

To refer to our datasets, the scripts used to produce them or the dataset documentation, please cite our documentation manuscript part 1, which details the aerosol optical property dataset (part 2 documenting emission dataset should be in open peer review in November 2025):

Aubry, T. J., Toohey, M., Khanal, S., Chim, M. M., Verkerk, M., Johnson, B., Schmidt, A., Kovilakam, M., Sigl, M., Nicholls, Z., Thomason, L., Naik, V., Rieger, L., Stiller, D., Ziegler, E., and Smith, I.: Stratospheric aerosol forcing for CMIP7 (part 1): Optical properties for pre-industrial, historical, and scenario simulations (version 2.2.1), EGU sphere [preprint], <https://doi.org/10.5194/egusphere-2025-4990>, 2025.

All codes and source datasets used to produce our datasets are available on zenodo (or at https://github.com/thomasaubry/CMIP7_stratforcing_v2.2.1, minus GloSSAC which was too big to upload on GitHub) :

Aubry, T. (2025). Scripts and source datasets for CMIP7 stratospheric aerosol forcing datasets (v2.2.1) (version 2.2.1). Zenodo. <https://doi.org/10.5281/zenodo.17295697>

Preliminary documentation for version 2.2.1 of the CMIP7 historical stratospheric aerosol optical properties and stratospheric volcanic sulfur emissions datasets

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Scope of this document: *This live document is a rough documentation of the datasets we provide and how they have evolved throughout the testing phase. The latest version of our dataset, v2.2.1, and it is the one recommended for use in phase 7 of the Coupled Model Intercomparison Project (CMIP7) Assessment Fast Track (AFT). It is available [on zenodo](#) and should be available on ESGF soon. No update for AFT simulations will be produced, and only retractions can occur. **Detailed documentation papers will be submitted for open peer review in the following months.** This document is read-only but you can leave feedback/questions by commenting on it, leaving a comment in the [dedicated Input4MIP GitHub discussion](#), or emailing Thomas Aubry.*

I – Datasets overview

We provide two datasets intended to be used by two classes of CMIP7 models:

i) **Stratospheric aerosol optical properties**, for climate models without interactive stratospheric aerosol modules. We expect most models will use this dataset.

ii) **Upper tropospheric – stratospheric volcanic sulfur emission**, for models with interactive stratospheric aerosol modules which are run from emissions of aerosol precursors. We included upper-tropospheric emissions as several factors could result in fast transport into the stratosphere such as vertical transport from the troposphere to the stratosphere, and potential volcanic cloud self-lofting via radiation absorption.

Both datasets currently cover Jan 1750 – Dec 2023, with the aim to facilitate running of extended historical runs starting in 1750 instead of 1850 by modelling groups wishing to do so. Climatologies for aerosol optical properties are calculated over 1850-2021, in line with the CMIP7 protocol (*Dunne et al., 2024*). No climatologies are currently provided for emissions, and we welcome community discussion/suggestion on how to best run emission-driven picontrol simulations with models with interactive stratospheric aerosols.

Note that the emission dataset only provides explosive volcanic sulfur emissions into the upper-troposphere and stratosphere. We do not provide, among other, OC/BC emissions from tall pyrocumulonimbus generated by intense fires, or stratospheric volcanic emissions of other species such as halogens or water vapor. Modelling centers wishing to run emission-driven currently have the responsibility to put together emission datasets of any species other than volcanic sulfur that they want to use, and to document these datasets. Whilst prioritizing production, documentation and development of our core datasets, we would happily try to facilitate and contribute to discussions on standardized emission datasets for stratospheric aerosol precursors other than volcanic sulfur.

II – Version history overview

Table 1 documents changes in our dataset since the first CMIP6plus era (testing phase for CMIP7). The rest of the document documents the latest version, version 2.2.1.

Version	Overview of key changes over previous version	Status
CMIP_UOEXE TER-CMIP-2-2 -1 <i>(CMIP7 era)</i>	- Removed satellite-era NaNs with updated Mie routines to produce optical properties - Corrected Agung 1963 for more SH transport - Masked tropospheric nd values instead of having zeroes - Updated EVA_H 2.0 effective radius scaling (0.06um minimum local value, 0.115um minimum global value, scaling factor updated to match Pinatubo with new 2.0 calibration of other parameters) - Updated EVA_H 2.0 background climatology: directly prescribe a background climatology of 525nm extinction (GloSSAC-derived) instead of having background emissions and the background climatology spatial structure matching EVA H shape functions	Expected to be available on ESGF by early June 2025: <a :https:="" aims2.llnl.gov="" href="https://aims2.llnl.gov/search?project=input4MIPs&activeFacets=%7B%22mip_era%22%3A%22CMIP7%22%2C%22source_id%22%3A%22UOEXETE%22%7D" search?project='input4MIPs&activeFacets=%7B%22mip_era%22%3A%22CMIP7%22%2C%22source_id%22%3A%22UOEXETE%22%7D"'>https://aims2.llnl.gov/search?project=input4MIPs&activeFacets=%7B%22mip_era%22%3A%22CMIP7%22%2C%22source_id%22%3A%22UOEXETE%22%7D

