Radiative Forcing and Climate Impact of explosive Central American Volcanic Arc Eruptions for the last 200 ka

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Motivation/Background

Explosive volcanic eruptions, especially those in the tropics, have a significant impact on global climate, which results from their stratospheric injection of SO_2. The adjacent formation of stratospheric sulfate aerosols leads to scattering of the incoming solar radiation back to space, therewith to a cooling at the Earth's surface. To evaluate the climatic response to paleo-volcanic eruptions state-of-the-art climate models are employed. These models need a volcanic forcing data set as input, which could be either a direct reduction in global radiative forcing (RF) as used for paleo simulations (Jansen et al., 2007), or latitudinally varying aerosol optical depth (ADO) as in the case of IPCC AR4 simulations (Stenchikov et al., 2006). Different independent methods for creating RF are commonly used, encompassing, e.g., atmospheric measurements or analysis of ice core records. Another method for determining the climate impact of large volcanic eruptions in the long-term past is the petrologic method (e.g., Devine et al., 1984) which estimates stratospheric SO_2 injections from a combination of geochemical and volcanological analyses of eruption deposits. In this study we present an unique data set of petrologically estimated SO_2 emissions from 36 detected Plinian volcanic eruptions occurring at the Central American Volcanic Arc (CAVA) during the past 200 ka. Using this record and simple parameterized relationships collected from past studies (e.g., Hyde and Crowley, 2000) we derive estimates of maximum AOD and RF for each eruption. In parallel, AOD and RF time series for selected CAVA eruptions are derived from the SO_2 emission record and simulations with the global aerosol climate model MAECHAM5-HAM. Potential climate impacts are projected using the earth system model of intermediate complexity (EMIC) CLIMBER-2 (Metzner et al., 2012, in revision).

SFB 574 Field Measurements

Phase I: Southern Central America - Nicaragua, Costa Rica and Panama (July 2001 – June 2004).

Phase II: Regional scope expanded to northern segment of the Central American subduction zone - El Salvador, Honduras and Guatamala (July 2004 – June 2008).

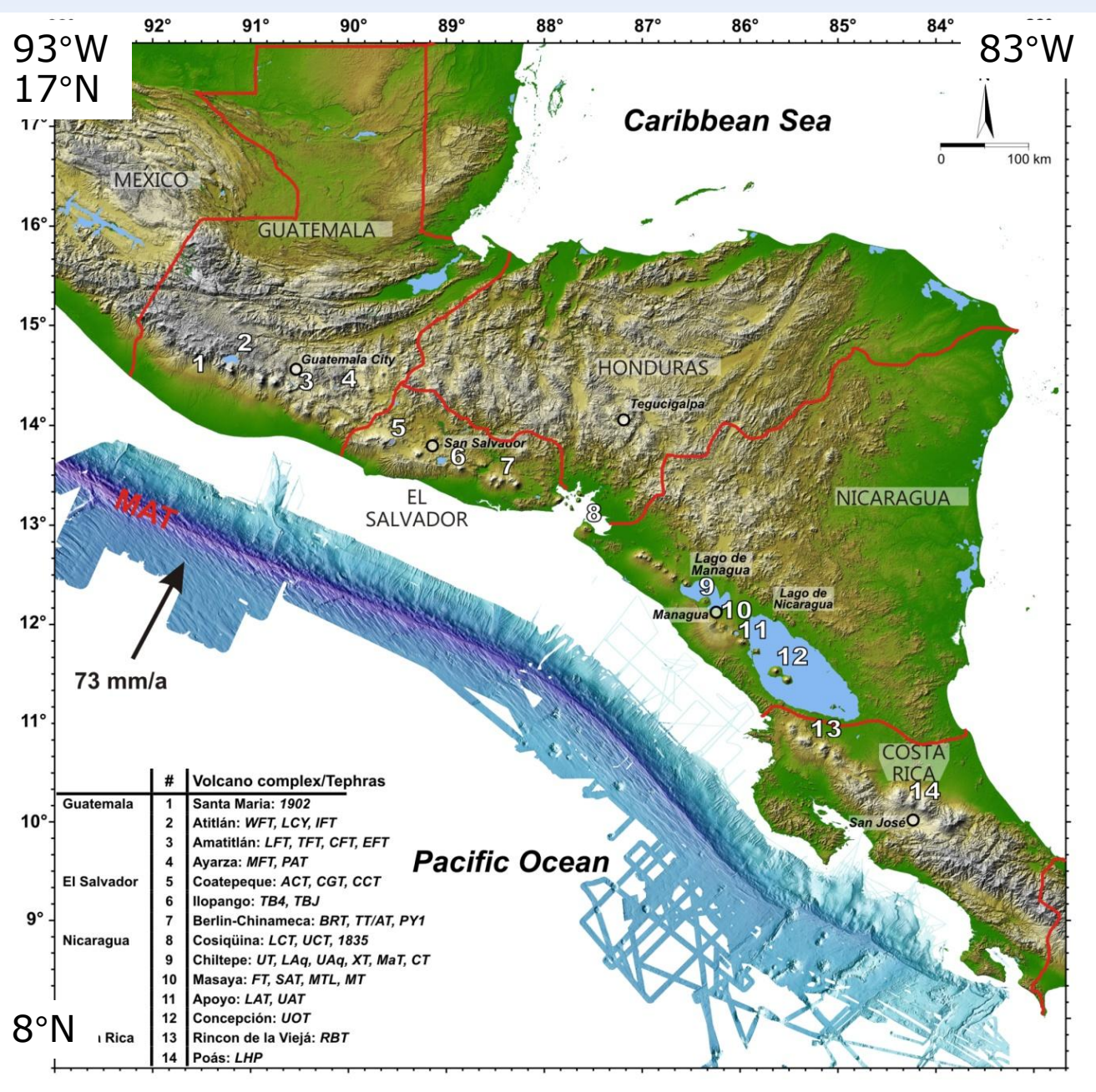
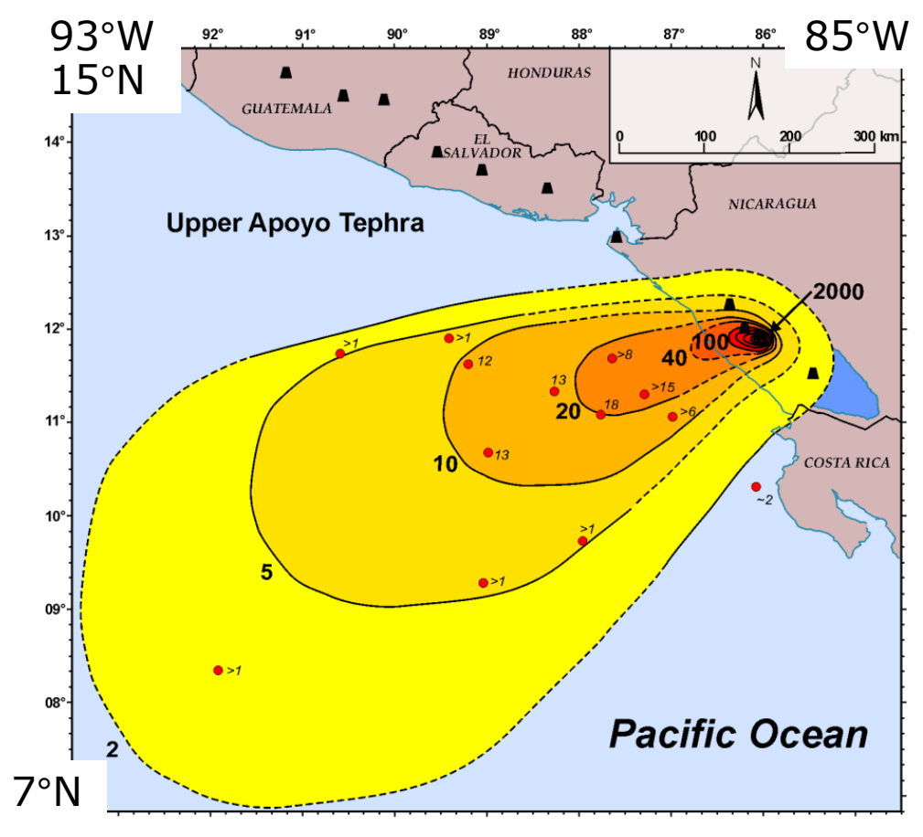


