Unknown Eruption Source Parameters Cause Large Uncertainty in Historical Volcanic Radiative Forcing Reconstructions

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Supporting Information for

Unknown eruption source parameters cause large uncertainty in historical volcanic radiative forcing reconstructions

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Introduction

Supporting figures referenced in the main text are included. Text S1 explains in further detail the use of a noise term when building the deposition emulators. Table S1 includes summary model output data.

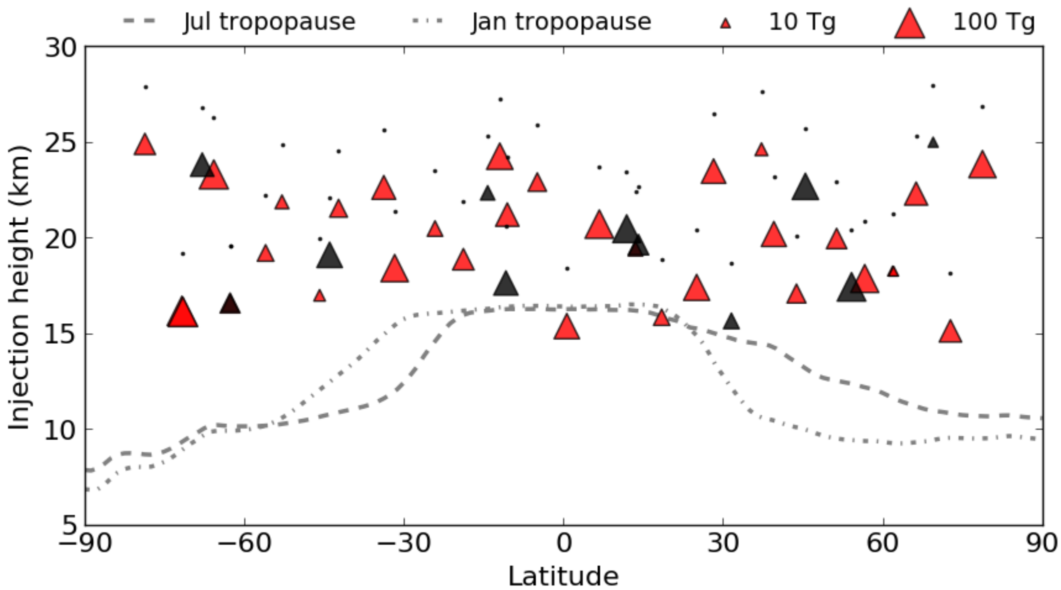

Figure S1. Volcanic eruptions simulated. Each triangle represents two model simulations that were conducted using UM-UKCA (one in January and one in July). The location of the triangle indicates the latitude and injection height of the SO_2 emission for each eruption. The injection height indicates the bottom of the emitted plume; emissions are distributed linearly between this value and 3 km higher, which is shown by the dots above each triangle. The size of the triangle represents the mass of SO_2 emitted. The simulations span SO_2 emissions between 10 and 100 Tg, latitudes between 80°S and 80°N and injection heights between 15-28 and 25-28 km. Red triangles are training runs, which are the simulations used to build the statistical emulators. Black triangles are simulations that were used to validate the statistical emulators after they were built. There are two simulations (one training run and one validation run) at ~63°S and ~17 km which have SO_2 emissions of 35 Tg and 45 Tg and are not easily distinguished by the marker size scale. The grey lines show the simulated monthly mean zonal mean January (Jan) and July (Jul) tropopause heights.