	Note: v2.1.0 and v2.2.0 was never released on ESGF hence jump to 2.2.1	R-CMIP-2-2-1%22%7D
CMIP_UOEXE TER-CMIP-2-0 -0 (<i>CMIP7 era</i>)	- Corrected Greenland ice-core deposition in the highly polluted 1920-1978 period, resulting in more consistency with pyrheliometer data (and CMIP6) for this period - Changed attribution of 1931 ice core signal - Corrected 1943 eruption latitude in <i>Sigl et al. (2015)</i> - changed cmip6_plus era to cmip7 and version to 1.0.0 - fixed number density bug and changed unit from number of aerosol particles/cm³ air to number of H₂SO₄ molecules/cm³ air as requested by MRI and CNRM groups	Available on ESGF but to be deprecated once version 2.2.1 is online
CMIP_UOEXE TER-CMIP-2-0 -0 (<i>CMIP6plus era</i>)	- Added aerosol number density - Updated small eruption source parameters	deprecated/ Available on ESGF
CMIP_UOEXE TER-CMIP-1-3 -0 (<i>CMIP6plus era</i>)	- Used new ice-core and geological dataset to include more small eruptions during pre-satellite era - Updated ice-core sulfate deposition event - volcanic eruption matches - Fixed minor issues in file formatting - Fixed minor issues with NaN values	deprecated/ Available on ESGF
CMIP_UOEXE TER-CMIP-1-2 -0 (<i>CMIP6plus era</i>)	- Bug fixed in surface area and volume densities provided pre-satellite era - Improved and re-calibrated volcanic aerosol model EVA_H pre-satellite era (pre-1979) - Seasonally-varying (instead of season-independent) non-volcanic aerosol background pre-satellite era - New injection depth variable in emission files - New files providing 1850-2021 aerosol optical properties climatologies to be used in piControl simulations - Consistently made tropospheric values NaN in aerosol optical properties files	deprecated/ Available on ESGF
CMIP_UOEXE TER-CMIP-1-1 -3 (<i>CMIP6plus era</i>)	NA – Started this document at version 1-1-3	deprecated/ Available on ESGF

Table 1: Overview of dataset versions to date. This document currently documents version 2.2.1.

III – Stratospheric aerosol optical properties: variables and implementation

Name	Full name	Unit	1750-2023 file name	1850-2021 climatology file name*
ext	Extinction	m ⁻¹	ext_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_175001-202312.nc	ext_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_185001-202112-clim.nc
ssa	Single scattering albedo	-	ssa_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_175001-202312.nc	ssa_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_185001-202112-clim.nc
asy	scattering asymmetry factor	-	asy_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_175001-202312.nc	asy_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_185001-202112-clim.nc
reff	Effective radius	m	reff_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_175001-202312.nc	reff_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_185001-202112-clim.nc
sad	Surface area density	μm ² cm ⁻³	sad_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_175001-202312.nc	sad_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_185001-202112-clim.nc
vd	Volume density	μm ³ cm ⁻³	vd_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_175001-202312.nc	vd_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_185001-202112-clim.nc
nd	H ₂ SO ₄ number density	mole cule H ₂ SO ₄ cm ⁻³	nd_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_175001-202312.nc	nd_input4MIPs_aerosolProperties_CMIP_UOEXETER-CMIP-2-2-1_gnz_185001-202112-clim.nc

Table 2: Variables provided in our aerosol optical properties dataset.

Variables dimensions: Table 2 provides details of the 7 variables provided in our dataset. All variables are provided as zonal averages. Each variable has dimensions of time, latitude and height, with ext, ssa and asy additionally depending on wavelength. Time ranges from January 1750 to December 2023 with monthly resolution. The length of the time dimension in climatology files is 12, corresponding to January to December. Climatologies were obtained from 1850-2021 averages. Latitude ranges from -87.5 to 87.5 degree North with resolution of 5°. Height ranges from 5 to 39.5 km a.s.l. with a resolution of 0.5 km.

Wavelength dimension: We provide ext, ssa and asy at 39 wavelengths listed below in μm:

wavelength=[0.16 0.23 0.3 0.39 0.46 0.525 0.53 0.55 0.61 0.7 0.8 0.9 1.01 1.02 1.27 1.46 1.78 2.05 2.33 2.79 3.418 4.016 4.319 4.618 5.154 6.097 6.8 7.782 8.02 8.849 9.708 11.111 13.157 15.037 17.699 20.0 23.529 35 50 75 100];

This list includes:

- Wavelengths required by the Rapid Radiative Transfer Model commonly used in climate models, e.g., by EC-Earth.
- Wavelengths that are key to building the dataset, i.e., GloSSAC wavelengths (0.525 and 1.02) and 0.550 used by the reduced-complexity aerosol model EVA_H.
- Additional wavelengths chosen to have a relatively regularly spaced (in logarithmic space) set of wavelengths.