Fig. 1: Shaded and colored SRTM (Shuttle Radar Topography Mission) elevation model of Central America (NASA/JPL/NGA, 2000) and high-resolution bathymetry along the Middle America Trench (MAT) from Kutterolf et al. (2008b). The line of Central American arc volcanoes runs through the two large lakes and parallel to the trench at about 200 km distance. Names of numbered volcano complexes and tephras are listed at lower left.

Measurement Methods

Volume and Eruption Height



- Onshore/offshore data.
- Total tephra volumes are obtained by exponential fitting of thickness vs. distance data (Fig. 2).
- Tephra thickness decreases with distance (Fig. 3) → controlled by eruption height and wind conditions (Carey and Sparks, 1986).
- Determined eruption column heights are sufficiently accurate to verify that stratospheric heights (>15 km) have been reached (Fig. 4).

Fig. 2: Isopach map (cm).

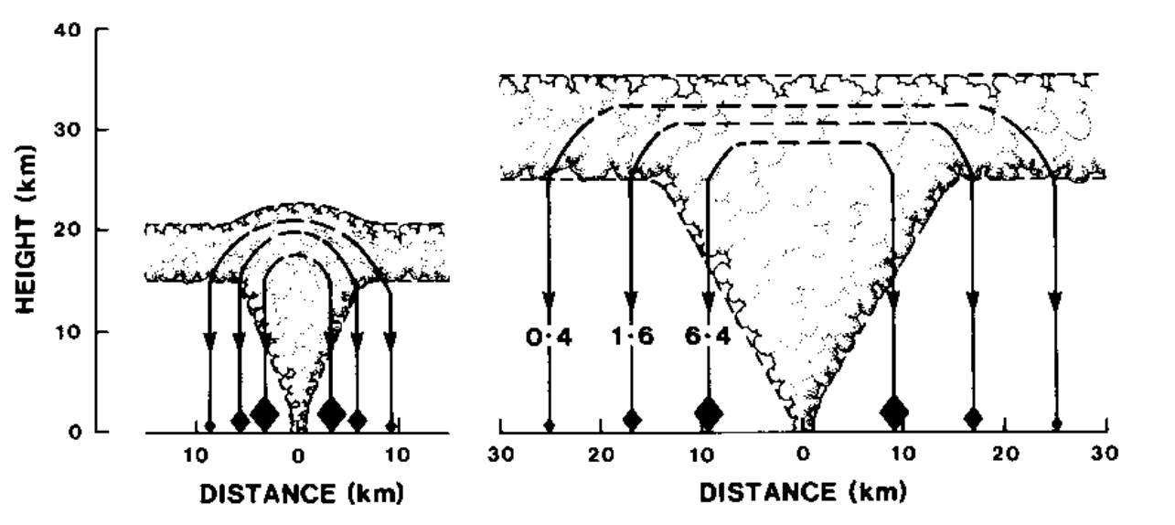


Fig. 3: Carey and Sparks (1986).