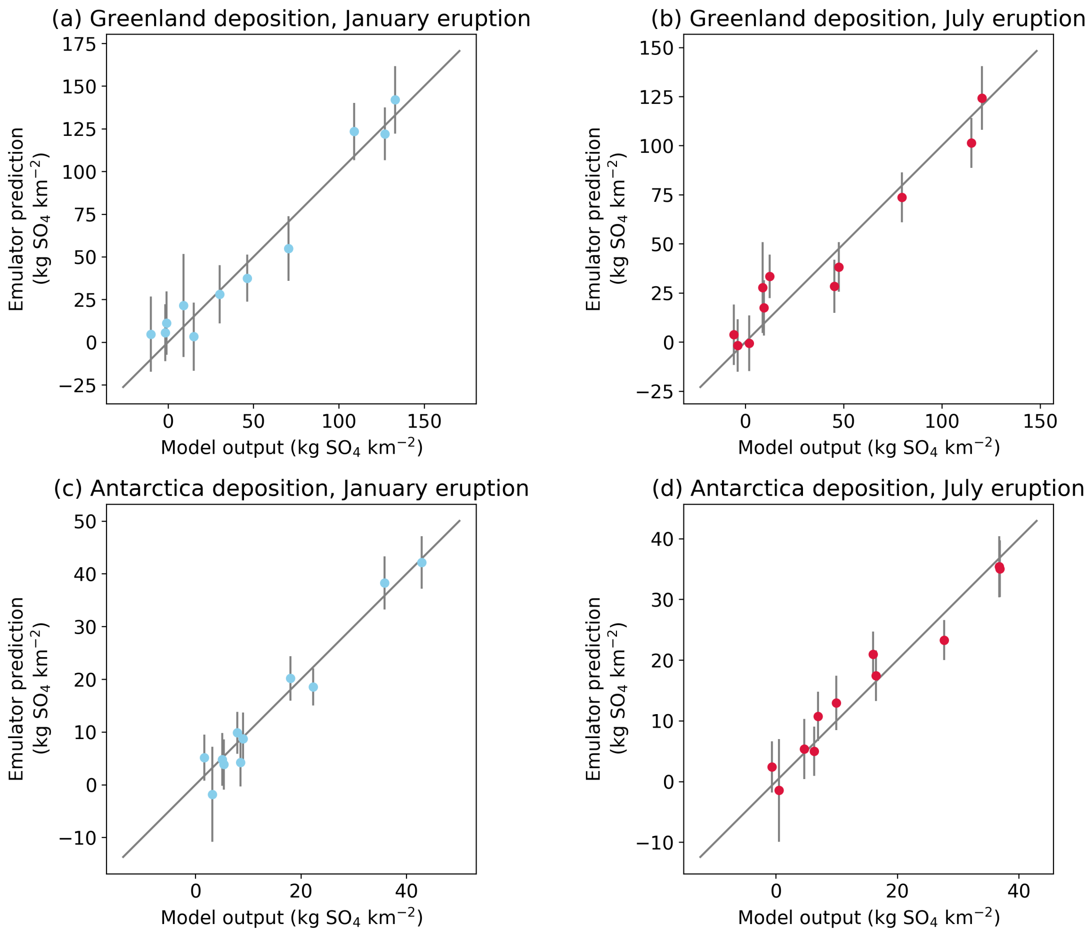

Figure S2. Validation of each deposition emulator. For each variable (a-d), the value of the model output for the 11 validation runs is plotted against that predicted by the emulator. The vertical lines are 95% confidence bounds on the emulator mean predictions. The solid grey line marks the 1:1 line.