To facilitate use of our dataset in any radiative model, we provide the community with [scripts](#) that can be used to interpolate the files we provide on ESGF on any list of wavelength inputted by the user. These include a simple method to linearly interpolate to waveband midpoints and a weighted averaging method that is more computationally expensive but provides more representative averages, particularly for radiation schemes with broad wavebands. We therefore recommend modelling groups use the latter method where possible. Modelling groups tweaking these scripts or using a different approach should simply document it. We welcome feedback and suggestions on the scripts provided and should you have important difficulties using them, Thomas Aubry can be contacted to provide a version of the dataset at your required model wavelength.

NaN values and tropopause height: Tropospheric values are always set to NaN. For the satellite era, the dataset also contains NaN values in the mid-upper stratosphere, where the GloSSAC dataset had NaN. We recommend that all modelling groups implement our values of aerosol optical properties wherever our datasets have an attributed value, regardless of model-generated tropopause height. This would ensure that all models prescribe the same total (vertically-integrated) forcing.

IV – Upper tropospheric – stratospheric volcanic sulfur emissions: **Variables and implementation**

Name	Full name	Unit	1750-2023 file name	1850-2021 climatology file name
time	SO ₂ injection time	Days since 1850/01/01	utsvolcemis_ input4MIPs_ emissions_C MIP_UOEXE TER-CMIP-2 -2-1_gn_175 00101-20231 201.nc	NA - Currently not provided.
lat	SO ₂ injection latitude	Degree north		
lon	SO ₂ injection longitude	Degree East		
height	SO ₂ injection height	m a.s.l.		
depth	SO ₂ injection depth	m		
utsvolcemis	SO ₂ mass	Kg of SO ₂		

Table 3: Variables provided in our emission dataset.

Dataset overview: Table 3 provides details of the 6 variables provided in our dataset, in a single file. All variables have a single dimension currently provided as an arbitrary *eruption_number*. Each eruption number corresponds to one volcanic event that happened at the eruption *time* and volcano *lat* and *lon* provided, injected a SO₂ mass *utsvolcemis* at an altitude *height*. The *depth* variable is the best estimate for the thickness of the injected SO₂ cloud. In addition to this netcdf file, we have an extensive table containing all information on each eruption provided, available [here](#). This includes the volcano and eruption number from the Global Volcanism Program, the volcano name, uncertainty estimate for most eruption parameter/eruption, source datasets, and information on how the eruption was matched to ice-core sulfur records for pre-satellite era eruptions.

Implementation in models: We recommend following these guidelines to implement our emission dataset:

- **Distribution in time:** We recommend an eruption duration of 24 hours, with the injection uniformly spread across that time.

- Horizontal distribution: We recommend a point injection, i.e. all the injected SO₂ should be emitted in the model column containing the latitude and longitude of the volcano.
- Vertical distribution: We recommend to distribute the SO₂ following a Gaussian vertical distribution, centered on *height* and of Gaussian width *depth*. Such distribution and the cloud depth estimate provided are consistent with 3-dimensional models of volcanic plumes (Aubry *et al.*, 2019).

Any deviation from the recommended implementation, or modification of provided injection parameters, should be rigorously documented in individual model publication. In particular, modelling centers commonly use bespoke injection parameters for the Pinatubo 1991 eruption to match the observed aerosol optical properties as closely as possible. However, we note that using different parameter values or implementation would defeat the purpose of a MIP. Should injection emission parameter be used, we recommend running simulations with recommended injection parameters to ensure availability of simulations directly comparable between models.

We acknowledge that the recommended Gaussian vertical injection profile might result in additional work for modelling groups. Should simpler profiles be implemented, the most important aspect is that they are centered on the provided *height*, and that their characteristic depth (thickness) scales with the provided *depth*. For example, for a uniform vertical injection profile, the SO₂ could be uniformly injected between altitudes *height-depth* and *height+depth*.

V – Overview of sources and dataset creation process

Disclaimer: this is a very rough documentation. Extensive documentation papers will be submitted with open preprint shortly after we freeze the datasets.

