the time average of the reconstructed 1850-2014 volcanic forcing. This approach does not account for how the sporadic occurrence of volcanic eruptions may affect the climate as opposed to a time-averaged forcing. In addition, volcanic injections into the stratosphere during the Holocene (past 11,500 years; Sigl et al., 2022) can vary

by as much as a factor of 25 on centennial timescales. The corresponding uncertainty on future volcanic forcing is currently unaccounted for in most climate projections. A handful of studies have attempted to quantify the role of volcanic forcing uncertainty in climate projections (Ammann and Naveau, 2010; Bethke et al., 2017; Dogar et al., 2020). Bethke et al. (2017) estimated the volcanic forcing of 60 different future eruption scenarios from 2015 to 2100 by resampling ice-core sulfate deposition records going back 2,500 years (Sigl et al., 2015). Up-to-date ice-core and satellite volcanic sulfur emission datasets enable us to account for the occurrence of (i) eruptions larger in magnitude than those that occurred between 1850 and 2014, which injected as much as 300 Tg of $SO_2$ into the atmosphere, and (ii) small-magnitude eruptions below the detection threshold of ice-core datasets (Figure 1a), which can contribute a significant fraction to stratospheric aerosol optical depth (SAOD) (Santer et al., 2014; Schmidt et al., 2018).