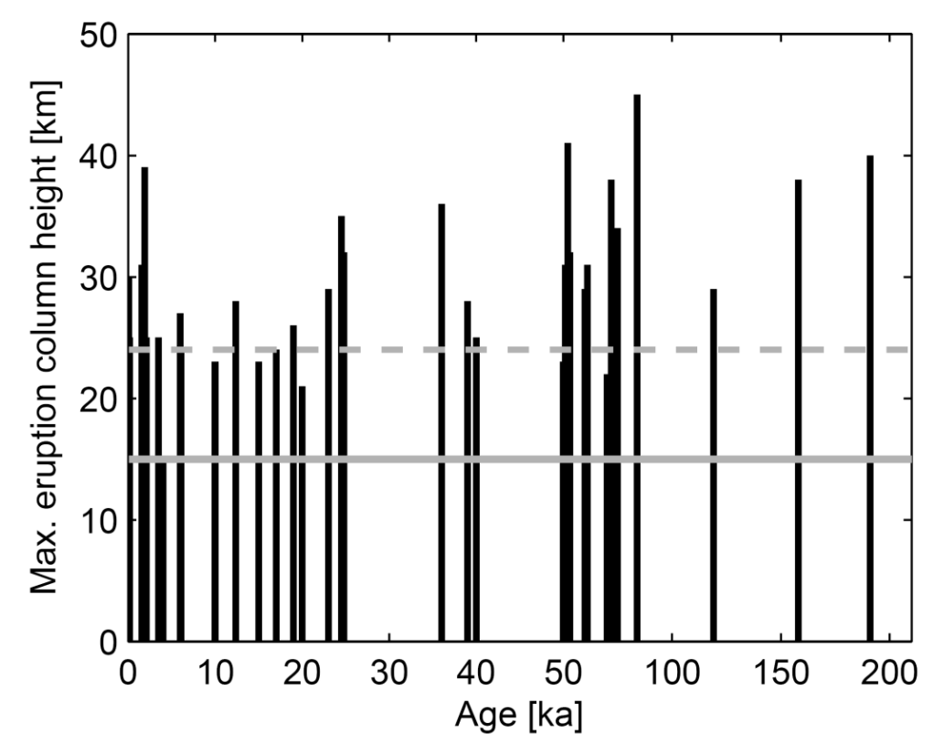


Fig. 4: Time series of 36 CAVA eruptions for the last 200 ka, according to their max. eruption column height (km) (black bars). Solid gray line indicates tropopause height, dashed gray line the eruption threshold at 24 km altitude.

Dating method

- Radiogenic decay of carbon-14 (up to 50 ka).
- Radiogenic dating with Ar/Ar, K/Ar, U/Th (>50 ka).
- Sedimentation rates in marine sediments.

→ dating error depends on the method used and on how far back the volcanic eruption reaches.

Erupted Magma Mass/Magnitude

- 36 tephras sufficiently well exposed to allow for determination of erupted magma masses (m), eruption column height and SO_2 emission; 19 tephras for which only erupted magma masses are presently available (Fig. 5 & 6).
- Magnitude (M) = log(m)-7; *(m in kg)*.

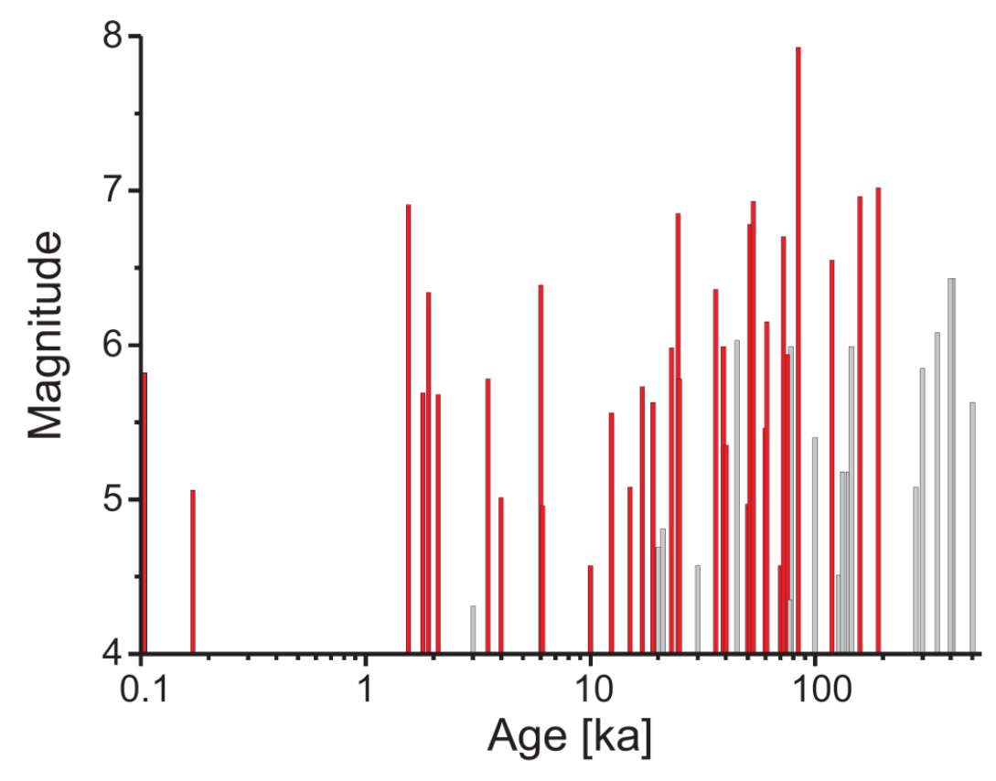


Fig. 5: Eruption magnitude vs. age (ka) for 36 CAVA eruptions (red bars) for which SO_2 emissions have been determined, and for additional 19 eruptions (gray bars) where only magma masses are presently available.