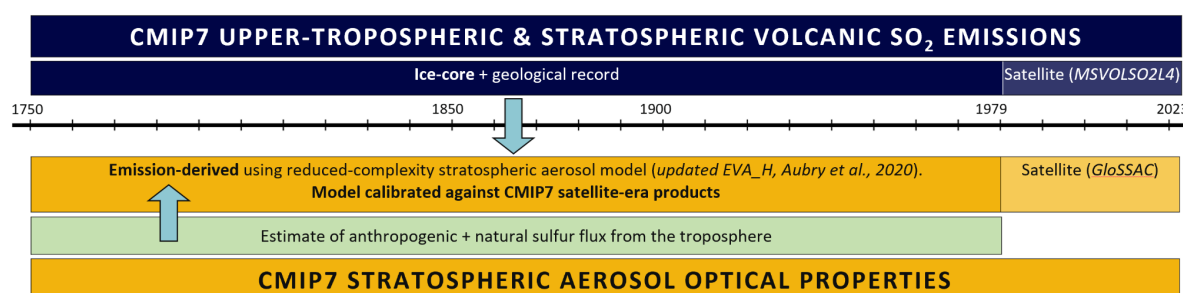


Figure 1: Overview of key sources and methodologies used in our emission dataset (blue) and our aerosol optical properties dataset (yellow).

Emission dataset:

For the satellite era (1979-present), we choose MSVOLSO2L4 (Carn, 2024) as our emission dataset. Our choice is motivated by the fact this is the only dataset covering the full satellite era and consistently updated. Before the satellite era, we use a combination of three ice-core dataset: eVolv2k (Toohey and Sigl, 2017) (1750-1900), Sigl et al. (2015) (1901-1978) and, for 1759-1900, Fang et al. (2023). The latter dataset only uses Greenland core, but its high resolution enables identification of moderate-magnitude eruptions in the tropics or Northern Hemisphere that are not detected in eVolv2k. For all these ice-core-derived events, we match them to known eruptions where possible. When we have a match, we find the best estimate of eruption parameters such as date and altitude of emissions using geological databases (e.g., Global Volcanism Program (Global Volcanism Program, 2025), and IVESPA (Aubry et al., 2021) and extensive literature search. For events with no match or matched eruption with missing parameters, we used empirical relationships or ad-hoc values that will be documented in detail later.

Last, even when using the high-resolution Fang et al. (2023) dataset, the frequency and total injections from small-moderate magnitude eruptions (<10 Tg SO_2) is still much smaller for the pre-satellite era compared to the satellite era. Consequently, for the pre-satellite era we add to the emission dataset any eruption of Volcanic Explosivity Index (VEI) ≥ 4 in the Global Volcanism Programme database that is not suggested as a match to one of the ice-core identified eruptions. The challenge is that these eruptions have no available SO_2 mass estimate and ad-hoc assumptions are thus required for this key injection parameter. All VEI ≥ 6 events have an ice-core match. For the 4 VEI 5 events not matched to an ice-core signal, we assume an SO_2 mass of equal to the mean mass of VEI 5 events with a known mass in the dataset, i.e. 2.78 Tg SO_2 . For the 64 VEI 4 events not matched to an ice-core signal, we use a mass of 0.08 Tg SO_2 for each event. This mass results in the same global mean SAOD for the 1998-2023 period, characterized by eruptions ≤ 2 Tg SO_2 , and for the 1850-1978 period, when we run the aerosol model EVA_H only using eruptions injecting ≤ 3 Tg SO_2 in our dataset (see figure below). By equating the pre-satellite SAOD anomaly from relatively small eruptions to the observed 1998-2023 anomaly characterized by the occurrence of small eruptions only, we aim to minimize bias in mean forcing from small-moderate magnitude eruptions between the pre- and satellite era datasets. We acknowledge this approach is subject to high uncertainties. Furthermore, owing to the underrecording of VEI 4 eruptions prior ~ 1950 , the dataset is still biased in terms of the frequency-magnitude distribution of small SAOD perturbations (Figure 2, bottom left), with too many years with near-zero SAOD anomalies compensated by too many years with SAOD perturbation of 0.01-0.02.