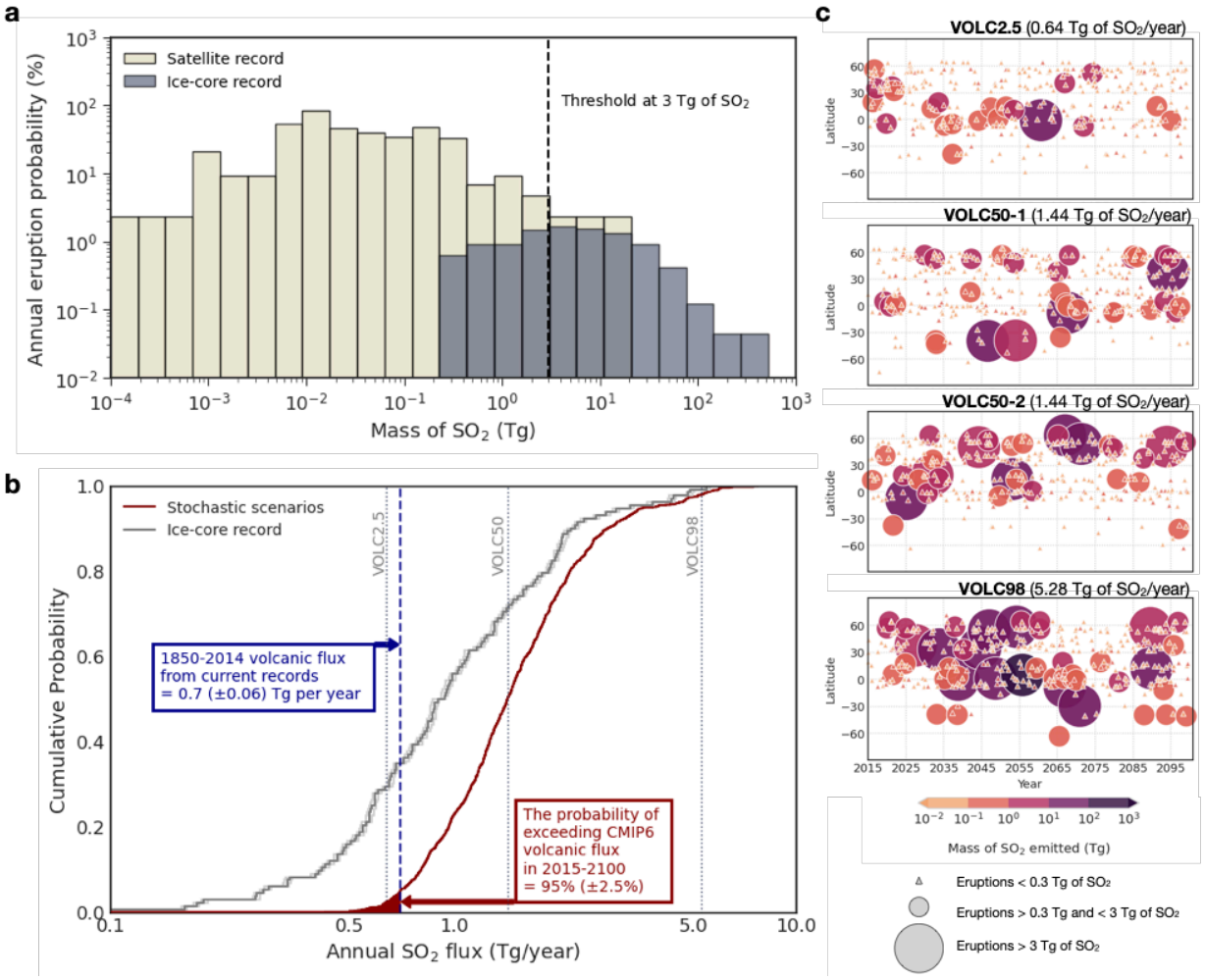


**Figure 1**. (**a**) Annual eruption probability based on ice-core (Sigl et al., 2022) and satellite (Carn et al., 2022) datasets. (**b**) Empirical cumulative probability density function of the $SO_2$ mass distribution of the 1000-member stochastic scenarios and the Holvol ice-core dataset (with 95% bootstrap confidence bounds, in light grey). We estimate the probability of exceeding CMIP6 volcanic flux using the 1850-2014 flux from current volcanic $SO_2$ emission records (Neely and Schmidt, 2016; Sigl et al., 2022; Carn, 2022). (**c**) Eruption time series of VOLC2.5, VOLC50-1, VOLC50-2, and VOLC98 with annual volcanic $SO_2$ flux of each scenario in brackets.

In addition, whether they apply a constant volcanic forcing (e.g., CMIP6 ScenarioMIP) or use stochastic eruption scenarios (Bethke et al., 2017), existing climate projections use prescribed volcanic aerosol optical properties derived from simplified volcanic aerosol models. Climate models with interactive stratospheric aerosols (Timmreck et al., 2018) showed a better agreement between the simulated surface temperature responses and tree-ring surface temperature reconstructions for the 1257 Mount Samalas and 1815 Mount Tambora eruptions (Stoffel et al., 2015) and the 1783-1784 Laki eruption (Pausata et al., 2015; Zambri et al., 2019). Furthermore, the prescribed aerosol approach cannot account for the impacts of global warming on the life cycle of volcanic sulfate aerosols (Aubry et al., 2021), including the impact of changing atmospheric stratification on volcanic plume height (Aubry et al., 2019). Such climate-volcano feedbacks might amplify the peak global-mean radiative forcing associated with large-magnitude tropical eruptions by 30% (Aubry et al., 2021).

Our study aims to improve our understanding of future volcanic impacts on climate. To this end, we perform model simulations from 2015 to 2100 with two innovations: (i) a stochastic resampling approach using the latest ice-core and satellite datasets to generate improved future volcanic eruption scenarios; and (ii) a plume-aerosol-chemistry-climate modeling framework (named UKESM-VPLUME), which combines a volcanic plume model and an Earth System Model with interactive stratospheric aerosols to simulate volcanic climate effects while accounting for climatic controls on plume-rise height.

## 2. Methodology

### 2.1 Stochastic future eruption scenarios

We generate 1000 stochastic future eruption scenarios for 2015 to 2100 by resampling $SO_2$ mass from volcanic emission inventories from a bipolar ice-core array covering the past 11,500 years (Holvol; Sigl et al., 2022) and a multi-satellite record from 1979 to 2021 (Carn et al., 2016; Carn, 2022) (Figure 1a and S1). Before resampling, we filter out: i) effusive eruptions; ii) in the satellite record, eruptions with eruptive plume heights more than 3 km below the thermal tropopause (obtained from NCEP/NCAR Reanalysis 1; Kalnay et al., 1996); we assume that aerosol lofting could result in stratospheric injections for tropospheric plumes less than 3 km below the tropopause. By examining the eruption frequency-magnitude (i.e., in this study, $SO_2$ mass) distribution of both ice-core and satellite records (Figure 1a), we identify 3 Tg of $SO_2$ as a threshold: i) below which ice-core records underestimate eruption frequency due to under-recording; and ii) above which the short duration of the satellite record precludes it from capturing the true frequency of eruptions with higher magnitude. Accordingly, we use a 3 Tg of $SO_2$ threshold to define "small-magnitude" and "large-magnitude" eruptions. We resample small-magnitude eruptions from the satellite record only, and large-magnitude ones from the combined ice-core and satellite record. Details of the resampling of the erupting volcano, $SO_2$ mass, and mass eruption rate are discussed in the Supplementary Information.

### 2.2 UKESM-VPLUME

Atmospheric stratification, wind and humidity affect volcanic plume dynamics and $SO_2$ injection height (e.g., Mastin, 2014), but $SO_2$ height is commonly prescribed in modelling studies of volcanic forcing (e.g., Timmreck et al., 2018). To account for meteorological controls on plume dynamics, we have developed UKESM-VPLUME, which couples the UK Earth System Model (UKESM; Mulcahy et al., 2023) with Plumeria (1-D eruptive plume model; Mastin, 2007, 2014) (details in Supplementary Information). We use version 1.1 of UKESM with fully-coupled atmosphere-land-ocean and interactive stratospheric aerosols. In brief, for each time step of the UKESM atmospheric model during an eruption, UKESM-VPLUME interactively passes the atmospheric conditions simulated at the eruption location to Plumeria. Plumeria then computes the neutral buoyancy height of the volcanic plume based on atmospheric conditions and the mass eruption rate generated for each eruption in the stochastic scenarios. Volcanic $SO_2$ is injected into UKESM at the neutral buoyancy height calculated in Plumeria using a gaussian profile with a width of 10% of the plume height (consistent with large-eddy simulations of volcanic plumes, Aubry et al., 2019). This approach ensures that plume heights of volcanic eruptions are consistent with the meteorological conditions simulated by UKESM.