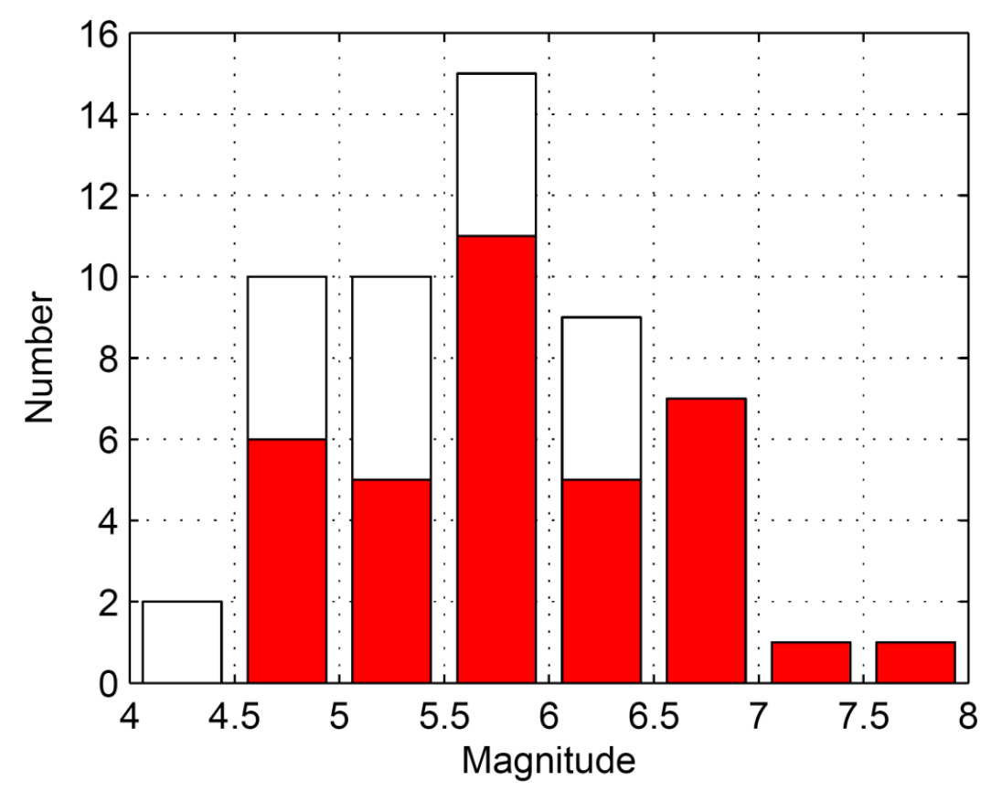


Fig. 6: Frequency distribution of magnitude (M≥4) calculated for 55 tephras of CAVA. Total number of given magnitudes arises from number of available tephras (white and red boxes), with measured SO_2 injections indicated by red color. Magnitudes are given in 0.5 bins.

Petrological Method

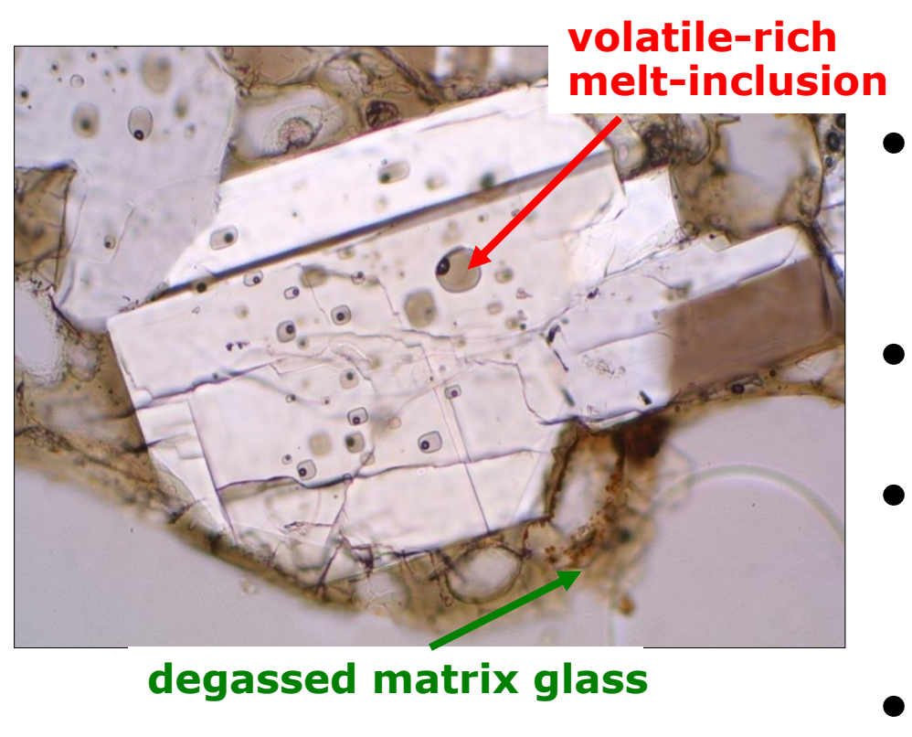


Fig. 7:

- Concentration of S in melt-inclusion and matrix determined by Electron microprobe (analytical error <20%).
- Melt-inclusion is assumed to preserve volatile concentration prior degassing.
- Matrix glass is considered to have degassed during equilibration to atmospheric pressure (Fig. 7).
- Concentration difference between melt-inclusions and matrix glasses yields sulfur fraction degassed during an eruption, multiplication with magma mass gives the mass of emitted sulfur (Fig. 8).

