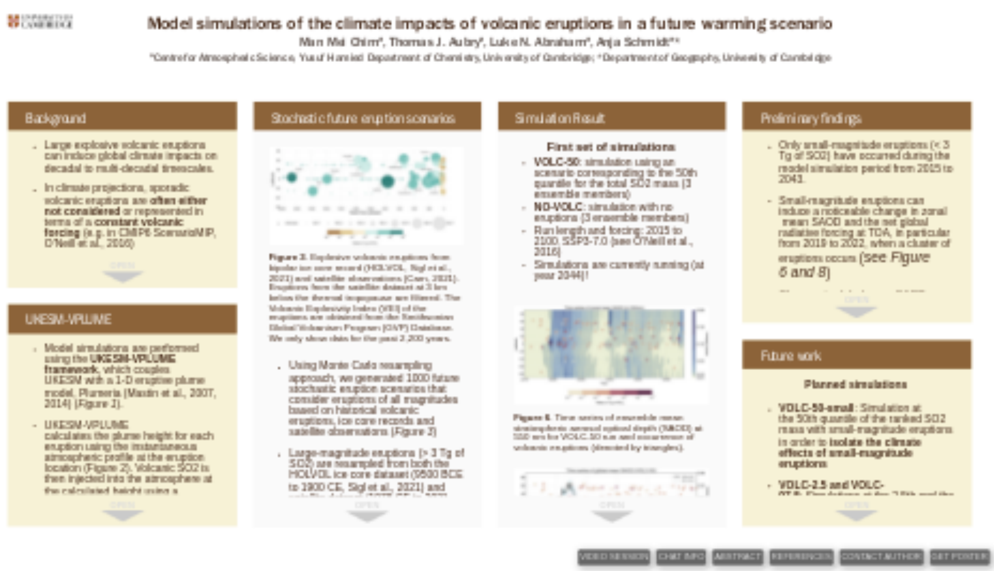
Model simulations of the climate impacts of volcanic eruptions in a future warming scenario



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PRESENTED AT:

BACKGROUND

- Large explosive volcanic eruptions can induce global climate impacts on decadal to multi-decadal timescales.

- In climate projections, sporadic volcanic eruptions are **often either not considered** or represented in terms of a **constant volcanic forcing** (e.g. in CMIP6 ScenarioMIP, O'Neill et al., 2016)

- The above strategy also **ignores climate-volcano feedbacks**, i.e. the potential impacts of climate change on volcanic forcing. For more details, please see Aurby et al. (2021) and the poster by Aubry et al. **(HERE) (https://agu2021fallmeeting-agu.ipostersessions.com/default.aspx?s=80-FE-74-16-9A-EF-05-25-2B-9B-36-76-CC-E5-DD-92)**

- To make progress, we are implementing statistically realistic future eruption scenarios in 2015-2100 projections run with the UK Earth System Model (UKESM, Sellar et al. 2019). Our study design has three major improvements over the handful of previous studies that have implemented stochastic eruption scenarios (Bethke et al., 2017, Man et al., 2021):

1. Our stochastic eruption scenarios represent eruptions of both large- and small-magnitudes, with SO_2 mass ranging from 0.001 to 378 Tg of SO_2, instead of 0.42 to 118 Tg of SO_2 in previous studies. Including small-magnitude eruptions is critical as they have recently been shown to lead to significant variability in stratospheric aerosol optical depth (SAOD), radiative forcing, surface temperature and ozone concentrations (Santer et al., 2014; Solomon et al., 2016; Schmidt et al., 2018).

2. The model we use is fully interactive and capable of explicitly simulating the stratospheric volcanic sulfate aerosol life cycle.

3. In our simulations we account for climate-volcano feedbacks, which affect the magnitude of the volcanic forcing (Aubry et al., 2021). This is enabled by the use of a fully interactive model that accounts for feedbacks related to aerosol transport, chemistry and microphysics in a warmer climate. Furthermore, our model is coupled to a plume model using (UKESM-VPLUME) to account for feedbacks related to volcanic plume dynamics (Aubry et al., 2016).

UKESM-VPLUME

- Model simulations are performed using the **UKESM-VPLUME framework**, which couples UKESM with a 1-D eruptive plume model, Plumeria (Mastin et al., 2007, 2014) (*Figure 1*).