### 2.3 Experimental design

We perform simulations using the UKESM-VPLUME framework for four stochastic future eruption scenarios at the 2.5$^{th}$, 50.0$^{th}$, 50.5$^{th}$ and 98.0$^{th}$ percentiles (termed VOLC2.5, VOLC50-1, VOLC50-2, VOLC98) of the distribution of the 2015-2100 average $SO_2$ flux across the 1000 future eruption scenarios (Figure 1b). We choose scenarios close (within 0.5 percentile) to the 2.5$^{th}$, 50$^{th}$ and 97.5$^{th}$ to sample the median and 95% confidence interval of the future volcanic stratospheric $SO_2$ injections. To test future climate trajectory sensitivity to the temporal and spatial distribution of eruptions, we run two scenarios near the 50$^{th}$ percentile. For instance, VOLC50-2 has more large-magnitude eruptions than VOLC50-1 in the early 21$^{st}$ century (Figure 1c). We also performed the VOLC50 runs with small-magnitude eruptions only (VOLC50-1S and VOLC50-2S) to isolate their contribution to the overall climate effects caused by eruptions of all magnitudes. We compare the results from VOLC runs with runs without volcanic eruptions (NOVOLC) and with CMIP6 ScenarioMIP constant volcanic forcing (CONST). We perform all simulations from 2015 to 2100 under a high-end future emission scenario (SSP3-7.0 in ScenarioMIP) running three ensemble members for each scenario.

## 3. Results

Figure 2 shows the global monthly-mean SAOD at 550 nm and the time-averaged values over 2015-2100. The time-averaged ensemble-mean SAOD ranges from 0.015 ± 0.0004 (VOLC2.5) to 0.062 ± 0.0018 (VOLC98), with an average value of 0.024 ± 0.0012 for the two median future eruption scenarios (VOLC50), while the SAOD in CONST, which followed the ScenarioMIP design, is 0.012 ± 0.0018 (one standard deviation uncertainty). Small-magnitude eruptions contribute 0.010 to 0.013 ± 0.0002 to the time-averaged SAOD in the VOLC50 scenarios, i.e., about 50% of the total SAOD. Comparing VOLC2.5 to CONST and assuming that the rank for the 2015-2100-year mean volcanic $SO_2$ flux and SAOD are the same, it is thus very likely (i.e., > 90% probability following IPCC guidance note; Mastrandrea et al., 2010) that the actual global 2015-2100 mean SAOD will be higher than that prescribed in ScenarioMIP, with the median (VOLC50) SAOD value being double that used in ScenarioMIP. The result is consistent

with Figure 1, given that the 1850-2014 time-averaged $SO_2$ flux used to define the ScenarioMIP volcanic forcing is close to the 2.5$^{th}$ percentile of the future volcanic $SO_2$ flux distribution. Beyond the time-averaged SAOD value, owing to the sporadic nature of volcanic eruptions, the global monthly-mean SAOD values in VOLC scenarios can be up to a factor of 60 greater than that in ScenarioMIP (Figures 2 and S2).

