Dear Editor,

please find below a revised version of manuscript gmd-2016-68, which we have modified based on the comments provided in the open discussion.

Our response to the reviewers, as well as to the comment by Ingo Bethke and by the CMIP Panel are available in the open discussion. As they were already structured as responses to specific comments, we refer to our contributions in the open discussion as our official responses to the reviewers' comments.

As a major change following the renaming of the VolMIP experiments (see comment AC3), we have reorganized section 2 of the manuscript in order to reflect the new branching of the experiments into "pinatubo", "long" and "cluster". Furthermore, two additional volcanic-perturbation experiments are included in the protocol (volc-cluster-21C and volc-long-hlS), following the Reviewers' suggestions. Please note that differently from our replies to the comments in the open discussion, both experiments are included in CMIP6.
A "control-slab" experiment has also been added as parent experiment for the volc-pinatubo-slab experiment.

We also polished the text during the revision process.

We have added Eugene Rozanov in the authors list, as he contributed to generate some of the modeling data that are used in Figure 3. Also, we have corrected the details of a couple of affiliations.

Please contact me for any further information or clarification about the revision of the manuscript.

Sincerely,

Davide Zanchettin
On behalf of all co-authors

The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP): Experimental design and forcing input data for CMIP6

Davide Zanchettin[1], Myriam Khodri[2], Claudia Timmreck[3], Matthew Toohey[3,4], Anja Schmidt[5], Edwin P. Gerber[6], Gabriele Hegerl[7], Alan Robock[8], Francesco S. R. Pausata[9], William T. Ball[10,11], Susanne E. Bauer[12], Slimane Bekki[13], Sandip S. Dhomse[5], Allegra N. LeGrande[12], Graham W. Mann[5,14], Lauren Marshall[5,14], Michael Mills[15], Marion Marchand[13], Ulrike Niemeier[3], Virginie Poulain[2], Eugene Rozanov[10], Angelo Rubino[1], Andrea Stenke[11], Kostas Tsigaridis[12], Fiona Tummon[11]

[1] Department of Environmental Sciences, Informatics and Statistics, University of Venice, Mestre, Italy

[2] IRD/IPSL/Laboratoire d'Océanographie et du Climat, Paris, France

[3] Max Planck Institute for Meteorology, Hamburg, Germany

[4] GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

[5] Institute for Climate & Atmospheric Science, School of Earth & Environment, University of Leeds, Leeds, UK

[6] Courant Institute of Mathematical Sciences, New York University, New York, NY, USA

[7] GeoScience, University of Edinburgh, UK

[8] Department of Environmental Sciences, Rutgers University, New Brunswick, NJ, USA

[9] Department of Meteorology (MISU), Stockholm, Sweden

[10] PMOD/WRC, Davos, Switzerland

[11] Institute for Atmospheric and Climate Science, Dept. of Environmental Systems Science, ETH Zürich, Switzerland

[12] NASA Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University, New York, NY, USA

[13] LATMOS/IPSL, UVSQ Université Paris-Saclay, UPMC Université Paris 06, CNRS, Guyancourt, FranceLATMOS, Université Pierre et Marie Curie, Paris, France

[14] National Centre for Atmospheric Science, University of Leeds, Leeds, U.K.

[15] Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, CO, USA

Abstract. The enhancement of the stratospheric aerosol layer by volcanic eruptions induces a complex set of responses causing global and regional climate effects on a broad range of timescales. Uncertainties exist regarding the climatic response to strong volcanic forcing identified in coupled climate simulations that contributed to the fifth phase of the ~~Climate~~ Coupled Model Intercomparison Project (CMIP5). In order to better understand the sources of these model diversities, the model intercomparison project on the ~~climate~~ climatic response to volcanic forcing (VolMIP) has defined a coordinated set of idealized volcanic perturbation experiments to be carried out in alignment with the CMIP6 protocol. VolMIP provides a common stratospheric aerosol dataset for each experiment to ~~eliminate~~ minimize differences in the applied volcanic forcing~~,~~. ~~and~~ It defines a set of initial conditions to ~~determine~~ assess how internal climate variability contributes to determining the response. VolMIP will assess to what extent volcanically-forced responses of the coupled ocean-atmosphere system are robustly simulated by state-of-the-art coupled climate models and identify the causes that limit robust simulated behavior, especially differences in the treatment of physical processes. This paper illustrates the design of the idealized volcanic perturbation experiments in the VolMIP protocol and describes the common aerosol forcing input datasets to be used.