- UKESM-VPLUME calculates the plume height for each eruption using the instantaneous atmospheric profile at the eruption location (Figure 2). Volcanic SO_2 is then injected into the atmosphere at the calculated height using a Gaussian injection profile (Aubry et al., 2019)

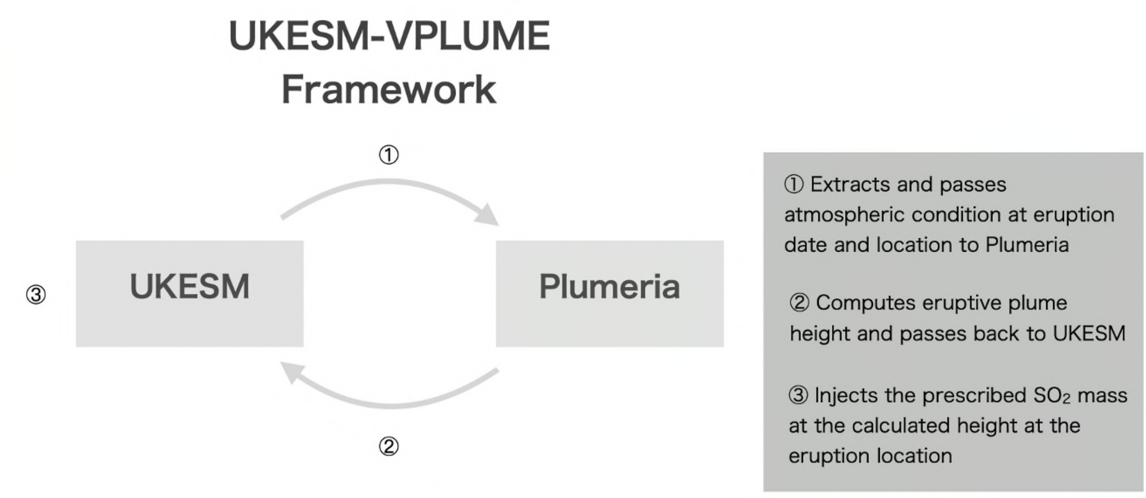

Figure 1. UKESM-VPLUME framework.

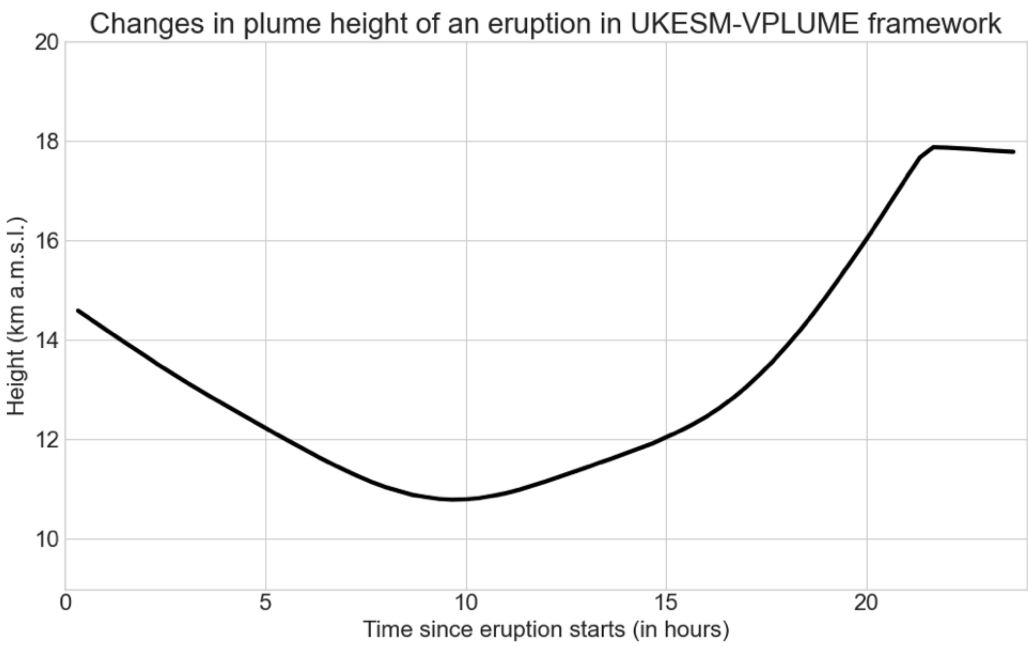

Figure 2. Time series of plume height changes for one of the eruptions (a moderate-magnitude extratropical eruption at 61.38 ºN) using UKESM-VPLUME framework.