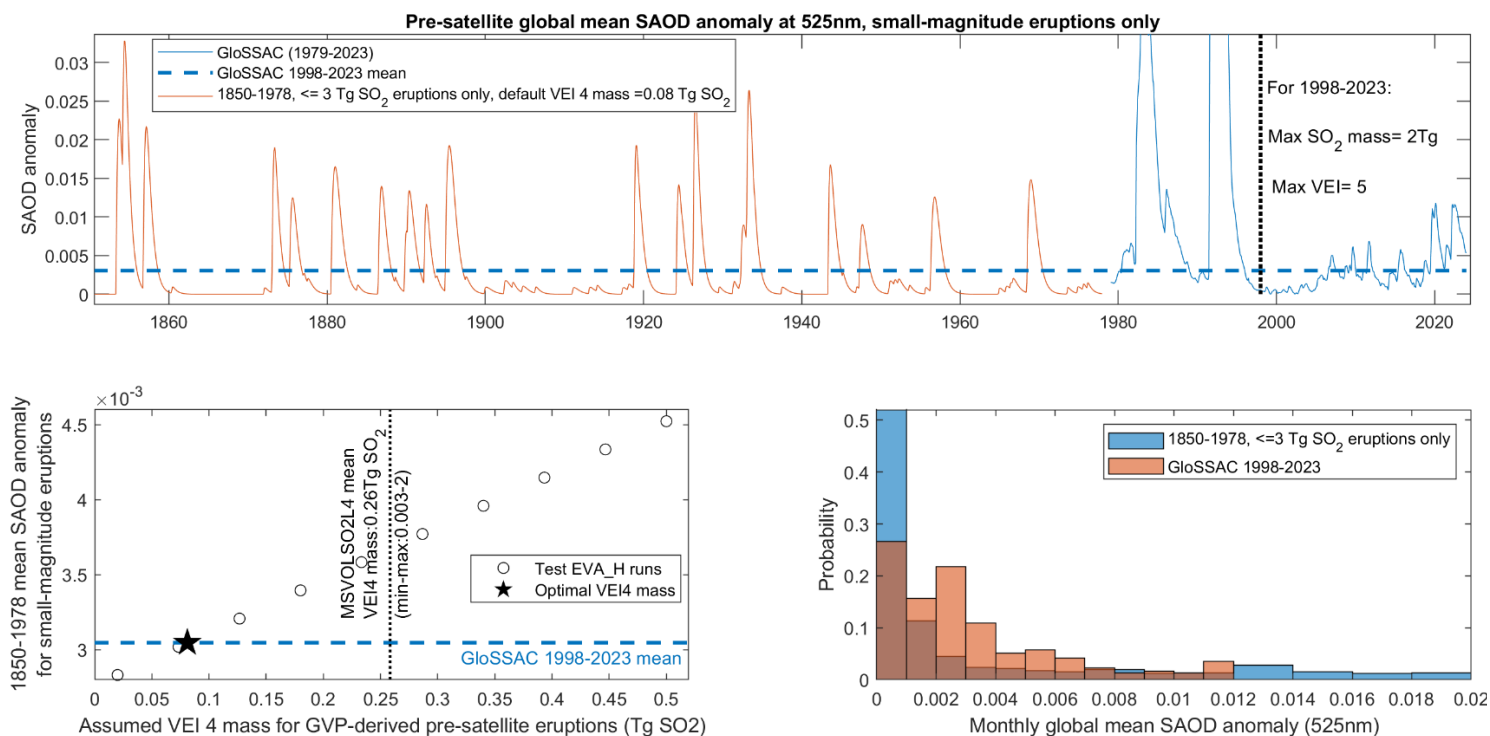


Figure 2: Key analyses for determining the default mass of SO_2 attributed to VEI 4 eruptions not matched to an ice-core sulfate deposition signal. Top: GloSSAC SAOD anomaly (blue) and pre-satellite SAOD anomaly obtained by running EVA_H using eruptions $\leq 3 \text{ Tg SO}_2$ only. Bottom left: 1850-1978 mean SAOD anomaly associated with eruptions $\leq 3 \text{ Tg SO}_2$ as a function of the assumed mass for VEI 4 eruptions for which the mass is not constrained from ice-core datasets. The blue horizontal dashed line is GloSSAC's 1998-2023 mean. The vertical dotted line is the mean VEI4 mass for satellite-era eruptions. The star shows the “optimal” VEI 4 mass to equate the 1850-1978 small eruption mean SAOD to GloSSAC 1998-2023 mean. Bottom right: Distribution of SAOD anomaly associated with small-magnitude eruptions for the pre-satellite era dataset and GloSSAC 1998-2023.

Aerosol optical properties dataset:

For the satellite era (1979-present), we use GloSSAC (Kovilakam *et al.*, 2020). For the pre-satellite era, aerosol optical properties are entirely derived from the reduced-complexity volcanic aerosol model EVA_H (Aubry *et al.*, 2020) using the emission dataset. We chose this approach to maximize consistency between the two datasets, as well as consistency with PMIP and VolMIP which also used aerosol optical properties derived from emission using the Easy Volcanic Aerosol (EVA) model (Toohey *et al.*, 2016), of which EVA_H is an extension. For CMIP7, we improved EVA_H by:

- Implementing new Mie lookup tables using a bimodal instead of single-mode aerosol size distribution
- Making the aerosol production timescale dependent on SO_2 mass and injection altitude, which enables to better capture the forcing time-evolution for both large and small magnitude eruptions
- Recalibrating the model against our satellite-era datasets (MSVOLSO2L4 and GloSSAC), to maximize consistency between the pre- and satellite era parts of our dataset.