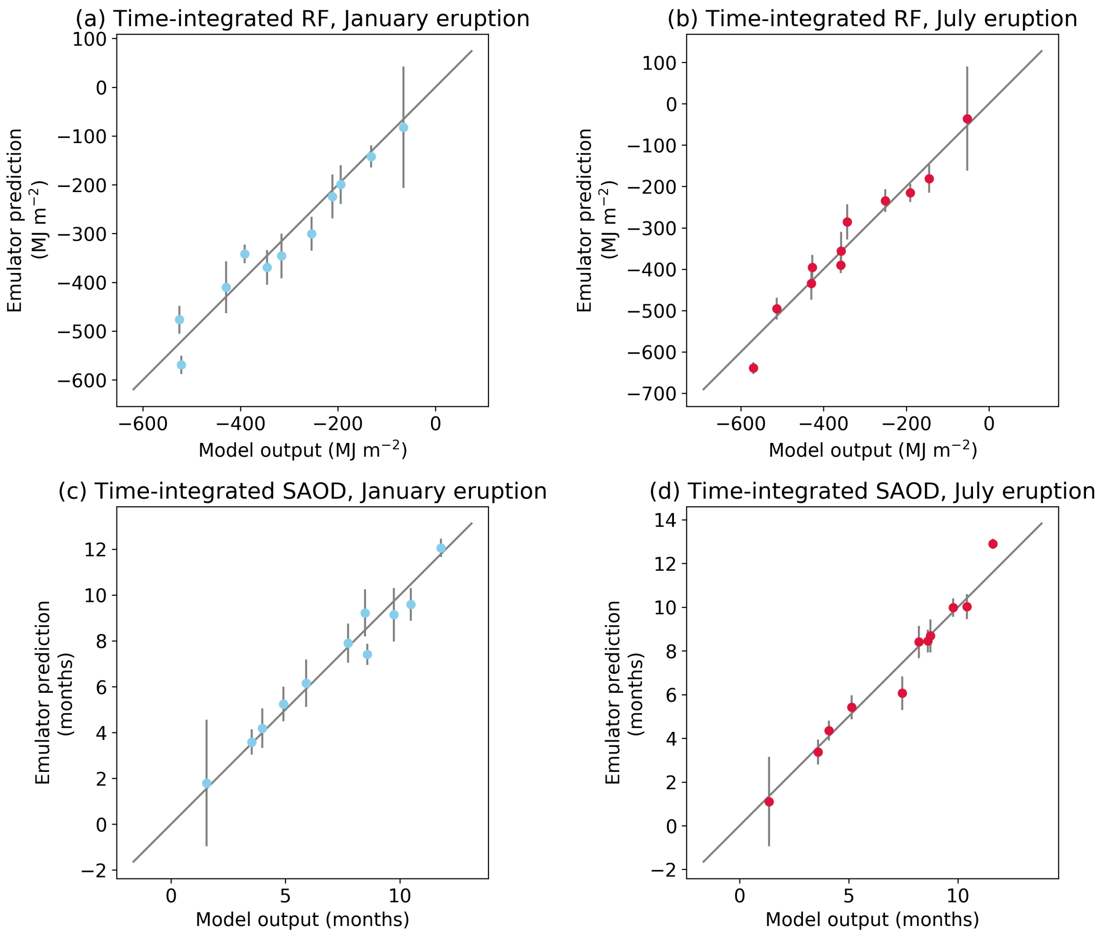

Figure S3. Validation of each time-integrated radiative forcing (RF) and stratospheric aerosol optical depth (SAOD) emulator. For each variable (a-d), the value of the model output for the 11 validation runs is plotted against that predicted by the emulator. The vertical lines are 95% confidence bounds on the emulator mean predictions. The solid grey line marks the 1:1 line.

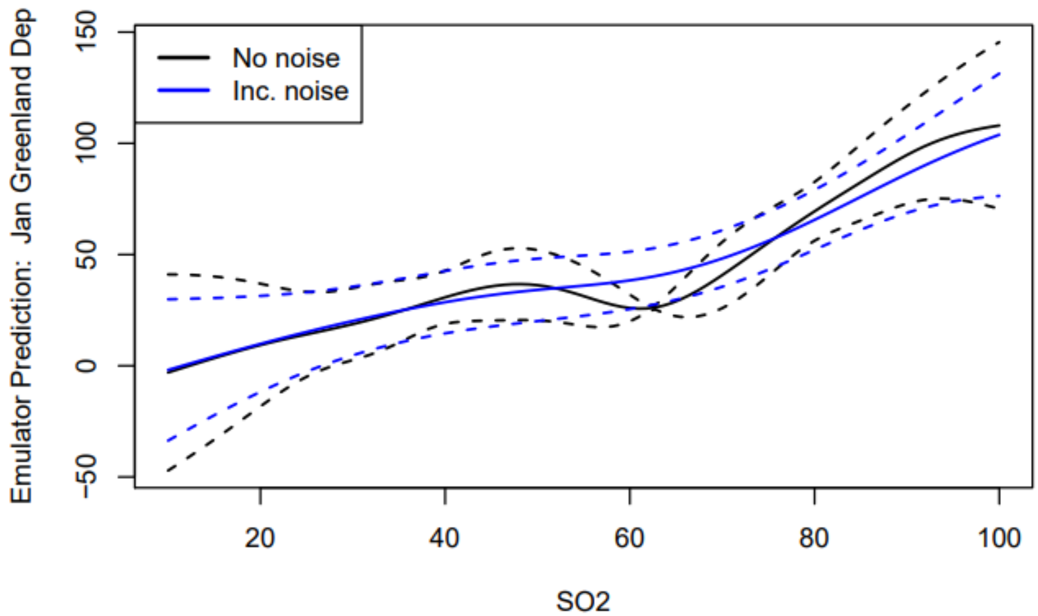

Figure S4. Example emulator-predicted Greenland deposition for an example January eruption (11°S and 23 km; one of the training points) with varying SO_2 emission for an emulator built with no noise (black) and with the noise term used in the paper (blue). The emulator mean prediction is shown by the solid line and the 95% confidence intervals are shown by the dashed lines. The training point has an SO_2 emission of 62 Tg.

Text S1

For the 1-D projection in Figure S4, two of the three inputs are fixed (eruption latitude and injection height), and the emulator is used to predict the Greenland deposition for a January eruption over the range of the remaining input (SO_2 emission). When no noise is included in the emulator fit (black), the confidence intervals pinch at the training point location (SO_2 emission of 62 Tg) since the deposition is assumed to be known exactly, and hence the emulator mean prediction has to pass through it with no uncertainty. For the emulator built with the additional noise variance term (blue), the emulator mean prediction at the training point is shifted higher and has an uncertainty. The mean prediction and confidence intervals for the fit with noise is smoother since the 3-D surface does not have to pass directly through the training point.