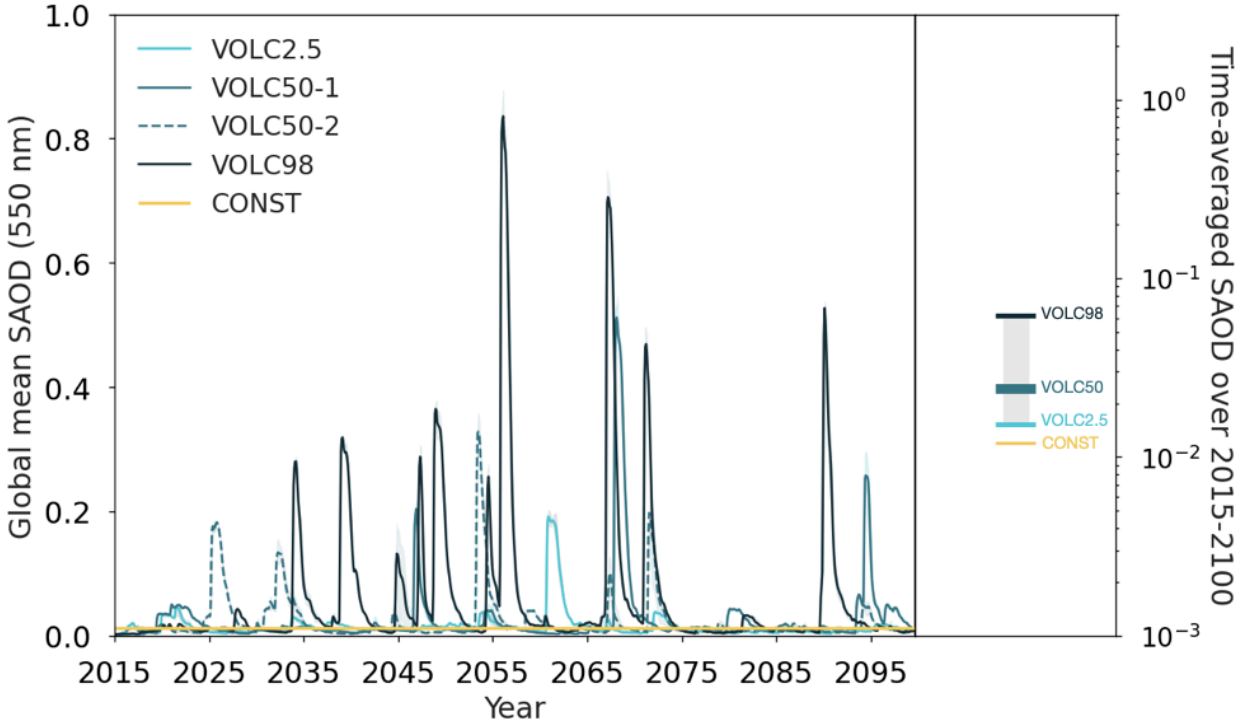


**Figure 2**. (Left) Global monthly-mean SAOD at 550 nm. The lines show the ensemble mean and the shading shows the spread of the maximum and minimum ensemble members. (Right) The corresponding time-averaged SAOD over 2015-2100 (in log scale).

Figure 3a shows the global annual-mean surface air temperature at 1.5 m (GMST) relative to the 1850-1900 period. Large-magnitude volcanic eruptions lead to a short-term drop in the annual-mean GMST for at least 1 year and up to 6 to 7 years for the largest eruptions. In the VOLC98 scenario where clusters of large-magnitude eruptions occur, they can induce multi-decadal global cooling. The 2015-2100 time-averaged GMST relative to detrended NOVOLC ensemble mean (Figure 3b) ranges between -0.16 ºC (VOLC2.5) and -0.56 ºC (VOLC98), with CONST lying outside this range at -0.12 ºC. Volcanic cooling for median eruption scenarios (VOLC50-1 and VOLC50-2) is 0.20 to 0.24 ºC, double that of CONST, and 0.09 to 0.10 ºC of cooling is attributable to small-magnitude eruptions (Table S1).