2.1.   Introduction

Volcanic eruptions that eject substantial amounts of sulfur dioxide (SO_2) into the atmosphere have been one of the dominant natural causes of externally-forced annual to multidecadal climate variability during the last millennium (Hegerl et al., 2003; Myhre et al., 2013; Schurer et al., 2014). Significant advances have been made in recent years in our understanding of the core microphysical, physical, and chemical processes that determine the radiative forcing resulting from volcanic sulfur emissions and the consequent dynamical responses of the coupled ocean-atmosphere system (e.g., Timmreck, 2012). However, the fifth phase of the Climate Coupled Model Intercomparison Project (CMIP5) has demonstrated that climate models' capability to accurately and robustly simulate observed and reconstructed volcanically-forced climate behavior remains poor.

For instance, the largest uncertainties in radiative forcings (Driscoll et al., 2012) and in lower troposphere temperature trends (Santer et al., 2014) from historical CMIP5 simulations occur during periods of strong volcanic activity. CMIP5 models tend to overestimate the observed post-eruption global surface cooling and subsequent warming during the decay phase (Marotzke and Forster, 2015), although the discrepancy decreases if accounting for the post-eruption phase of the El Niño-Southern Oscillation (ENSO) (Lehner et al., 2016). Driscoll et al. (2012) and Charlton-Perez et al. (2013) foundThere is also large uncertainty across CMIP5 models concerning the short-termaverage dynamical atmospheric response during the first two post-eruption winters, especially the post-eruption strengthening of the Northern Hemisphere's winter polar vortex and its tropospheric signature (Driscoll et al., 2012; Charlton-Perez et al., 2013).

Climate models reproduce the main features of observed precipitation response to volcanic forcing, but significantly underestimate the magnitude of the regional responses in particular seasons (Iles and Hegerl, 2014).

Volcanic events during the instrumental period are, however, few and of limited magnitude, and their associated dynamical climate response is very noisy (e.g., Hegerl et al., 2011). Furthermore, there is inter-model disagreement about post-eruption oceanic evolutions, particularly concerning the response of the thermohaline circulation (e.g., Mignot et al., 2011; Hofer et al., 2011; Zanchettin et al., 2012; Ding et al., 2014). Substantial uncertainties still exist about decadal-scale climate variability during periods of strong volcanic forcing and in the role of the ocean in determining the surface air temperature response to volcanic eruptions.

Climate-proxy based reconstructions covering the last millennium are a major source of information about how the climate system responds to volcanic forcing (e.g., D'Arrigo et al., 2009; Corona et al. 2010; Gennaretti et al., 2014). Recent studies have explored new reconstruction methods applied on high-quality proxy records to produce more rigorous regional climate reconstructions and allow for an improved evaluation of climate models (e.g., Ortega et al., 2015; Luterbacher et al., 2016). ~~Discrepancies~~ However, discrepancies ~~also~~ exist between simulated and reconstructed climate variability during periods of the last millennium characterized by strong volcanic activity, concerning, for instance, the magnitude of post-eruption surface cooling (e.g., Mann et al., 2012, 2013; Anchukaitis et al., 2012; Stoffel et al., 2015; Luterbacher et al., 2016) and the interdecadal response to volcanic clusters of tropical precipitation (Winter et al., 2015) and large-scale modes of atmospheric variability (Zanchettin et al., 2015a).