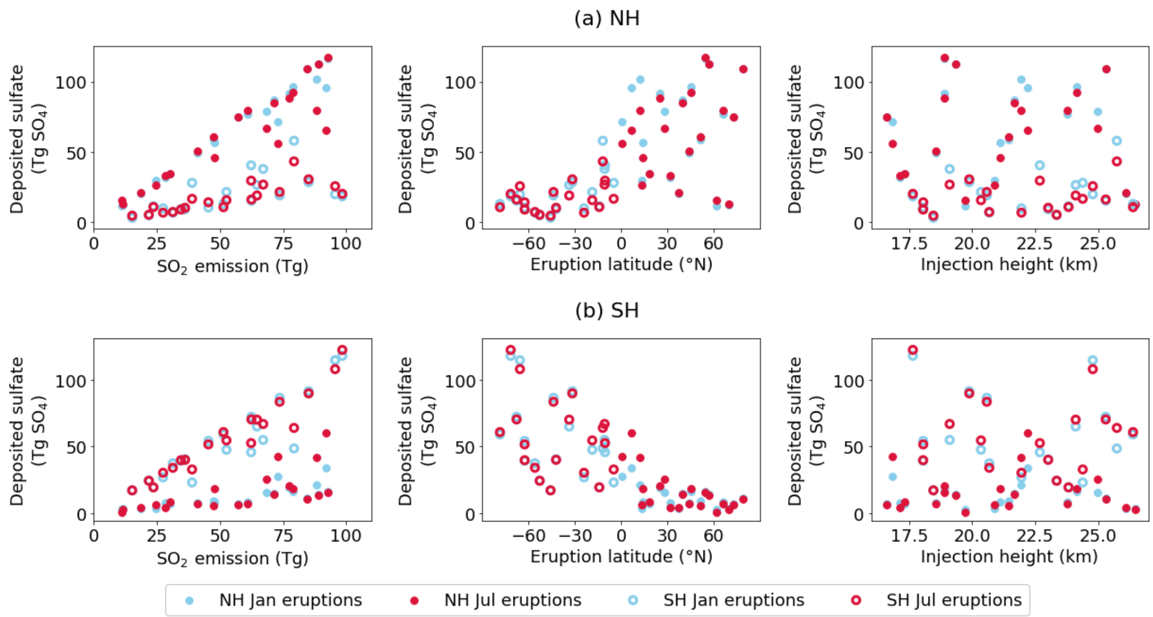

Figure S5. Time-integrated deposited volcanic sulfate in the Northern Hemisphere (NH) (a) and in the Southern hemisphere (SH) (b) in each simulation versus the value of SO_2 emission (left), eruption latitude (middle) and injection height (right) in that simulation. Deposition is shown in blue for the January eruptions and in red for the July eruptions. NH eruptions are shown by the closed circle markers; SH eruptions are shown by the open markers. There are different scales on the y-axes between (a) and (b). Injection height marks the middle of the 3-km deep plume.