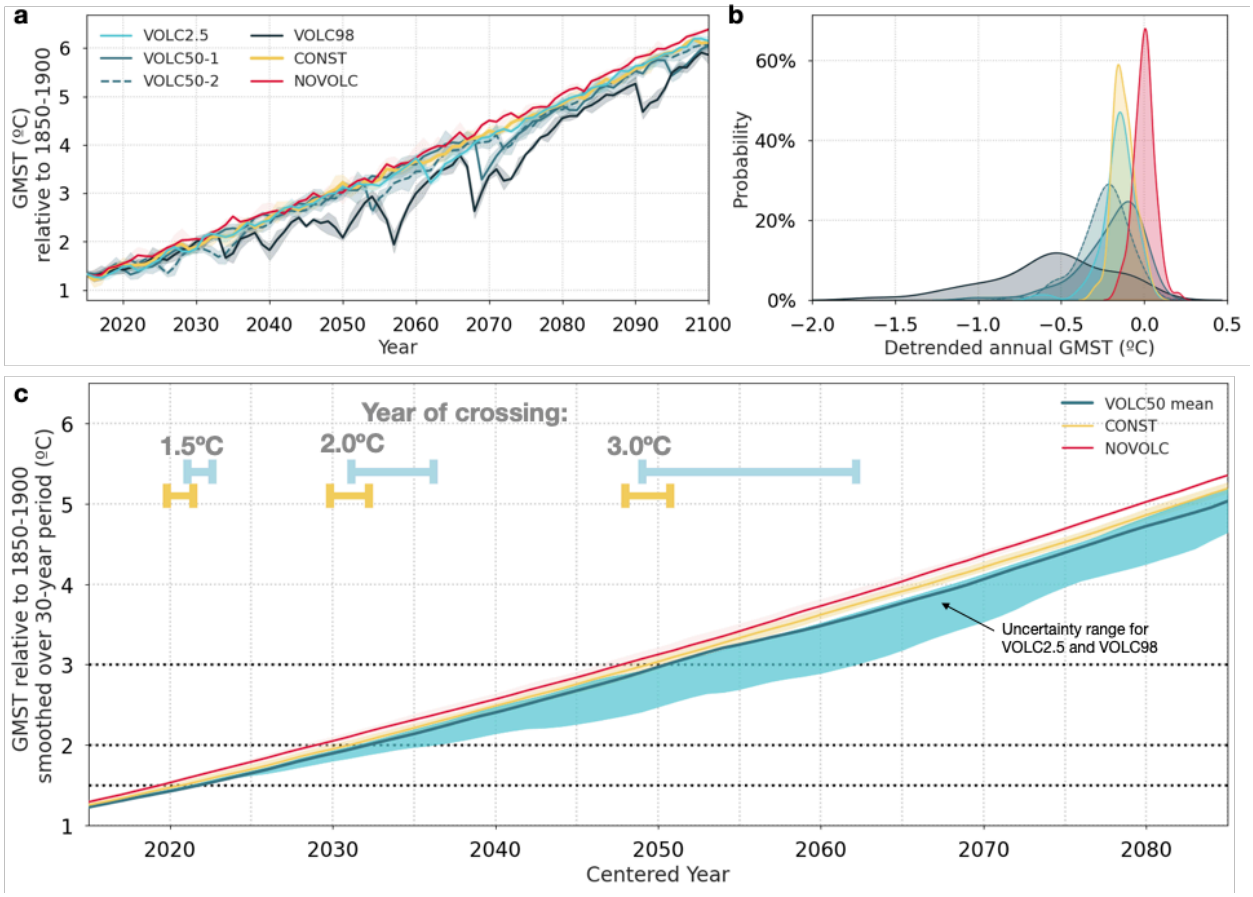


**Figure 3**. (**a**) Annual-mean GMST relative to 1850-1900. The lines show the ensemble mean and the shading shows the spread of the maximum and minimum ensemble members. (**b**) Probability density function of the annual-mean GMST relative to detrended NOVOLC ensemble mean (see Supplementary Information). (**c**) 30-year moving mean GMST with years of crossing 1.5 ºC, 2 ºC, and 3 ºC for VOLC and CONST runs.

The IPCC defines global warming as an increase, relative to 1850-1900, in the global mean surface air and sea surface temperatures over a period of 30 years (IPCC, 2021). Using this definition, we examine the year of crossing of 1.5 ºC, 2 ºC, and 3 ºC warming thresholds for VOLC and CONST runs (Figure 3c). Volcanic eruptions delay the time of crossing 1.5 ºC by about 1.6 to 3.2 years when compared to NOVOLC (Table S2), consistent with Bethke et al. (2017). Compared to CONST, times of temperature threshold crossings are significantly delayed by 1.8 to 2.5 years in VOLC50-2, but unaffected in VOLC50-1. This highlights the sensitivity of the time of crossing to the temporal distribution of large-magnitude eruptions. The occurrence of volcanic clusters in VOLC98 causes an extended cooling period between 2034 to 2060 (Figure 3a) which delays the crossing of 2 ºC and 3 ºC by 7 and 14 years, respectively.

In Figure 4, we examine volcanic effects on large-scale climate indicators other than GMST. The 2015-2100 time-averaged global annual-mean precipitation fluxes in all VOLC runs show a greater reduction than CONST, with a range between -0.014 mm/day (VOLC2.5) to -0.052 mm/day (VOLC98), and -0.010 mm/day for CONST (Figure 4a). In VOLC50 scenarios, the global

annual-mean precipitation flux is reduced by 0.019 mm/day with small-magnitude eruptions alone contributing between 0.008 and 0.009 mm/day, comparable to the effects of the volcanic forcing implemented in ScenarioMIP. It is thus very likely that the reduction of global mean precipitation due to volcanic effects is underestimated in ScenarioMIP.