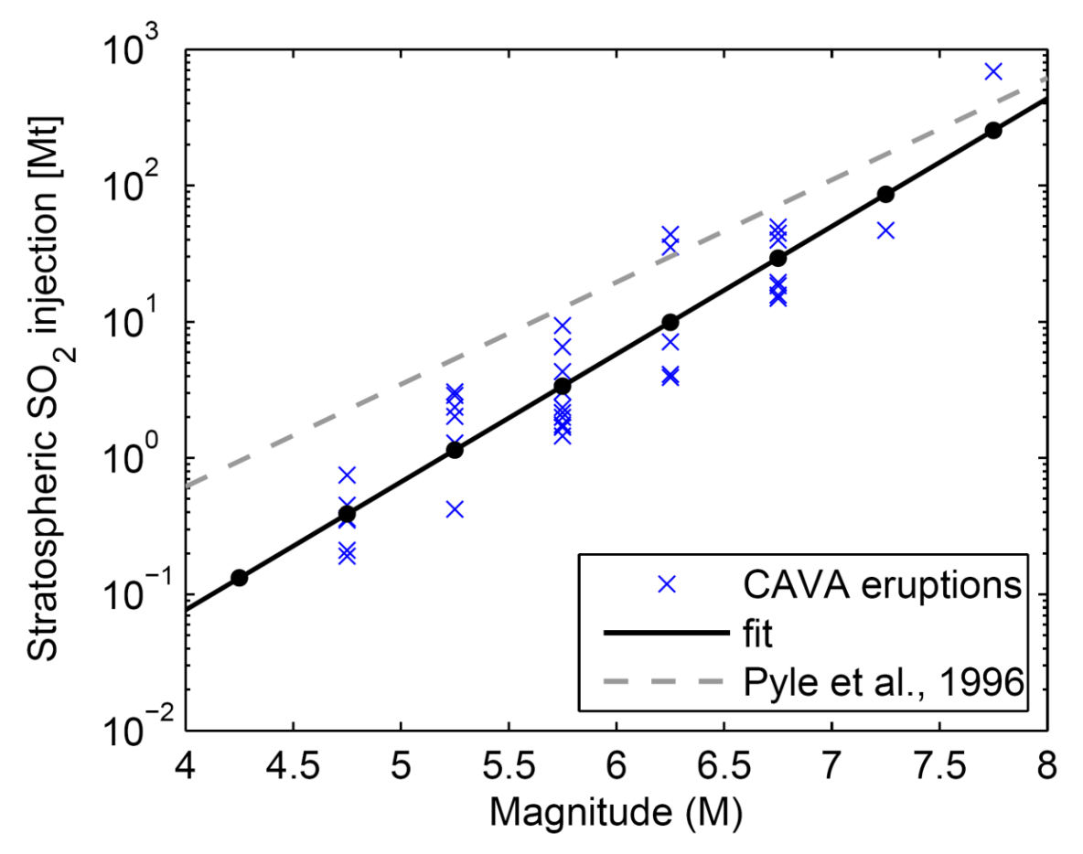
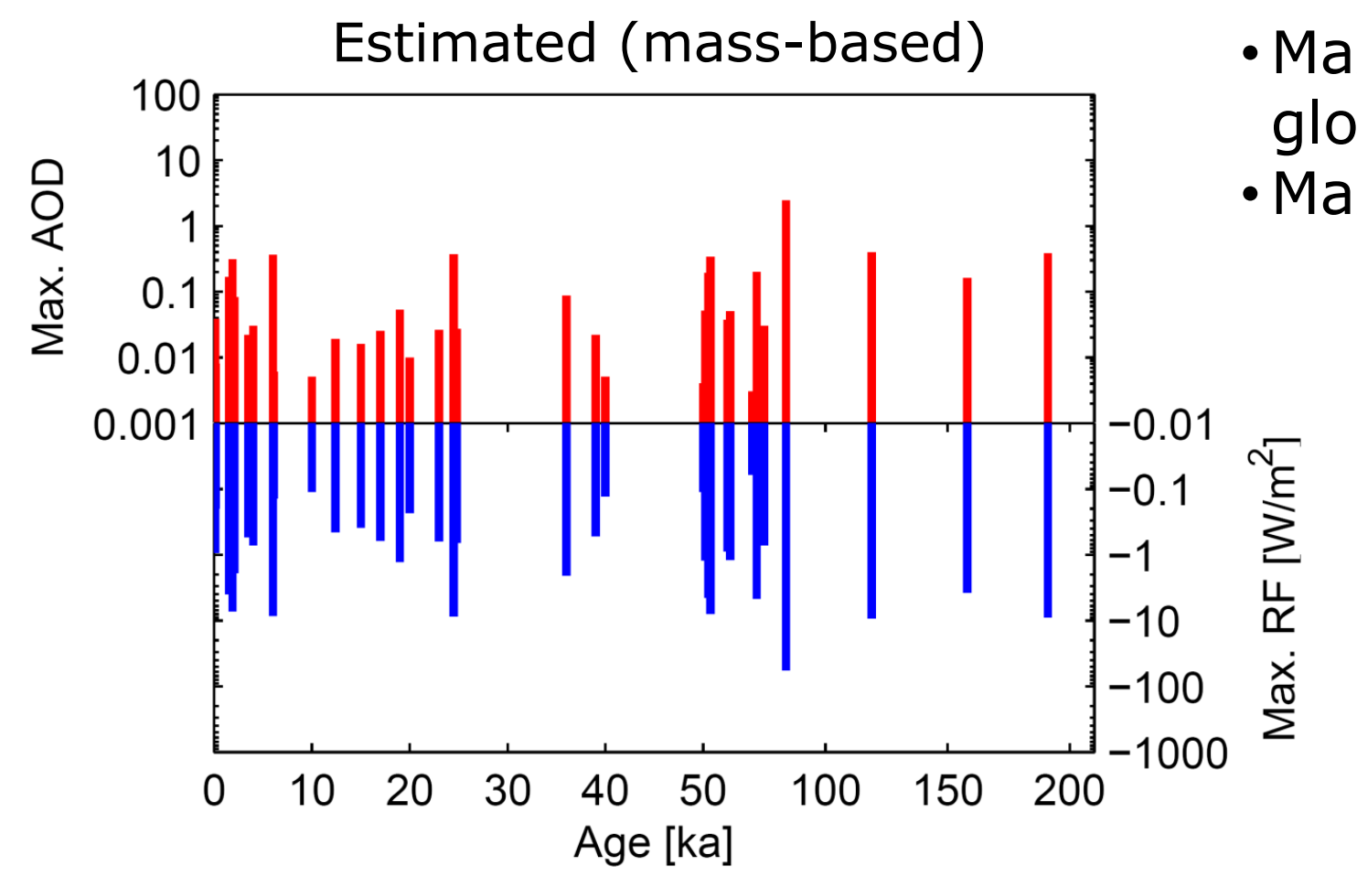


Fig. 8: Measured stratospheric SO_2 (Mt) for the 36 CAVA eruptions (blue crosses) as a function of magnitude in a lin-log scale. Black line is the fit of SO_2 release per given magnitude, gray dashed line shows the relationship obtained by Pyle et al. (1996). Magnitudes are given in 0.5 bins.