These updates will be documented in detail later. The 1979-1981 period is used to harmonize the emission-derived and satellite-derived portions of the dataset. As in CMIP6, a background aerosol contribution is represented pre-satellite era, with an increasing trend from 1850. This background is directly measured in the satellite era. The background aerosol mostly reflects tropospheric aerosol (and aerosol precursor) transported from the troposphere to the stratosphere, although it includes contributions such as those from meteorites. The trend is primarily related to increase in anthropogenic aerosol emissions from the 1850s until the end of the 20th century. Note that for models that use our prescribed stratospheric aerosol dataset but interactively generate a non-volcanic stratospheric aerosol background, this background will be double-counted. This was already the case in CMIP6, and this small bias should be investigated during CMIP7 and corrected in future CMIP phases.

VI – Comparison between our datasets and CMIP6

Disclaimer: Rudimentary comparison for now, more extensive comparisons will be included in documentation papers.

Period	Global mean SAOD 550nm		Global mean ERF (W/m ²)	
	CMIP7 v2.2.1	CMIP6	CMIP7 v2.2.1	CMIP6
1850-2014	0.0138	0.0107	-0.22	-0.16
1850-2021	0.0135	NA	-0.22	NA
1750-2023	0.0204	NA		NA

Table 4: Global mean SAOD at 550 nm and global mean effective radiative forcing (ERF), averaged over three different time periods. Numbers in bold are the global mean SAOD for the recommended picontrol climatology for CMIP6 and CMIP7. Note the ~30% increase in CMIP7.

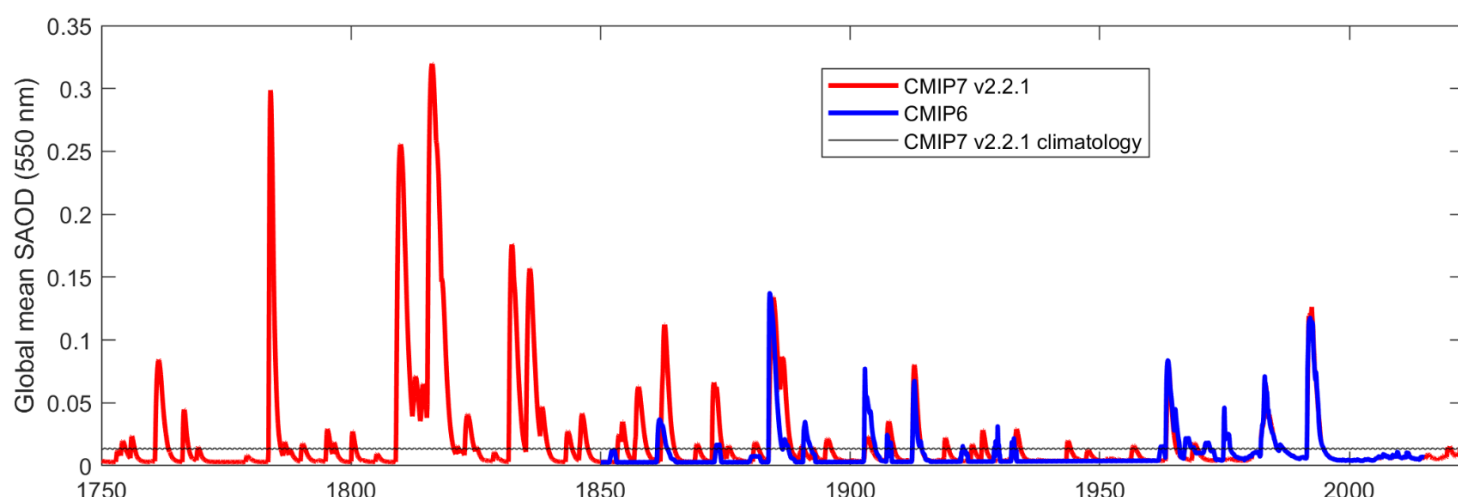


Figure 3: Global mean SAOD at 550nm.