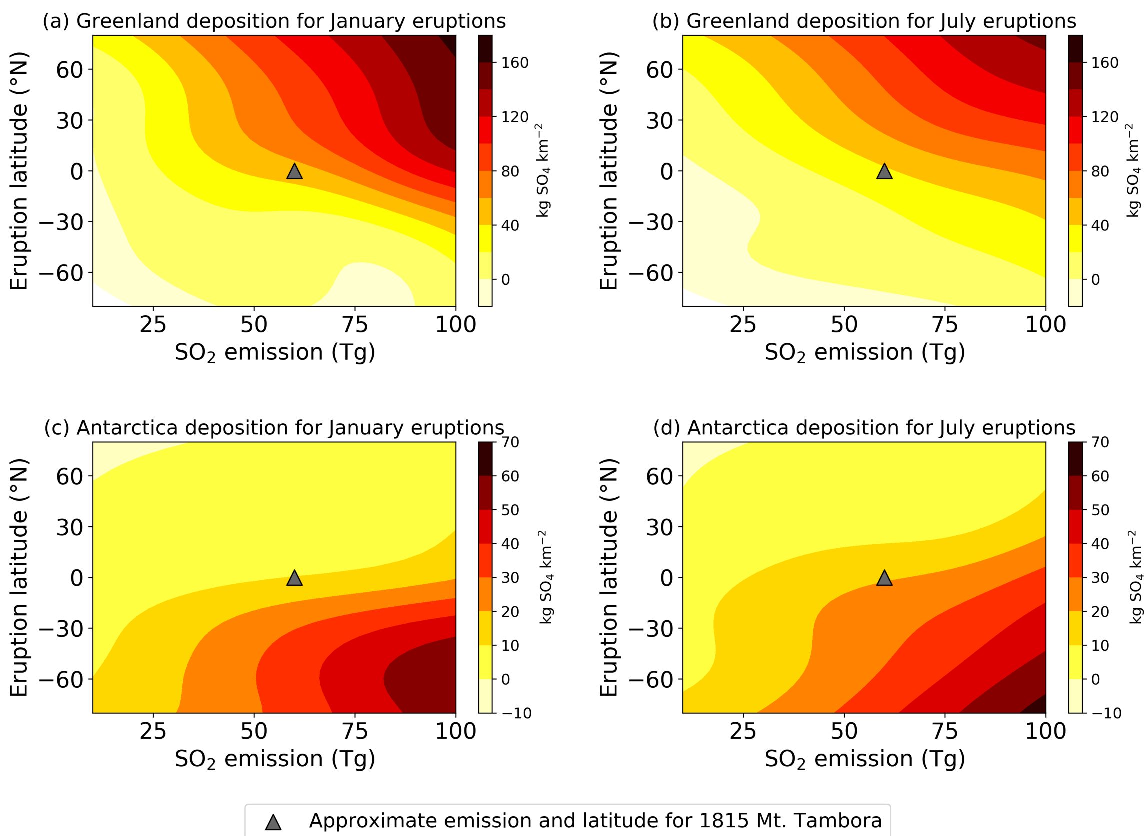

Figure S6. Emulator-predicted response surfaces for each of the deposition emulators: (a) Greenland deposition following a January eruption, (b) Greenland deposition following a July eruption, (c) Antarctica deposition following a January eruption and (d) Antarctica deposition following a July eruption. The surfaces show the emulator mean prediction of the ice-sheet deposition against SO_2 emission and eruption latitude for injections at 20-23 km (the middle value in the parameter range perturbed in this study); surfaces sampled at other injection heights were extremely similar. These 2D surfaces were built by sampling the emulator 1600 times over a grid of 40 equally spaced values of the SO_2 emission and the eruption latitude. The grey triangle marks the approximate SO_2 emission and latitude corresponding to the 1815 eruption of Mt. Tambora. There are different color scales for the Greenland and Antarctica deposition.

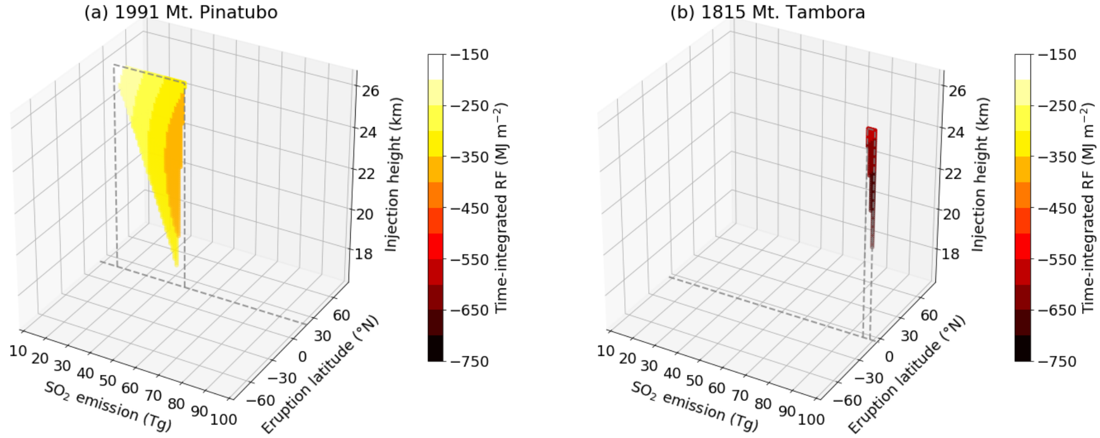

Figure S7. (a) Constrained parameter space for the 1991 Mt. Pinatubo sulfate deposition for an eruption in July and at 15.4°N (closest available sample from the emulator). For visualization, the grey lines mark the SO_2 values at the edges of the constrained space for the fixed 2D slice (18 and 49 Tg of SO_2). (b) Constrained parameter space for the 1815 Mt. Tambora sulfate deposition for an eruption in July and at 8.9°S (closest available sample from the emulator). For visualization, the grey lines mark the SO_2 values at the edges of the constrained space for the fixed 2D slice (97 and 100 Tg of SO_2).