STOCHASTIC FUTURE ERUPTION SCENARIOS

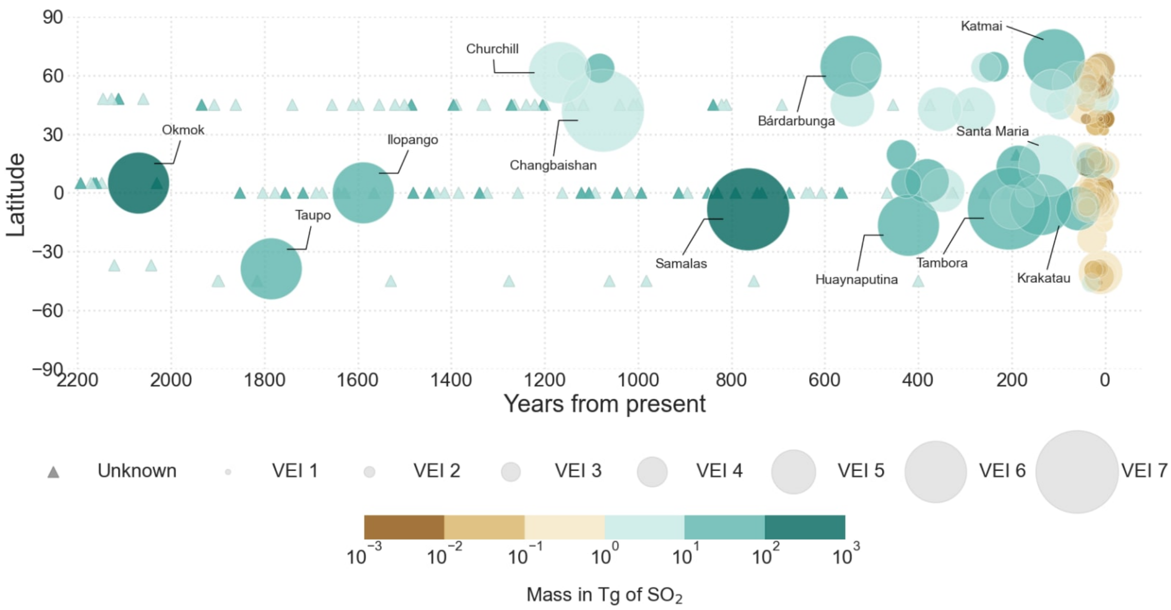

Figure 3. Explosive volcanic eruptions from bipolar ice core record (HOLVOL, Sigl et al., 2021) and satellite observations (Carn, 2021). Eruptions from the satellite dataset at 3 km below the thermal tropopause are filtered. The Volcanic Explosivity Index (VEI) of the eruptions are obtained from the Smithsonian Global Volcanism Program (GVP) Database. We only show data for the past 2,200 years.

- Using Monte Carlo resampling approach, we generated 1000 future stochastic eruption scenarios that consider eruptions of all magnitudes based on historical volcanic eruptions, ice core records and satellite observations (*Figure 3*)

- Large-magnitude eruptions (> 3 Tg of SO_2) are resampled from both the HOLVOL ice core dataset (9500 BCE to 1900 CE, Sigl et al., 2021) and satellite dataset (1978 CE to 2021 CE, Carn et al., 2021), and small-magnitude eruptions (< 3 Tg of SO_2) are resampled from the satellite dataset only.

- The **three scenarios corresponding to the 2.5th, 50th (VOLC-50) and 97.5th quantiles in terms of the ranked total SO_2 mass** are chosen for model simulations (*Figure 4*). *Figure 5* shows the future stochastic scenario that corresponds to the 50th quantile of the ranked SO_2 mass.