- Since magmatic sulfur concentrations typically vary over an order of magnitude, but erupted magma masses vary over several order of magnitudes, emitted masses of SO_2 generally increase with eruption magnitude.
- Variation around the regression through our data for any given magnitude covers one order of magnitude in SO_2 emissions.
- Comparison with Pyle et al. (1996), who used satellite data to correlate SO_2 emissions with eruption magnitudes, provides an estimate of potential underestimation of SO_2 emissions by the petrological method.

Volcanic Forcing

- Based on petrologically estimated SO_2 emissions, and parameterized relationships collected from past studies and tested with the global aerosol climate model MAECHAM5-HAM (Niemeier et al., 2009), we derive (Fig. 9 & 10):



- Max. stratospheric global mean AOD
- Max. globlal mean RF

Fig. 9: Time series of 36 CAVA eruptions for the last 200 ka, according to their max. global mean AOD (red bars) and max. global mean RF (W/m²) (blue bars).

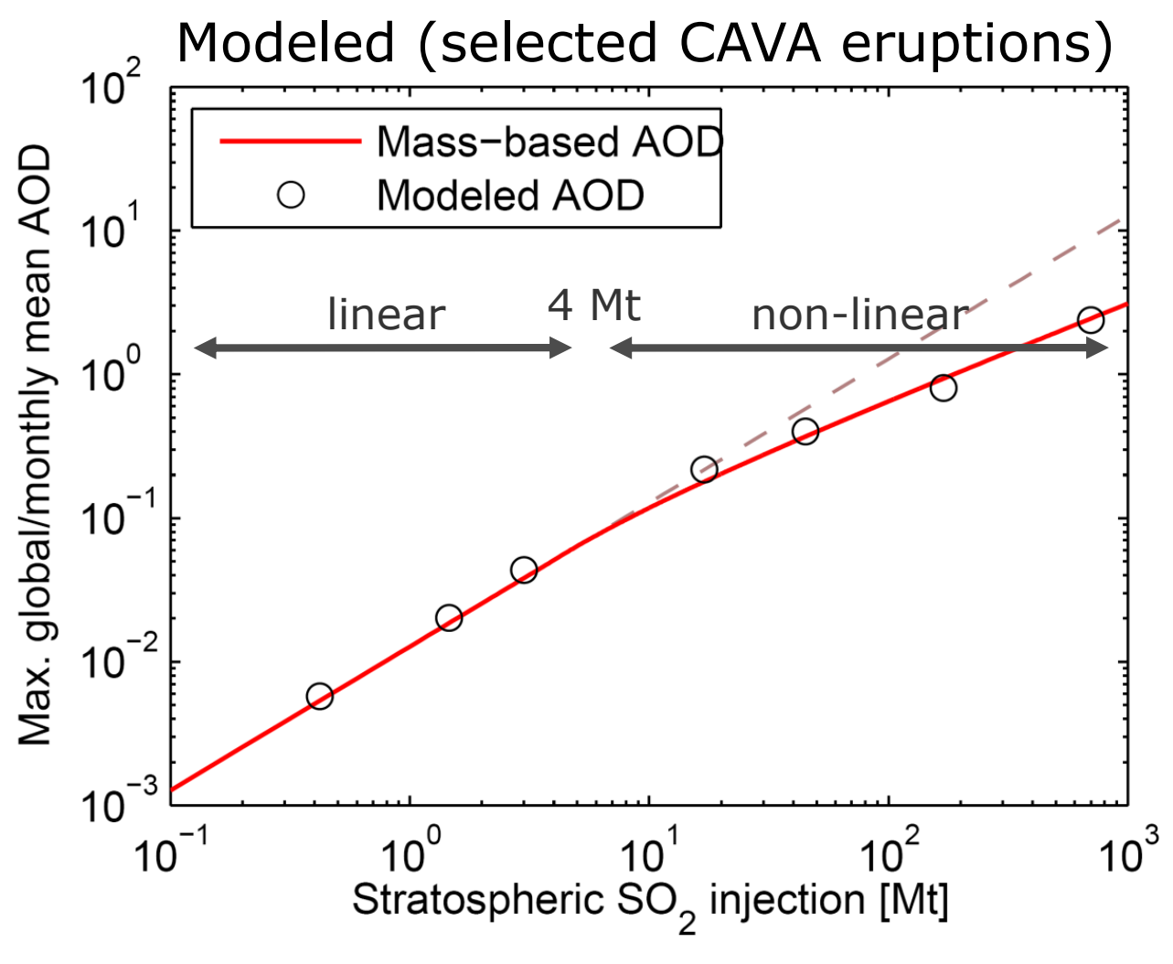


Fig. 10: Max. global/monthly mean AOD as function of stratospheric SO_2 injection (Mt), as described by parameterized relationship (red line). Open circles show results from MAECHAM5-HAM eruption simulations with SO_2 injections corresponding to those in Tab. 1. Linear relationship used for SO_2 injections <4 Mt is extrapolated to higher SO_2 injections (dashed line) for comparison.

Calculation of mass-based RF time series

- Max. RF is derived from max. global mean AOD.
- RF is assumed to increase linearly to its max. value (Fig. 9 & 10, Tab. 1) over 4 months, subsequently decays with an e-folding lifetime of 12 months.
- From the monthly mean RF time series we calculated the annual mean RF for each year after the eruption assuming an eruption time of June.

Calculation of model-based RF time series

- Taking the same calculations, but using modelled monthly mean and latitudinally resolved AOD and calculating the global mean AOD value, we derived the monthly mean model-based RF time series.
- E-folding lifetime varies according to the strength of SO_2 emission
- Annual mean RF time series are derived in the same way as for the mass-based RF.
- RF time series are used as forcing for climate simulations with the EMIC CLIMBER-2.