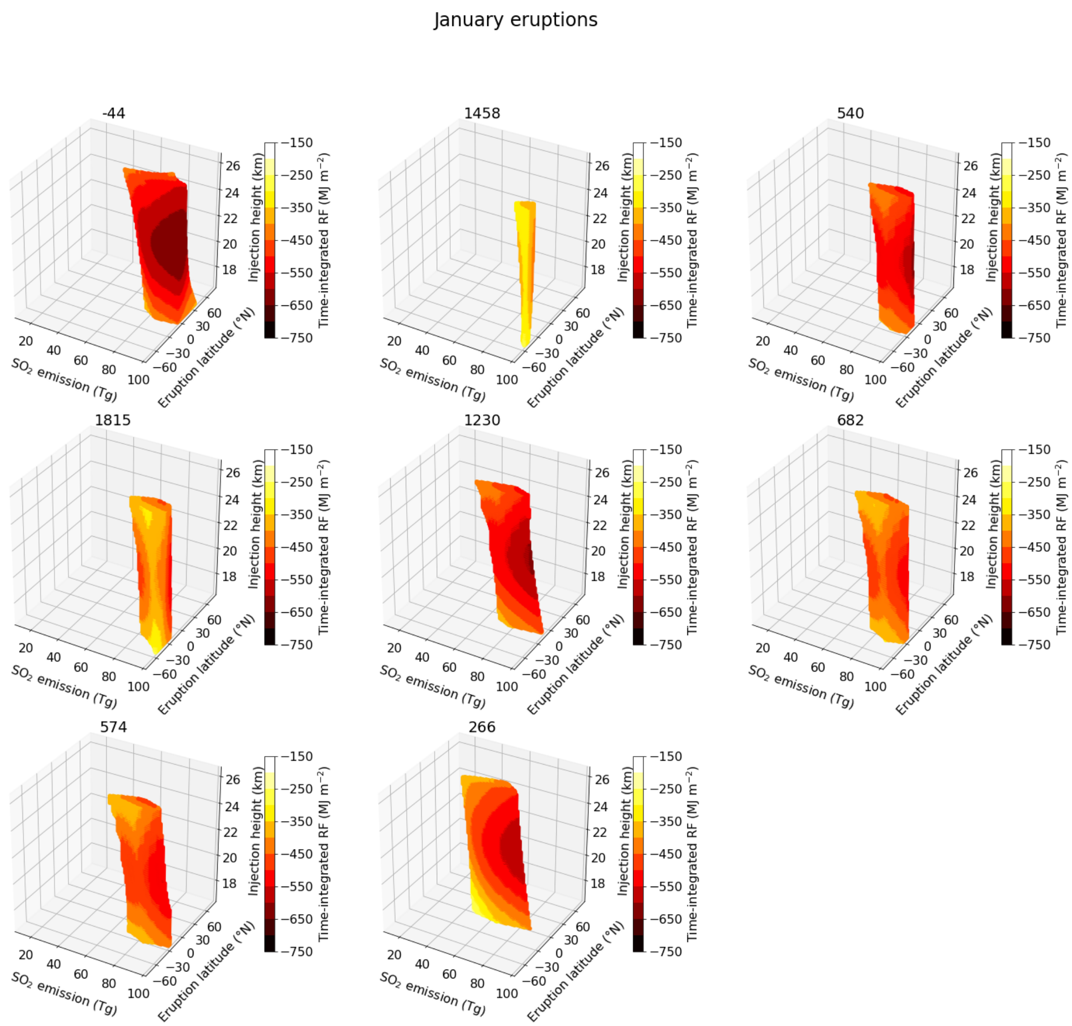

Figure S8. Constrained parameter space for eight of the ten largest deposition signals in the last 2500 years (Sigl et al., 2015) if the eruption occurred in January. Each panel shows for one bipolar signal the combinations of SO_2 emission, eruption latitude and injection height that result in Greenland and Antarctica deposition that is consistent with the ice-core-derived sulfate deposition estimates. The constrained space is made up of scatter points of the parameter combinations and the color of each scatter point shows the emulator mean prediction of time-integrated RF for each of these eruptions (as in Figure 2 in the main text). Injection height is the middle of the 3 km plume.