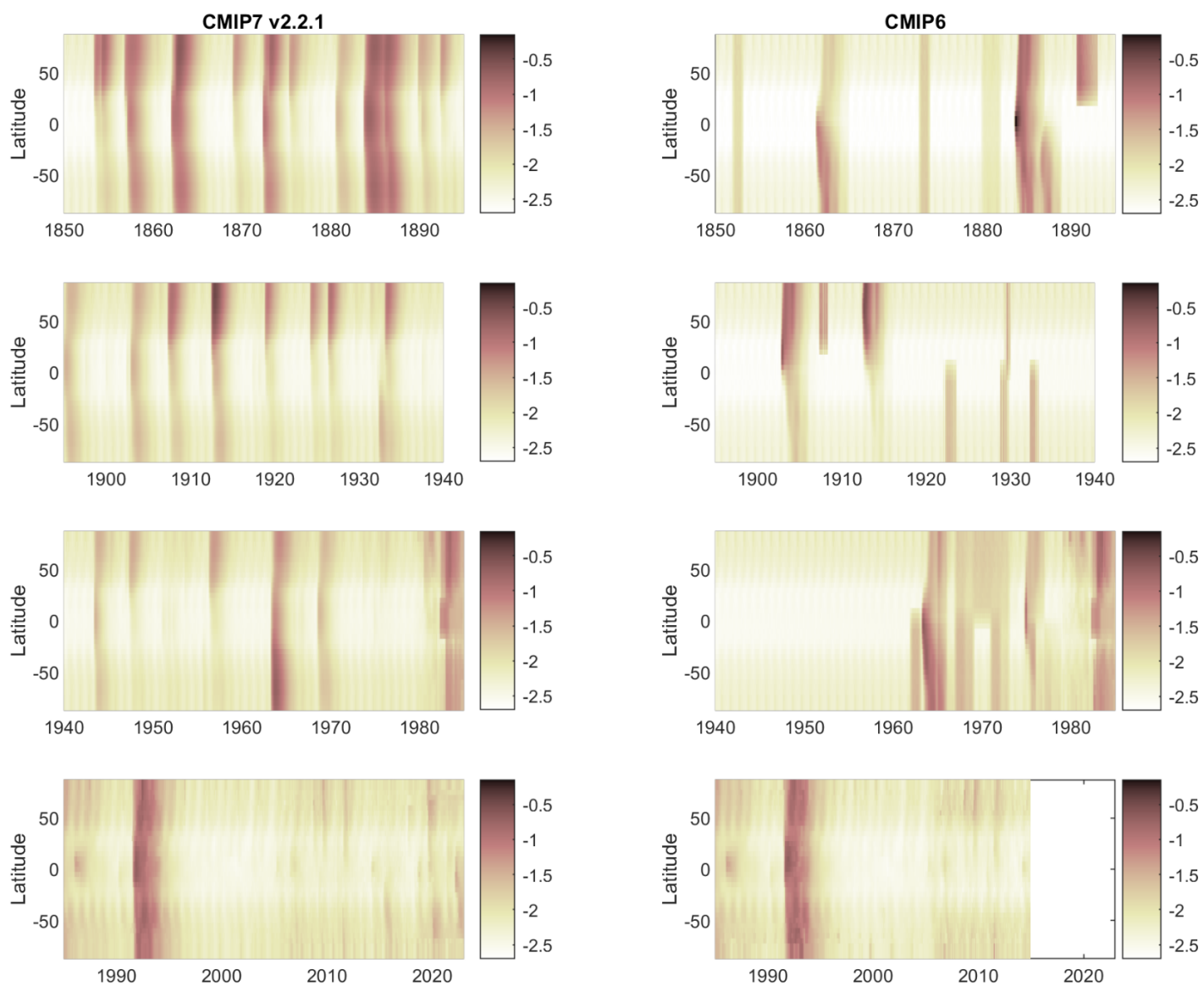


Figure 4: SAOD at 550 nm (log scale).