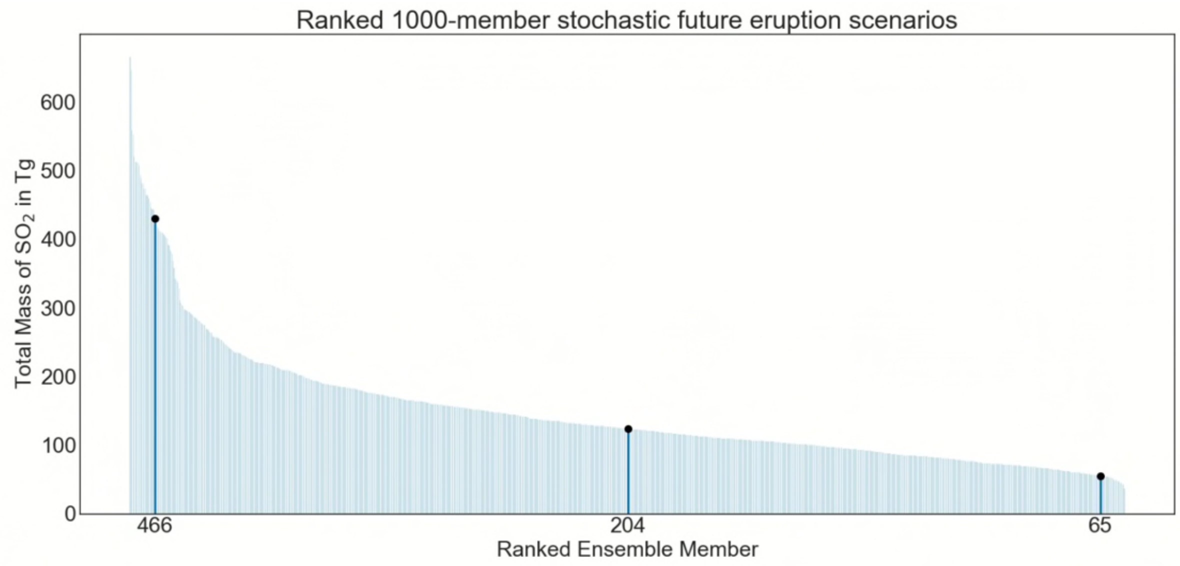

Figure 4. 1000-member stochastic future eruption scenarios according to the ranked total SO_2 mass. The three vertical stems represents the scenarios corresponding to the 97.5th, 50th and 2.5th quantile for the total mass in Tg of SO_2.

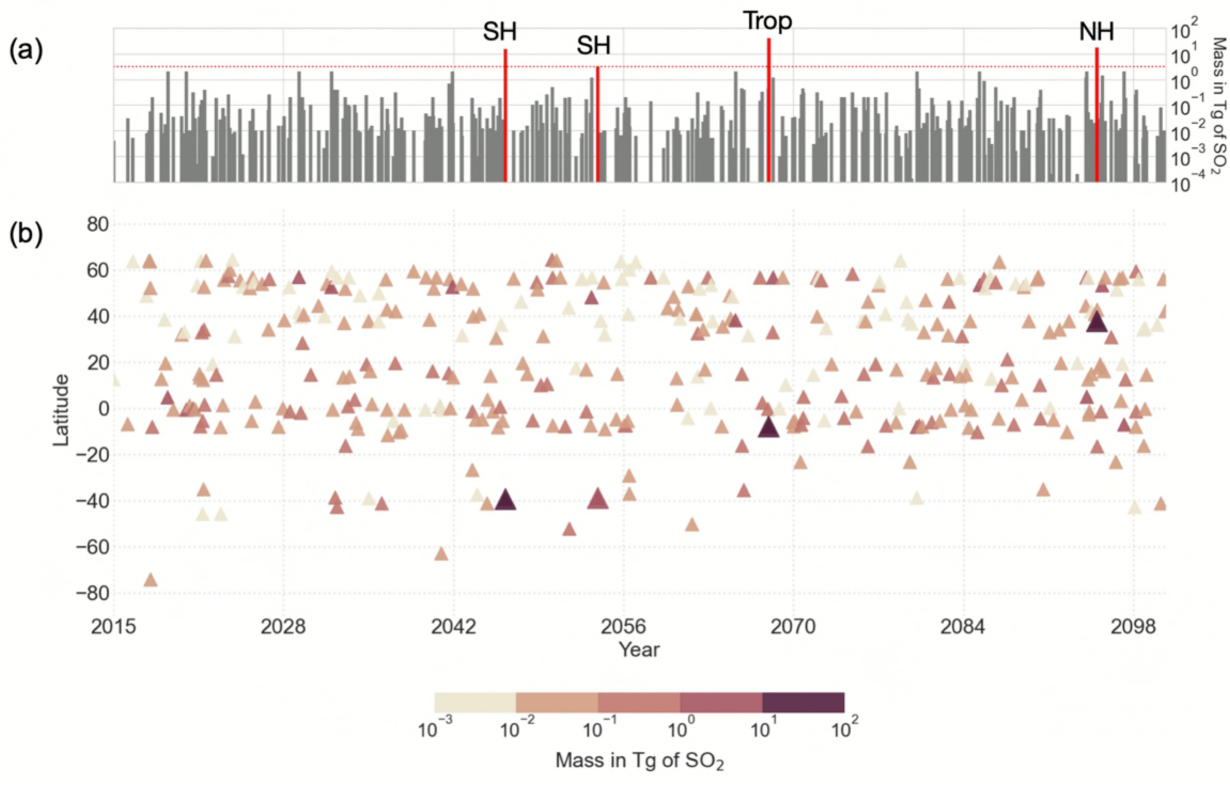

Figure 5. Time series of stochastic future eruption scenario at the 50th quantile of ranked total mass in Tg of SO_2. **(a)** Mass in Tg of SO_2 of the eruptions in log scale. The red bars refer to large-magnitude eruptions and the grey bars refer to small-magnitude eruptions. The red dotted line shows the 3 Tg of SO_2 threshold. **(b)** Latitudinal distribution of the eruptions. The colour bar shows the mass in Tg of SO_2.