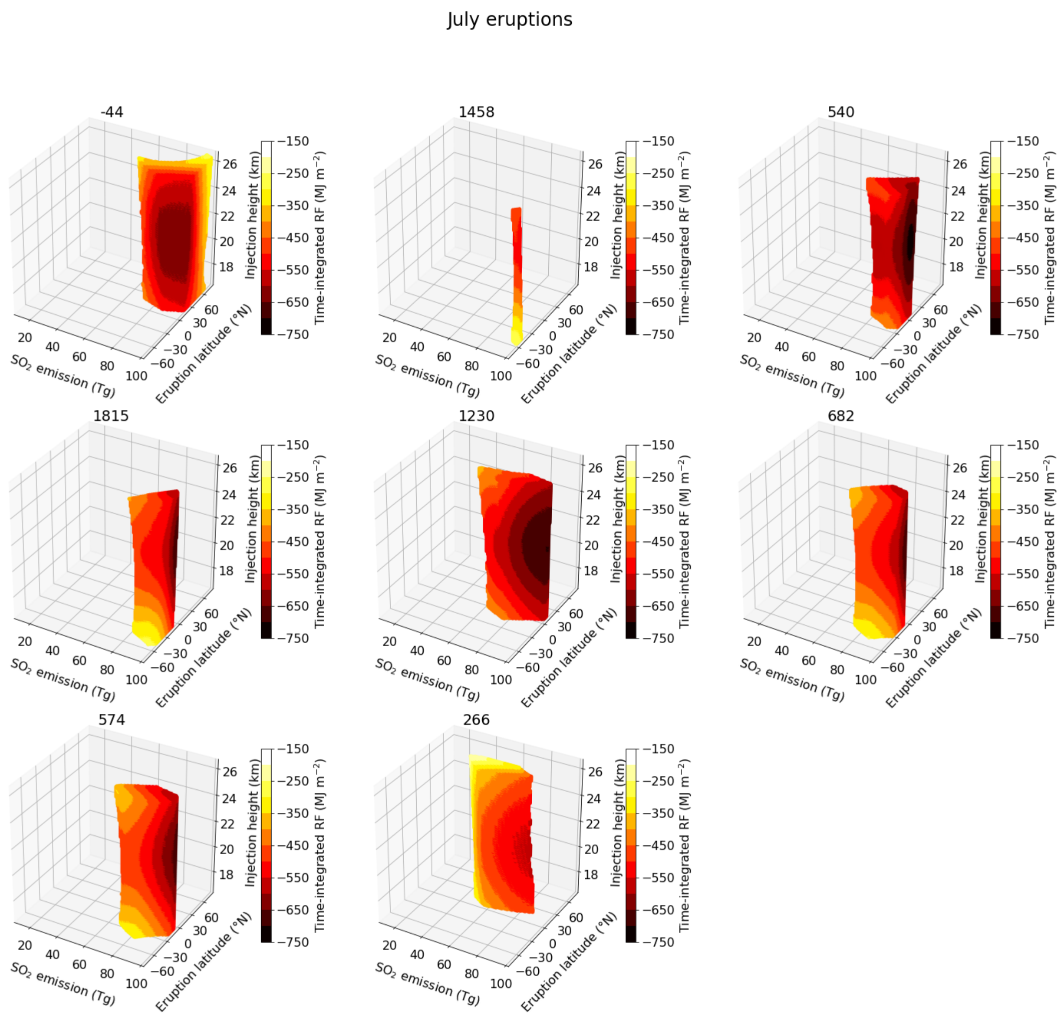

Figure S9. As Figure S8 but for July eruptions.

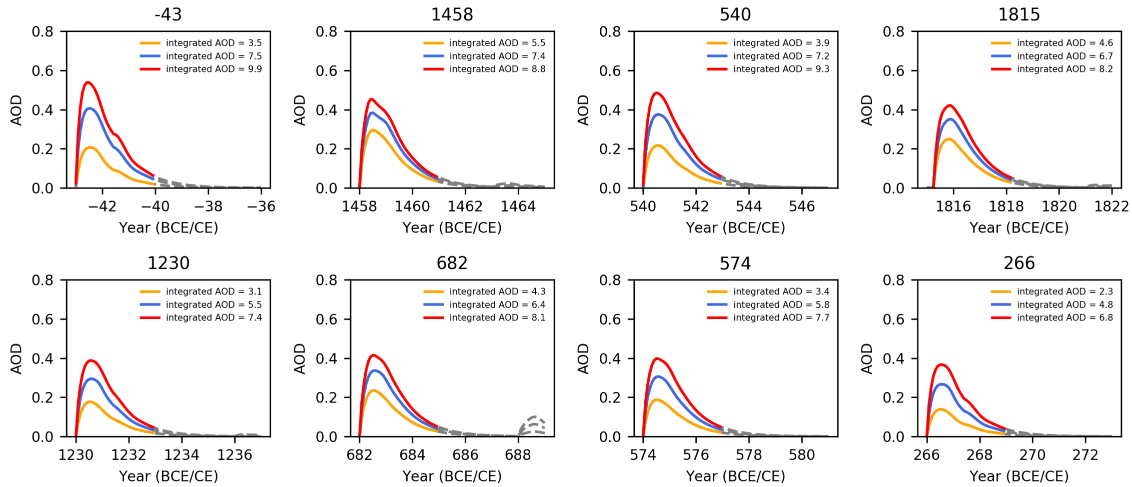

Figure S10. Time series of global mean stratospheric aerosol optical depth (SAOD) from the EVA(2k) reconstruction (Toohey & Sigl, 2017) for the eight eruptions considered. For each eruption (each panel) we examine the global mean SAOD following a low (orange), medium (blue) and high (red) estimate of the volcanic stratospheric sulfur injection. The low and high estimates correspond to the medium estimate minus/plus 2 times the standard deviation sulfur emission uncertainty. The reconstruction includes a year zero; the 43 BCE eruption corresponds to the 44 BCE eruption referred to in the main text. For each eruption we summed the SAOD over 36 months to compare directly to the time-integrated SAOD derived from the UM-UKCA simulations. The EVA simulations do not include background aerosol so that the SAOD represents the volcanic SAOD only.