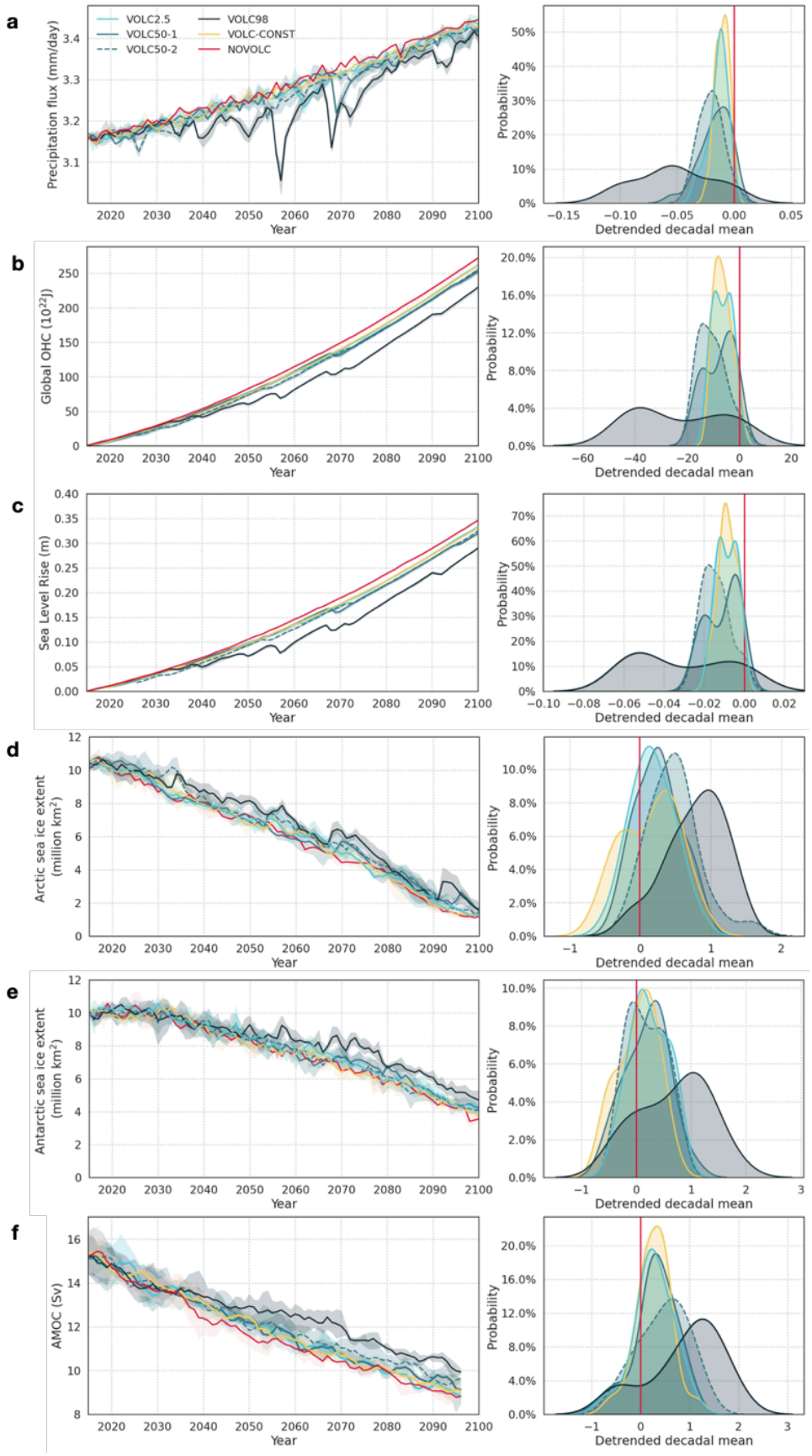
a
b
c
d
e
f
VOLC2.5
VOLC50-1
VOLC50-2
VOLC98
VOLC-CONST
NOVOLC
Precipitation flux (mm/day)
Global OHC ($10^{22}$J)
Sea Level Rise (m)
Arctic sea ice extent (million km$^2$)
Antarctic sea ice extent (million km$^2$)
AMOC (Sv)
Year
Probability
Detrended decadal mean

**Figure 4**. (Left) Annual mean time series of selected large-scale climate indicators. The line shows the ensemble mean and the shading shows the spread of the maximum and minimum ensemble members. (Right) The corresponding decadal-mean probability density function relative to the detrended NOVOLC ensemble mean, with the red vertical line showing the mean of NOVOLC. (**a**) global precipitation flux (in mm/day), (**b**) global ocean heat content (in $10^{22}$ J), (**c**) global thermosteric sea level rise (in m), (**d** and **e**) Arctic and Antarctic sea ice extent (in million km$^2$), defined as the area with >15% sea ice, (f) 5-year moving mean AMOC at 26ºN (in Sv).

Volcanic-induced surface cooling penetrates into the deep ocean layer and decreases the global ocean heat content (Figures 4b and S3), which in turn leads to less thermal expansion in seawater and a reduction in thermosteric sea level (Figure 4c). Volcanic forcing in VOLC50 reduces global ocean heat content and thermosteric sea level by 6% to 7% compared to NOVOLC by 2100, whereby about half is attributed to small-magnitude eruptions (Figure S3). Although volcanic forcing can cause considerable impacts on large-scale ocean metrics, it does not offset the anthropogenic-induced ocean warming trends even for the upper-end volcanic emission scenario VOLC98 (Figures 4b, 4c and 4f).

Depending on the eruption magnitude and location, the Arctic and Antarctic sea ice extents show an immediate increase for 1-2 years after large-magnitude eruptions (Figures 4d and 4e). The time-averaged global sea ice extent in VOLC runs over 2015 to 2100 increases by 0.43 million km$^2$ (VOLC2.5) to 1.53 million km$^2$ (VOLC98) as compared to 0.20 million km$^2$ for CONST. Comparing VOLC2.5 to CONST suggests that for similar time-averaged SAOD, the use of a constant forcing instead of a stochastic eruption distribution halves the magnitude of the sea ice response.