SIMULATION RESULT

First set of simulations

- **VOLC-50**: simulation using an scenario corresponding to the 50th quantile for the total SO_2 mass (3 ensemble members)
- **NO-VOLC**: simulation with no eruptions (3 ensemble members)
- Run length and forcing: 2015 to 2100, SSP3-7.0 (see O'Neill et al., 2016)
- Simulations are currently running (at year 2044)!

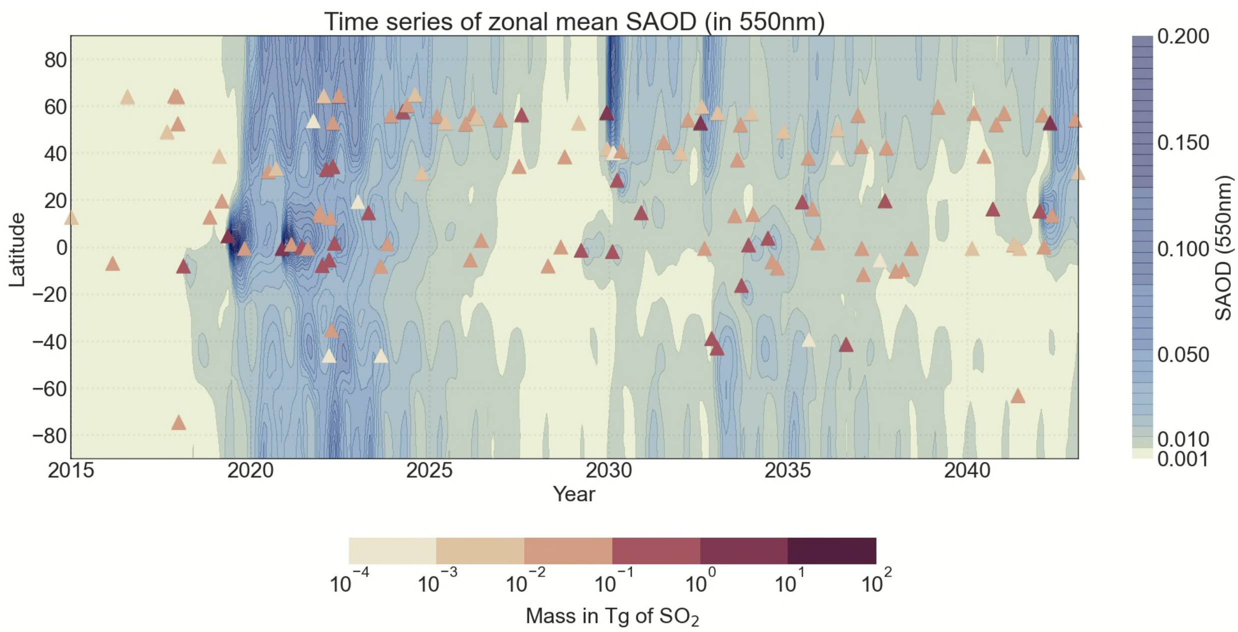

Figure 6. Time series of ensemble mean stratospheric aerosol optical depth (SAOD) at 550 nm for VOLC-50 run and occurrence of volcanic eruptions (denoted by triangles).