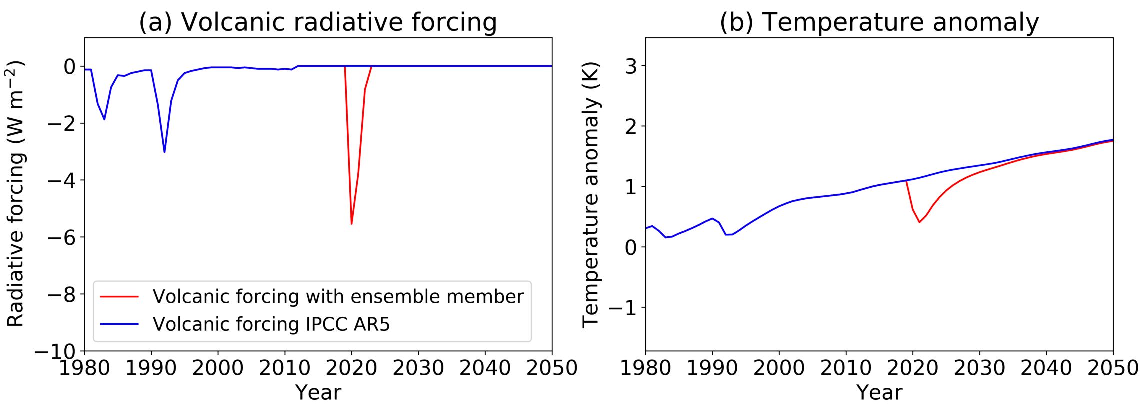

Figure S11. Volcanic radiative forcing as input to the simple climate model FaIR (a) and simulated global mean surface temperature anomaly since preindustrial (b) for the IPCC AR5 RCP4.5 scenario (blue) and with the additional forcing from one of the 82 model simulations (red). The anomaly due to the volcanic eruption is taken as the difference between the red and blue lines.

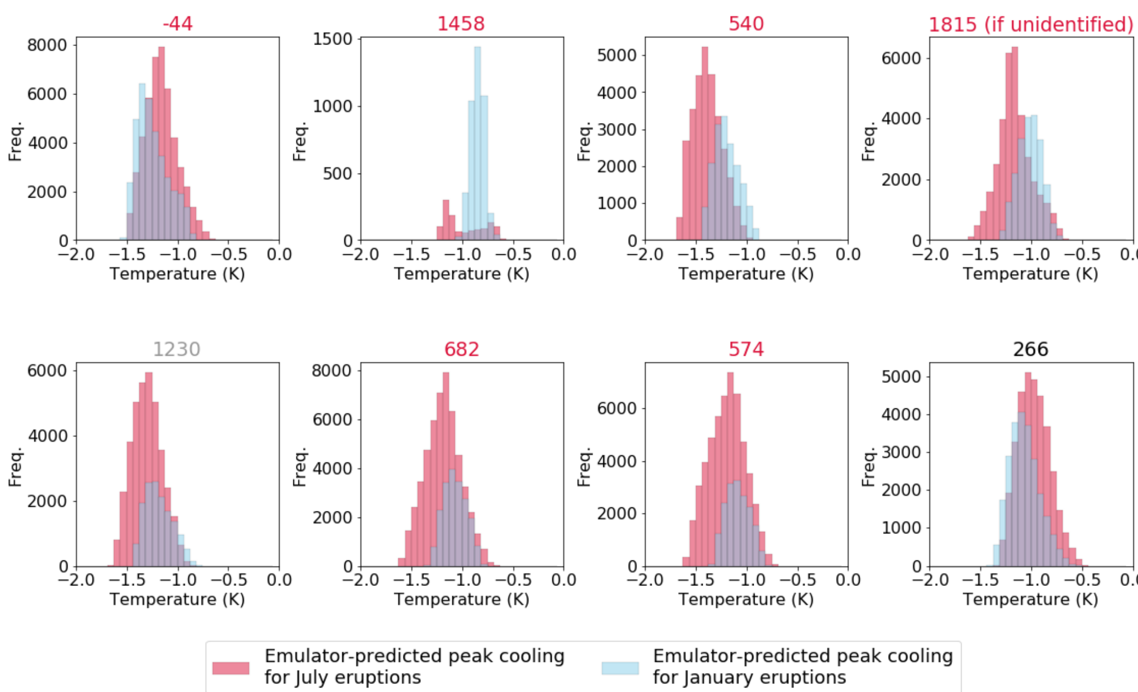

Figure S12. Range and distributions of the constrained peak annual global mean surface cooling for each of the eight constrained deposition signals.

Table caption

Table S1. Eruption source parameter values and model output values (time-integrated anomalous deposited sulfate and time-integrated global mean effective radiative forcing and stratospheric aerosol optical depth) for the 41 January and July eruptions. Simulations 1-30 are the training runs (60 runs in total) and simulations 31-41 are the validation runs (22 runs in total). Injection height is the bottom of the 3 km plume.

References

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., et al. (2015). Timing and climate forcing of volcanic eruptions for the past 2,500 years. Nature, 523(7562), 543–549. 10.1038/nature14565

Toohey, M., & Sigl, M. (2017). Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE. Earth System Science Data, 9(2), 809-831. 10.5194/essd-9-809-2017