The time-averaged Atlantic Meridional Overturning Circulation (AMOC) at 26ºN over 2015 to 2100 is strengthened by between 0.26 Sv (VOLC2.5) and 0.93 Sv (VOLC98) as compared to NOVOLC, with all VOLC scenarios exhibiting an increased decadal mean AMOC strength (Figure 4f). The stronger AMOC responses in VOLC runs are consistent with reduced precipitation over the Northern Hemisphere, which increases salinity and enhances deep-water formation (Pausata et al., 2015). Small-magnitude eruptions alone can increase the time-averaged AMOC strength by 0.36-0.38 Sv (VOLC50-1S and VOLC50-2S), which is greater than CONST at 0.28 Sv, and contribute to over 77% of the AMOC response in the median future scenarios (Table S1). One of the median future scenarios (VOLC50-1) has a weaker time-averaged AMOC than the same run with small-magnitude eruptions only (VOLC50-1S) due to an extended period of weakened AMOC after the occurrence of large-magnitude eruptions (Figure S4), suggesting AMOC may have different responses towards different latitudinal and $SO_2$ distributions of large-magnitude eruptions.

## 4. Discussion

Small-magnitude eruptions (< 3 Tg of $SO_2$) contribute a considerable fraction (between 33% and 40%) of the total upper atmospheric volcanic $SO_2$ emissions in VOLC50, and in turn, are responsible for 30% to 50% of the volcanic impact on selected large-scale climate indicators and over 77% of the AMOC response (Figure 5 and Table S1). For future eruption scenarios with fewer

eruptions than VOLC50, the contribution from small-magnitude eruptions is expected to be even greater because the total mass injected by small-magnitude eruptions is relatively similar across all scenarios. Despite the importance of volcanic forcing from small-magnitude eruptions, they are mostly unaccounted for in historical simulations before satellite measurements are available. In the pre-satellite historical period (1850-1978), the Neely and Schmidt (2016) and Sigl et al. (2022) volcanic $SO_2$ inventories have an average flux of 0.21 and 0.26 Tg of $SO_2$ per year from small-magnitude eruptions, respectively. By comparison, the flux is 0.50 Tg of $SO_2$ per year over 1979-2021 (Carn, 2022). This suggests a missing flux from small-magnitude eruptions of between 0.24 and 0.29 Tg of $SO_2$ per year in the pre-satellite historical period, which is the equivalent of injections from about 1 to 2 Mount Pinatubo 1991 eruptions.

Our stochastic scenarios imply that CMIP6 ScenarioMIP very likely (95 ± 2.5%) underestimates the 2015-2100 volcanic $SO_2$ flux from explosive eruptions and, in turn, forcing (Figure 1b). Figure 1b shows the cumulative probability against the annual $SO_2$ flux obtained by resampling ice-core record of volcanic $SO_2$ injection only (i.e., Holvol; Sigl et al. 2022) and both ice-core and satellite (Carn, 2022) records as in our stochastic scenarios. CMIP6 ScenarioMIP uses a constant volcanic forcing inferred from the 1850-2014 period during which the mean volcanic $SO_2$ flux recorded in emission inventories was 0.7 ± 0.06 Tg per year. However, we find a 95% confidence interval for the 2015-2100 mean volcanic $SO_2$ flux between 0.64 to 5.28 Tg per year in our eruption scenarios (Figure 1b). Our stochastic approach, which represents better the frequency-magnitude distribution of small-magnitude eruptions, results in a higher annual $SO_2$ flux than resampling from the ice-core record only (e.g., Bethke et al., 2017).

Our future volcanic eruption scenarios greatly enhance the variability of large-scale climate indicators as compared to the ScenarioMIP forcing (Figure 5). Future volcanic emissions in our scenarios cause a 3.5% (VOLC2.5) to 15.0% (VOLC98) decrease in the 2015-2100 time-averaged global net radiative forcing at the top-of-the-atmosphere relative to the anthropogenic contribution (Figures 5 and S5, see Supplementary Information). The time-averaged climate responses of our selected climate indicators scale with the magnitude of volcanic forcing except for the Antarctic sea ice extent and AMOC, which may depend on the latitudinal distribution of eruptions. We also find that the magnitude of volcanic effects on climate indicators are comparable between CONST and VOLC2.5, which is a scenario with only one Pinatubo-like eruption over 2015-2100. Our results suggest that due to the low volcanic forcing used in ScenarioMIP, it is very likely (97.5%) that ScenarioMIP underestimates the climate effects of the large-scale climate indicators examined in this study.