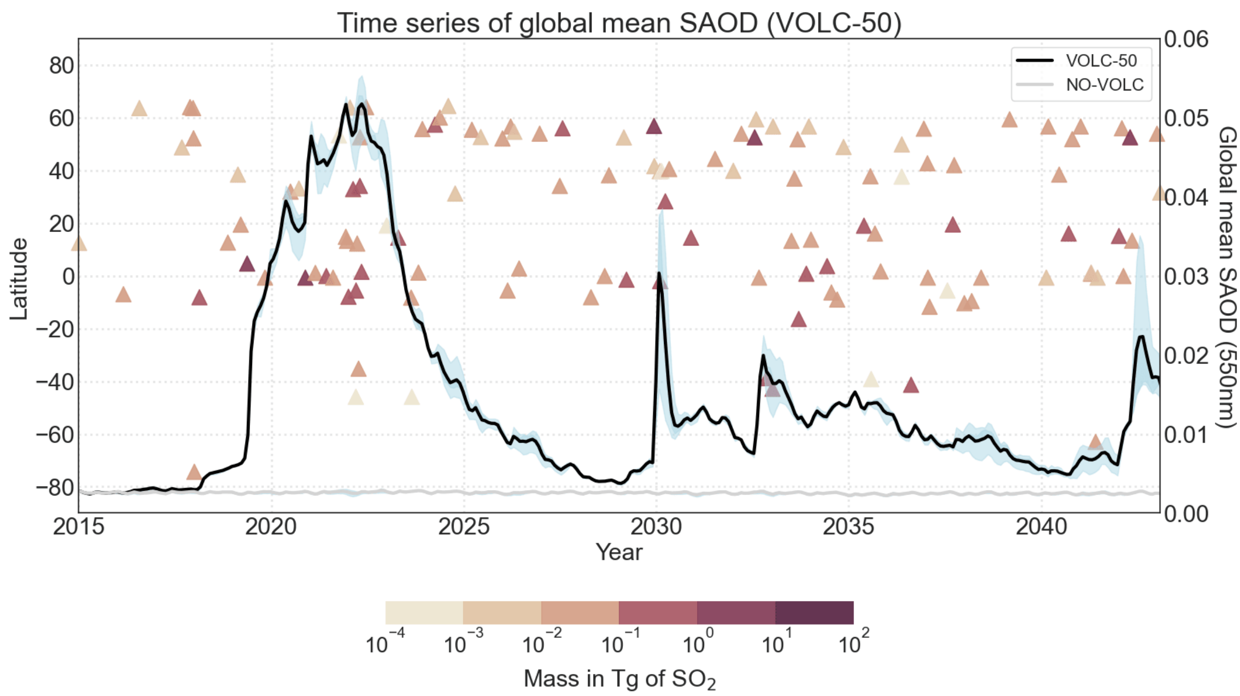

Figure 7. Time series of global mean SAOD at 550 nm for VOLC-50 and NO-VOLC. The shaded region denotes the maximum and minimum values of the ensemble members.

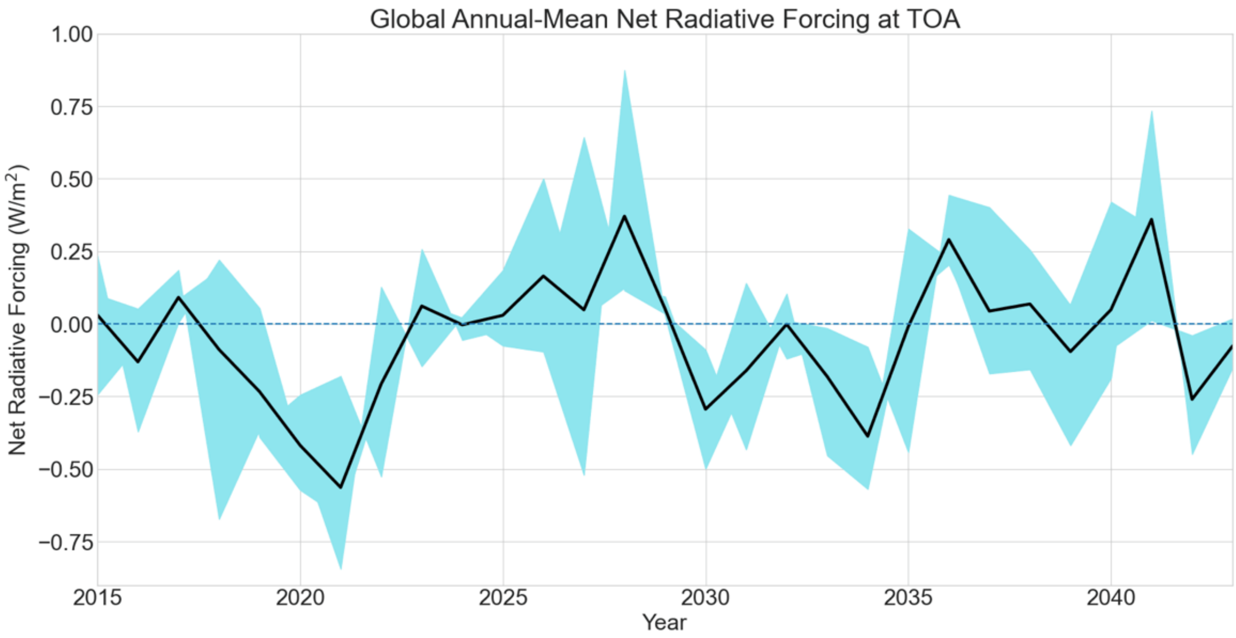

Figure 8. Changes in global annual-mean net radiative forcing (in W/m2) at top-of-the-atmosphere (TOA) calculated as the difference between VOLC-50 and NO-VOLC simulations. The shaded region denotes the maximum and minimum changes of the ensemble members.