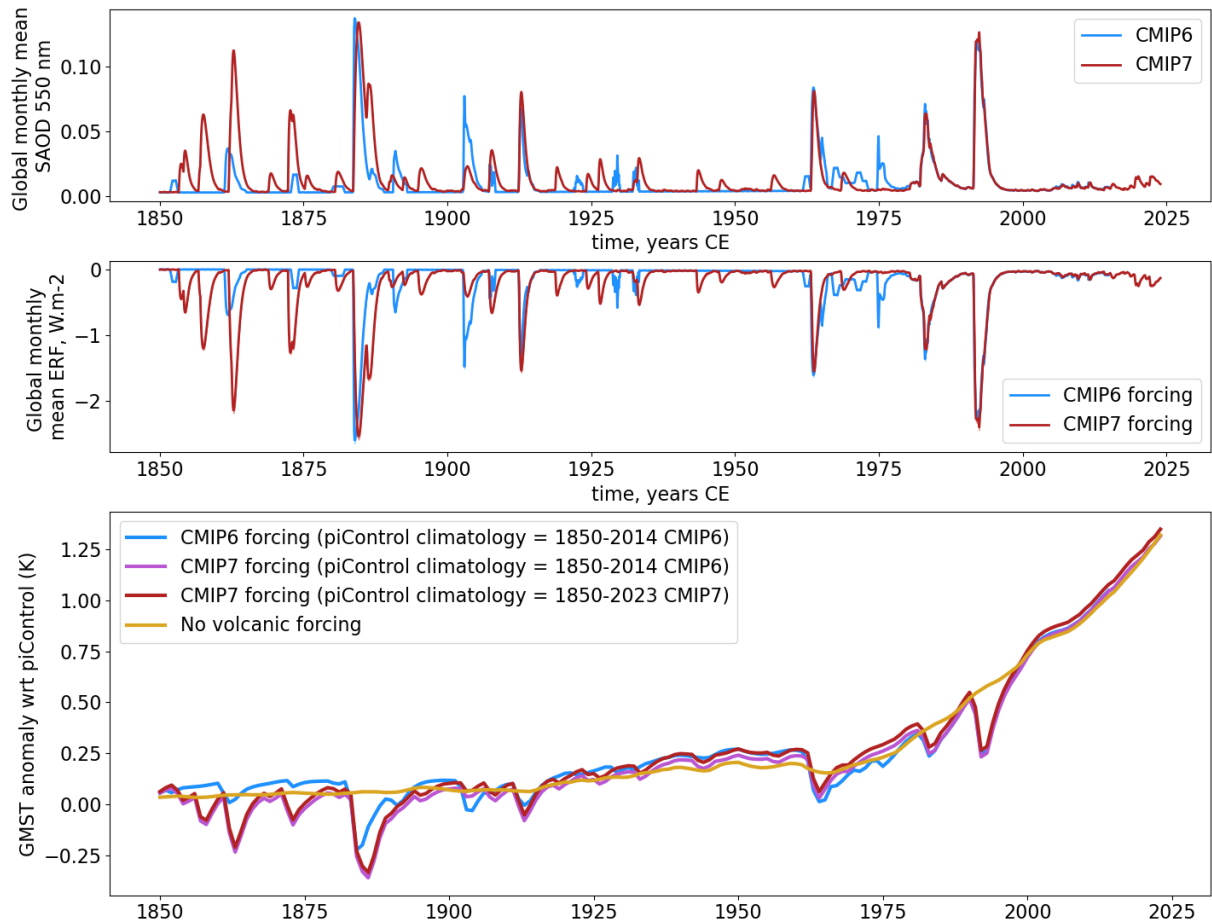


Figure 5: Global mean surface temperature (GMST) anomaly wrt picontrol, for CMIP6 and CMIP7 v2.2.1. Two simulation ensembles were run with the CMIP7 stratospheric aerosol forcing: i) with the CMIP7 climatology implemented in the picontrol run (showing how our new dataset will affect temperature anomalies); ii) with the CMIP6 climatology implemented in the picontrol run (showing our new dataset will affect temperature, in absolute terms). Simulation ensembles were run with the FaIR model (version 2.1.4, Smith et al., 2018, Leach et al., 2021), sampling 1000 different model parameter sets (calibration v1.4.2, Smith et al. 2024). Volcanic forcing is estimated based on the gmSAOD time series (exponential scaling from Marshall et al., 2020), for other forcings, we use the estimated emissions, concentrations and forcing from RCMIP (Nicholls et al., 2020). Ensemble mean values are shown.

Period	CMIP7 v2.2.1 (CMIP7 climatology in picontrol)	CMIP7 v2.2.1 (CMIP6 climatology in picontrol)	CMIP6
1850-1900	-0.01	-0.03	0.06
1901-1950	0.15	0.12	0.15
1950-2000	0.33	0.30	0.29
2001-2014	0.92	0.89	0.89

Table 5: Global mean surface temperature anomaly wrt piconrol for 1850-1899, 1900-1949, 1950-1999 and 2000-2014, for CMIP6 and CMIP7 v2.2.1, for the simulations shown in figure 5. Comparing the 2nd and 4th column, note the relatively cooler 1850-1900 period in CMIP7, and the warmer 1950-present day period.

VII – FAQ

Please feel free to ask additional questions on our dedicated GitHub discussion or by emailing Thomas Aubry (see links at the document top).

1) Will you provide aerosol optical properties at bespoke wavelengths for each modelling center?

We instead provide the community with [a script](#) that can be used to interpolate the files we provide on ESGF on any list of wavelength inputted by the user. This will make our workload lighter and make users independent on our response time for generating new files at their requested wavelength.

However, should you need files at bespoke wavelength and have important issues using our script, please email thomas.aubry@earth.ox.ac.uk with the list of wavelengths requested and a clear date by which you'd like the files to help us prioritize workload.

2) Why are CMIP6 and CMIP7 forcing datasets so different in the pre-satellite era?

Pre-satellite era, the CMIP6 dataset was derived from a combination of three sources (*Luo et al., 2018*): i) Aerosol model (AER2D) run from sulfur emissions (*Gao et al., 2008*) for 7 large eruptions; ii) Pyrheliometer measurements for a total of 97 months, distributed within 11 years. These measurements required scaling to visible SAOD and hemispheric or global scale, with 74 months having data from a single station; iii) for any other time, an aerosol climatology derived from satellite.

For CMIP7, we completely revised the method with aerosol property entirely derived from emissions using the EVA_H model pre-satellite era. Our emission dataset is based on the latest ice-core and geological datasets.

These radically different approaches and the different source datasets used for large eruption emission result in numerous differences in the occurrence, latitude, timing and magnitude of eruptions of all sizes pre-satellite era.

3) Will you provide climatology files for piControl simulations and scenario simulations?

Yes. These files are provided from versions 1.2.0 onwards for piControl, and 2.2.1 onwards for scenarios.

VIII – References

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