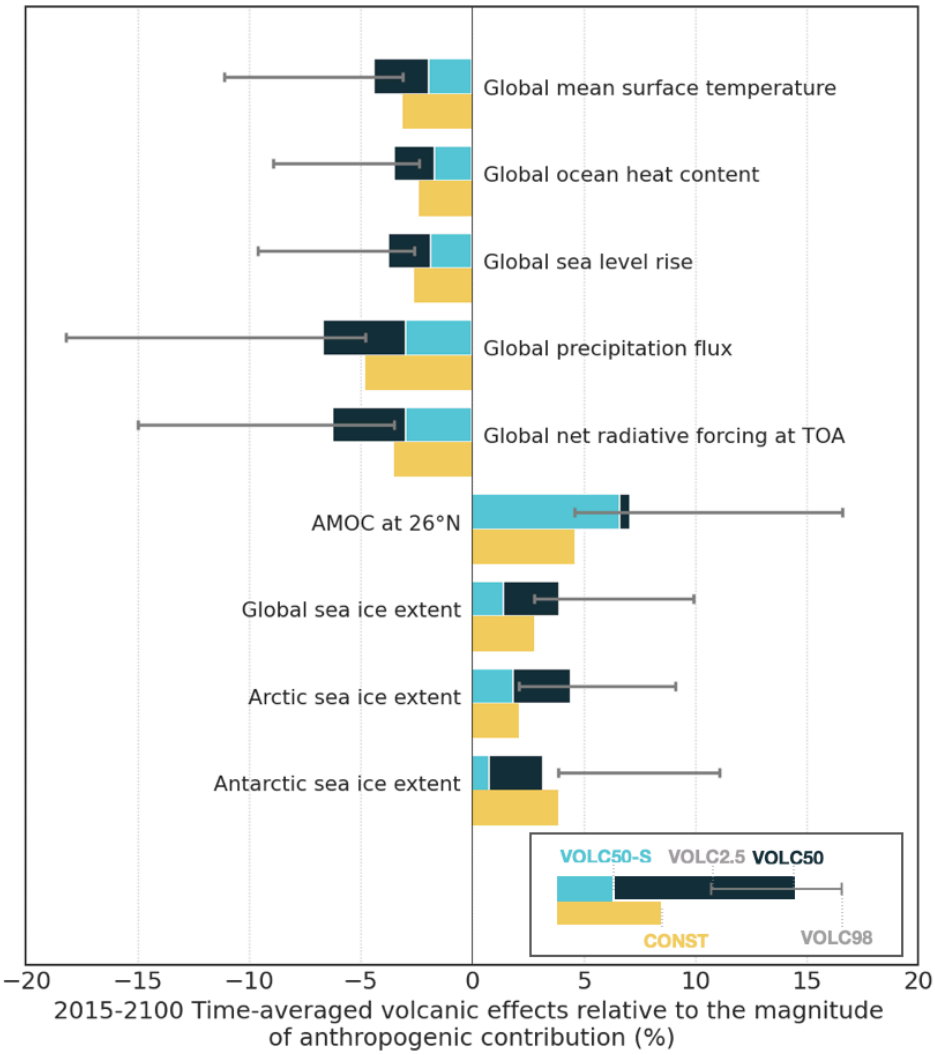


**Figure 5**. Bar chart showing the time-averaged volcanic effects on large-scale climate indicators relative to the magnitude of anthropogenic contribution over the period of 2015 to 2100, i.e., VOLC50-S refers to average effects of the two VOLC50 runs with small-magnitude eruptions only.

Our simulation results show that for the SSP3-7.0 scenario, volcanic forcing can offset 2.1% to 18.2% of the anthropogenic effects to large-scale climate indicators depending on the future eruption scenarios (Figure 5). In a future scenario with low-end anthropogenic emission (SSP1-2.6), we would expect the relative effect between future volcanism and anthropogenic forcing to be much greater, e.g., by a factor of 3 for GMST since the 2015-2100 warming is 4.8 ºC in SSP3-7.0 and 1.4 ºC in SSP1-2.6. Our work highlights how the high level of uncertainty on volcanic forcing affects climate projections. For the same future eruption scenario, the volcanic effects on climate will also vary between SSP scenarios owing to climate-volcano feedbacks (e.g., Hopcroft et al., 2017; Fasullo et al., 2018; Aubry et al., 2022), which need to be quantified.

## 5. Conclusion

We performed climate model simulations from 2015 to 2100 with stochastic future eruption scenarios using UKESM-VPLUME (a plume-aerosol-chemistry-climate model framework that accounts for climate-volcano feedbacks) to examine how the uncertainties on volcanic forcing affect climate projections. Using the latest ice-core and satellite datasets, we show that the 2015 to 2100 volcanic $SO_2$ flux from explosive eruptions has a 95% probability to exceed the 1850-2014 flux, which was used to derive volcanic forcing in CMIP6 ScenarioMIP. Our simulations suggest that the time-averaged SAOD in a median future scenario is 0.024 (95% uncertainty: 0.015-0.062), which is double that in ScenarioMIP, and that ScenarioMIP very likely underestimates the future volcanic effects on climate. Our study emphasizes the importance of the climate effects of future volcanic eruptions relative to the anthropogenic contribution, which even for an upper end anthropogenic forcing scenario (SSP3-7.0) can range between 2.1% to 18.2% for large-scale climate indicators. We also highlight the climate-relevance of small-magnitude eruptions, which are responsible for 30% to 50% of the volcanic effects on selected climate indicators. Future climate projection studies could either use our stochastic eruption scenarios generated using state-of-the-art volcanic emission inventories, or use a time-averaged constant forcing that better represents long-term volcanic activity and accounts for small-magnitude eruption contributions.

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## Data Availability Statement

The data presented in this study are available in the University of Cambridge data repository: https://doi.org/10.17863/CAM.94912. 

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