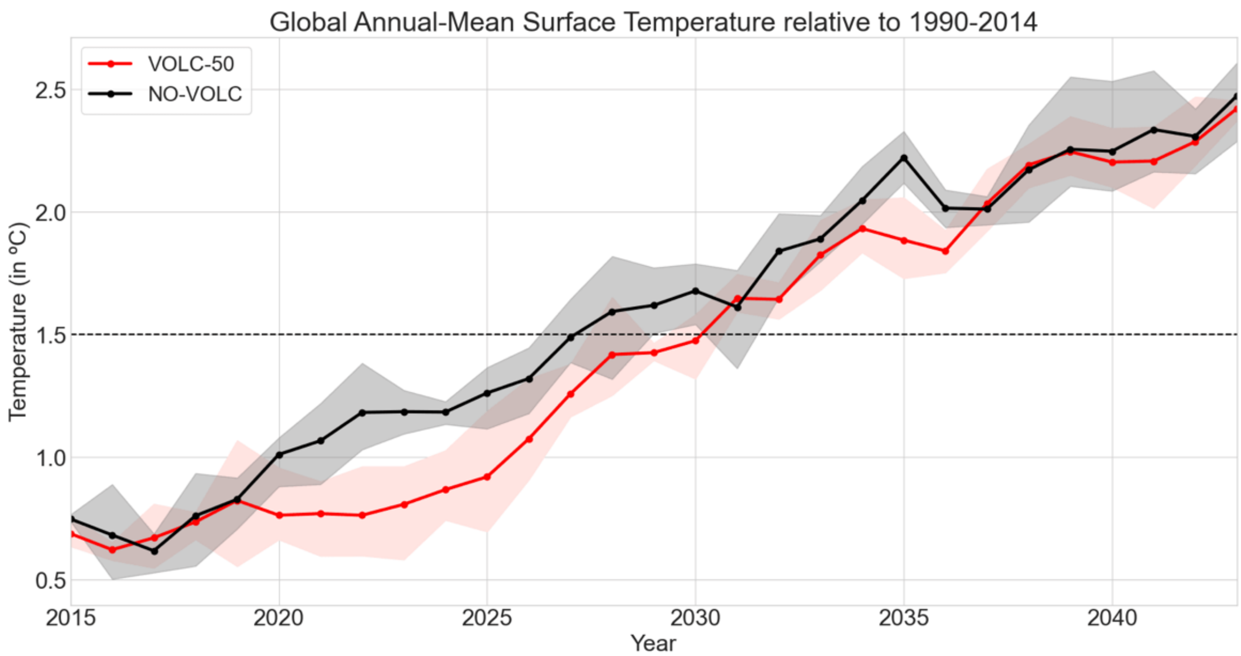

Figure 9. Changes in global annual-mean surface temperature relative to 1900-2014. The shaded region denotes the maximum and minimum changes of the ensemble members.