Overview of volcanic forcing and global climate impact

Tephra	Acronym	Age (ka)	SO_2 (Mt)	Max. stratospheric AOD	Max. RF (W/m²)	SAT anomaly (K)	Duration of SAT signal (yr)
Santa Maria (GUA)	SMT	0.1	3.07	0.039	-0.94	-0.08 | -0.05	1 | 2
U. Apoyeque Pumice (NCA)	UAQ	12.4	1.46	0.019	-0.45	-0.04 | -0.02	<1 | <1
U. Apoyo Tephra (NCA)	UAT	24.5	44.56	0.359	-8.62	-0.65 | -0.47	10 | 11
I-Tephra (GUA)	IFT	40	0.42	0.005	-0.13	-0.01 | -0.01	<1 | <1
E-Fall (GUA)	EFT	51	18.35	0.186	-4.47	-0.38 | -0.24	5 | 7
Los Chocoyos (GUA)	LCY	84	686.59	2.370	-56.89	-2.12 | -3.10	90 | 61
hypothetical eruption	170 MT		170	0.918	-22.02	-1.20 | -1.01	26 | 23

Tab. 1: Selected volcanic eruptions taken for volcanic climate modelling ordered by age (ka). Included are the SO_2 release (Mt), the max. stratospheric AOD, the max. RF (W/m²), the surface air temperature (SAT) anomaly (K), and the duration of the temperature signal (yr). In the last two columns first values are derived using the mass-based RF time series, the second values indicate the results using the model-based RF time series.

Global Climate Impact/Conclusion

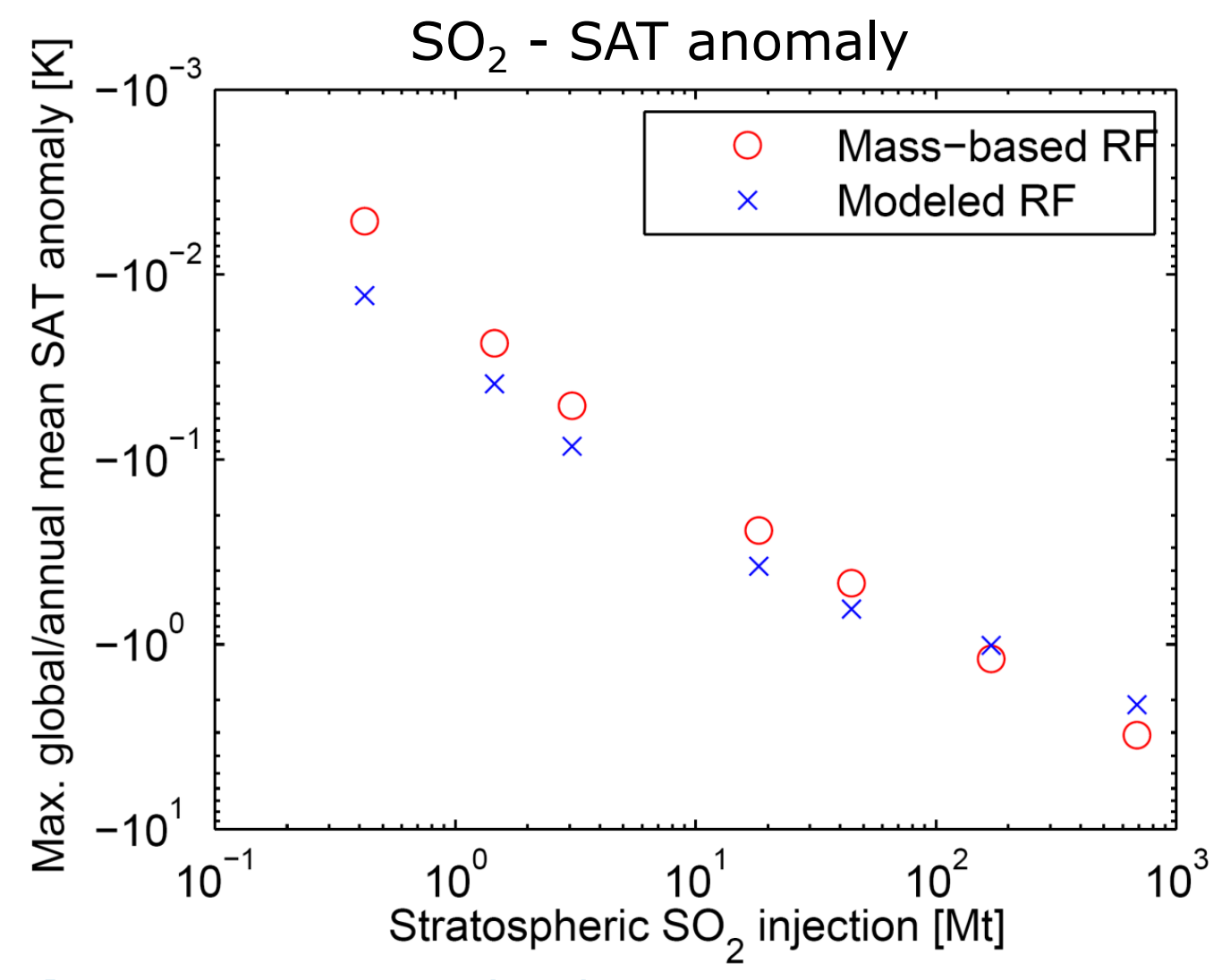


Fig. 11: Max. global/annual mean SAT anomaly (K) calculated with CLIMBER-2 for different stratospheric SO_2 injections (Mt) taken as in Figure 10. Open red circles show results for simulations forced with mass-based RF, blue crosses represent simulations forced with modeled RF.