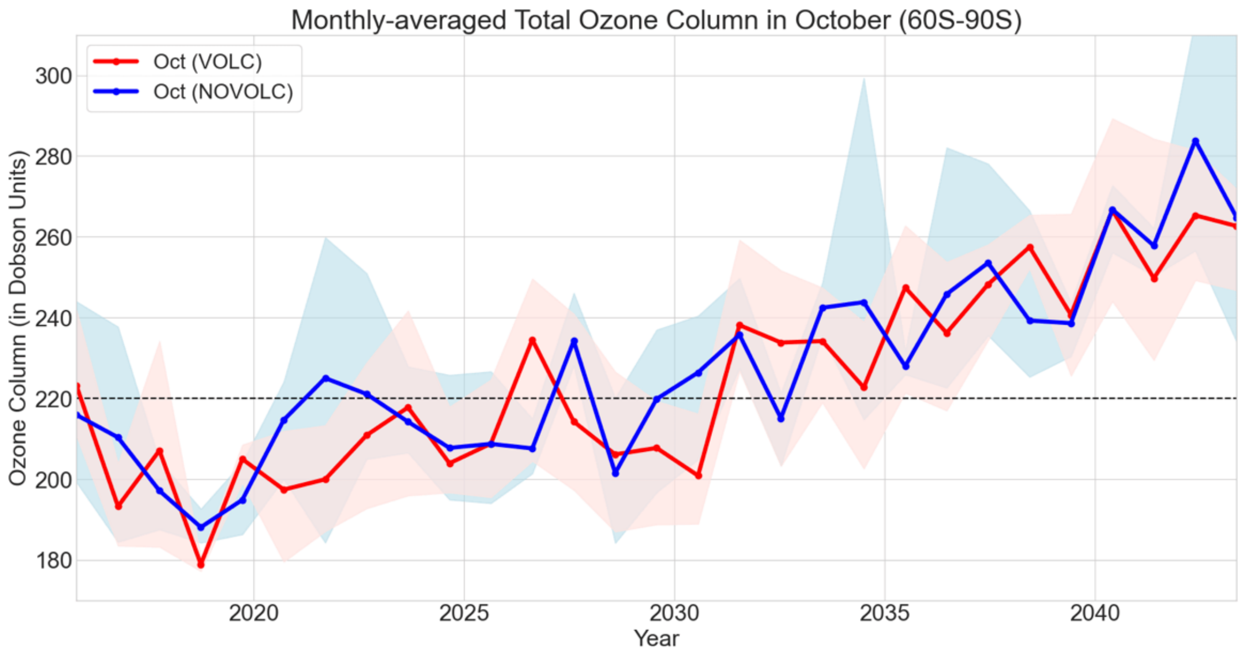

Figure 10. Changes in global monthly-averaged total ozone column (in Dobson Unit) in October averaged over the region 60S to 90S for VOLC-50 and NO-VOLC runs. The shaded region denotes the maximum and minimum values of the ensemble members.

PRELIMINARY FINDINGS

- Only small-magnitude eruptions (< 3 Tg of SO_2) have occurred during the model simulation period from 2015 to 2043.

- Small-magnitude eruptions can induce a noticeable change in zonal mean SAOD and the net global radiative forcing at TOA, in particular from 2019 to 2022, when a cluster of eruptions occurs (see *Figure 6 and 8*)

- Changes in global mean SAOD induced by small-magnitude eruptions are significant as compared to the baseline SSP3-7.0 run which used a constant volcanic forcing, with an approximate value of 0.01 (see *Figure 7*)

- Noticeable reduction in global surface temperature by 0.4 ºC comparing VOLC-50 and NO-VOLC runs after a series of small-magnitude eruptions from 2019 to 2022 (see *Figure 9*) in our scenario

- A deeper October ozone hole in VOLC-50 run is found as compared to NO-VOLC from 2020 to 2023 after two tropical eruptions with 2 Tg of SO_2 occurred in 2019 and 2020 (see *Figure 10*)

FUTURE WORK

Planned simulations

- **VOLC-50-small**: Simulation at the 50th quantile of the ranked SO2 mass with small-magnitude eruptions in order to **isolate the climate effects of small-magnitude eruptions**

- **VOLC-2.5 and VOLC-97.5**: Simulations at the 2.5th and the 97.5th quantile of the ranked SO2 mass in order to **constrain the uncertainty on future volcanic forcing and its climate impacts**

- **VOLC runs at SSP1-2.6**: VOLC runs (at different quantiles of ranked SO2 mass) at SSP1-2.6 in order to **compare between SSPs and study the net effect of global warming on the climate effects of volcanic eruptions**

ABSTRACT

Episodic volcanic eruptions are often either not considered in future climate projections, or represented in terms of a constant volcanic forcing. This conventional representation of volcanic eruptions in climate models does not account for how climate change might affect the dynamics of volcanic plumes and the stratospheric sulfate aerosol lifecycle and, ultimately, volcanic radiative forcing. The height of eruptive plumes is indeed sensitive to atmospheric conditions such as stratification and the strength of wind. In addition, climate change will affect tropopause height, the Brewer Dobson circulation and stratospheric temperatures which all govern volcanic sulfate aerosol cycle. A recent study showed that for tropical eruptions, these changes would either lead to a dampening or an amplification of volcanic forcing depending on the eruption intensity. In this study, to account for volcano-climate interactions in future climate projections, we present a new modelling approach through coupling a 1-D plume-rise model (Plumeria) with an Earth System model (UKESM). In this approach, each time a volcanic eruption of prescribed intensity (i.e., mass eruption rate) and SO_2 mass occur, atmospheric conditions simulated by UKESM are passed interactively to Plumeria which then computes the corresponding height of eruptive plumes. Volcanic SO_2 is then injected at the same height in UKESM stratospheric aerosol module. With this new methodology, plume heights are consistent with the climate conditions simulated by UKESM. Our study thus represents a first attempt to consider the impacts of climate change on volcanic eruptions in an Earth System model, which allows us to better evaluate the climate impacts of volcanoes under global warming.

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