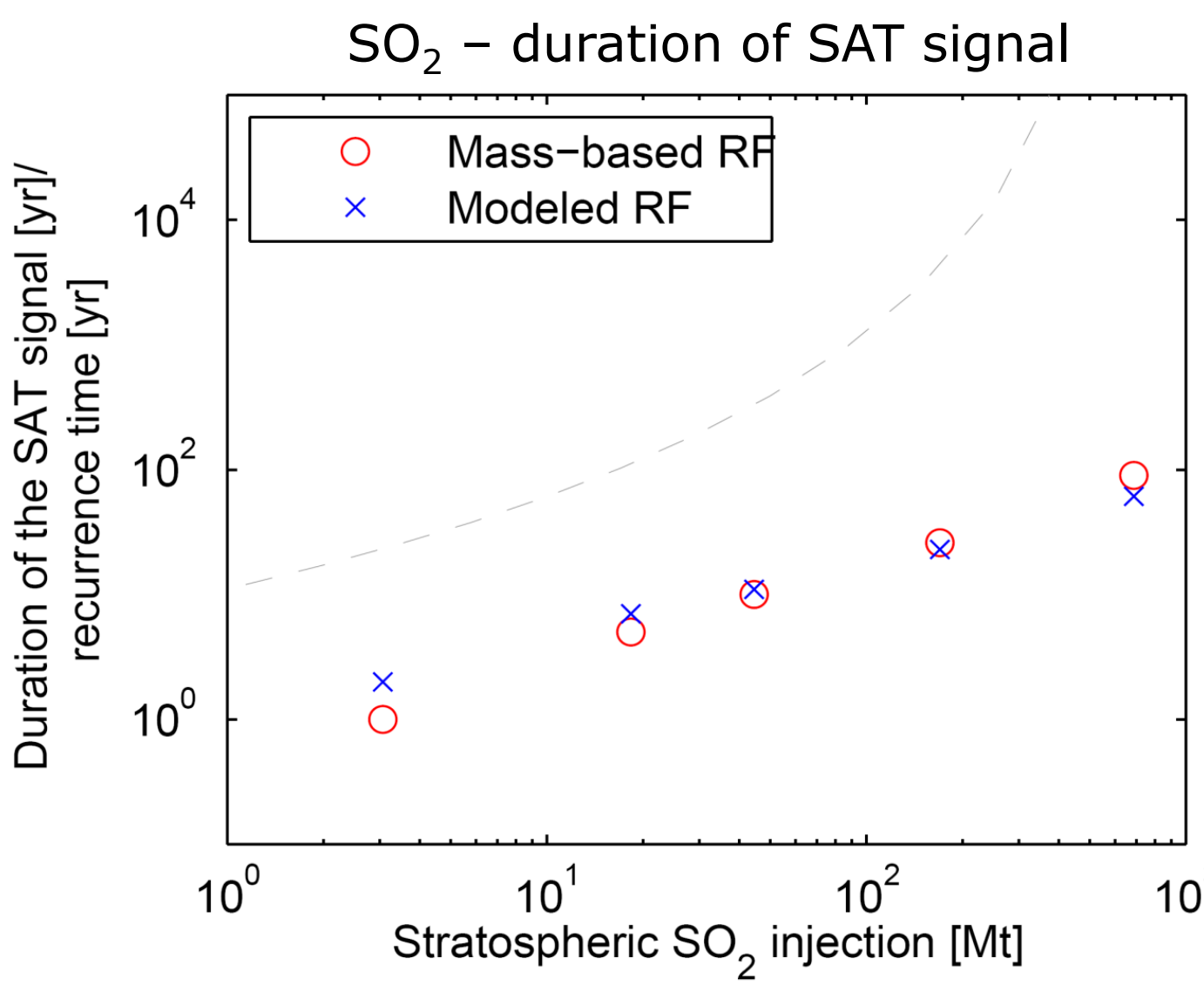


Fig. 12: Duration (yr) of simulated SAT signal according to Figure 11. Results are shown for global/annual mean SAT anomalies ≥0.05 K, duration for IFT and UAQ is <1 yr and can therefore not be included. Thin dashed gray line shows the recurrence time for SO_2 emissions given by the magnitude-SO_2 fit for Fig. 8 applying global data by Deligne et al. (2010).

- The EMIC CLIMBER-2 (Petoukhov et al., 2000) is used for volcanic-climate simulations using the mass-based and modeled RF time series, respectively.
- With increasing SO_2 emissions stronger surface cooling (Fig. 11).
- Simulated max. surface air temperature (SAT) anomalies depend on which RF time series is used varying between 2.1 and 3.1 K (Tab. 1).

- Corresponding max. duration of temperature response varying between ~60 and 90 years (Fig. 12, Tab. 1).
- Duration of climate disturbance for any stratospheric SO_2 injection remains significantly shorter than the recurrence time of such a SO_2 emission

→ cumulative climate effect of successive eruptions seems unlikely

- Qualitative good agreement between E-Fall eruption (18 Mt SO_2) yielding 0.24-0.38 K global cooling, and temperature anomalies analyzed for the 1st year after the Mt. Pinatubo eruption (~17 Mt SO_2).
- Relaxation (5-7 years) of post E-Fall eruption temperature anomalies consistent with the one of Mt. Pinatubo eruption.

→ less complex ESM CLIMBER-2 is able to simulate global climate response in agreement with other observational and model studies (Thompson et al, 2009; Stenchikov et al., 2009).

- Presented results can be used to calculate volcanic forcings and potential climate impacts from sulfur emissions, sulfate aerosols or ADO data for any eruption that reached the stratosphere.

References

Carey and Sparks, *Bull. Volcanol.*, 48 (1986); **Deligne et al.**, *J. Geophys. Res.*, 115, B06203 (2010); **Devine et al.**, *J. Geophys. Res.*, 89 (1984); **Hyde and Crowley**, *J. Clim.*, 13 (2000); **Jansen et al.**, in Climate Change 2007: The physical Science Basis (2007); **Kutterolf et al.**, *Geochem. Geophys. Geosystem*, 9(2) (2008b); **Metzner et al.**, under revision (2012); **Niemeier et al.**, *ACP*, 9 (2009); **Pyle et al.**, *Bull., Volcanol.*, 57 (1996); **Petoukhov et al.**, *Clim. Dyn.*, 16 (2000); **Stenchikov et al.**, *J. Geophys. Res.*, 114, D16104 (2009); **Stenchikov et al.**, *J. Geophys. Res.*, 111, D07107 (2006); **Thompson et al.**, *J. Clim.*, 22 (2009).

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