The lack of robust behavior in climate simulations likely depends on various reasons. First, inter-model spread can be caused by differences in the models' characteristics, such as the spatial resolution, and the imposed volcanic forcing. The latter stems from choices about the employed dataset describing climatically relevant parameters related to the eruption source – especially the mass of emitted SO_2 – and about the stratospheric aerosol properties such as spatial extent of the cloud, optical depth, and aerosol size distribution (e.g., Timmreck, 2012). As instrumental observations of volcanic eruptions are limited, with the 1991 eruption of Mt Pinatubo being the best documented event (e.g., Minnis et al., 1993), ~~For eruptions that occurred prior to the instrumental period,~~ forcing characteristics must often be reconstructed based on indirect evidence such as ice-core measurements (e.g., Devine et al., 1984; Sigl et al., 2014). These reconstructions rely on a simplified hypothesis of scaling between ice-core sulfate concentrations and aerosol optical depths based on the relation observed for the 1991 eruption of Mt Pinatubo (Crowley and Unterman, 2013). The consideration of aerosol microphysical processes also produces substantial inconsistencies between available volcanological datasets (Timmreck, 2012). Furthermore, even when the same volcanic aerosol forcing is ~~prescribed~~ used to force different models, these may generate different radiative forcing due to the model-specific implementation of the volcanic forcing (Timmreck, 2012; Toohey et al., 2014).

The simulated climatic response to individual volcanic eruptions also critically depends on the background climate, including the mean climate state (Berdahl and Robock, 2013; Muthers et al., 2014, 2015), the ongoing internal climate variability (e.g., Thomas et al., 2009; Pausata et al., 2015a; Swingedouw et al., 2015; Zanchettin et al., 2013a, ; Lehner et al., 2016) and the presence of additional forcing factors such as variations in solar irradiance (Zanchettin et al., 2013a; Anet et al., 2014). As a result, different models, forcing inputs, and internal climate variability similarly contribute to simulation-

ensemble spread. This can be seen, for instance, by comparing hemispheric temperature evolutions from a multi-model ensemble and a single-model ensemble of last-millennium simulations during the early 19th century (Figure 1), a period characterized by the close succession of two strong tropical volcanic eruptions in 1809 and 1815.

The individual impact of these sources of uncertainty can be ~~hardly~~ hard to be distinguished in transient climate simulations. Therefore, the Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP) – an endorsed contribution to CMIP6 (Eyring et al., ~~2015~~2016, this issue) – provides the basis for a coordinated multi-model assessment of climate models' performances under strong volcanic forcing conditions. It defines a set of idealized volcanic-perturbation experiments where volcanic forcing – defined in terms of volcanic aerosol optical properties – is well constrained across participating models. VolMIP will therefore assess to what extent responses of the coupled ocean-atmosphere system to the same applied strong volcanic forcing are robustly simulated across state-of-the-art coupled climate models and identify the causes that limit robust simulated behavior, especially differences in their treatment of physical processes. Ensemble simulations sampling appropriate initial conditions and using the same volcanic forcing dataset accounting for aerosol microphysical processes can help ~~increase~~ assess the signal-to-noise ratio and reduce uncertainties regarding the magnitude of post-eruption surface cooling (Stoffel et al., 2015). Careful sampling of initial climate conditions and the ~~possibility~~ opportunity to consider volcanic eruptions of different strengths will allow VolMIP to better assess the relative role of internally generated and externally forced climate variability during periods of strong volcanic activity. VolMIP also contributes toward more reliable climate models by helping to identify the origins and consequences of systematic model biases affecting the dynamical climate response to volcanic forcing. As a consequence, VolMIP will improve our confidence in the attribution and dynamical interpretation of reconstructed post-eruption regional features and provide insights into regional climate predictability during periods of strong volcanic forcing.

VolMIP experiments will provide context to CMIP6-DECK AMIP and *historical* simulations (Eyring et al., ~~2015~~2016), the decadal climate prediction experiments of the Decadal Climate Prediction Panel (DCPP) (Boer et al., 2016) and the *past1000* simulations of the Paleoclimate MIP (PMIP) (Kageyama et al., 2016) where volcanic forcing is among the dominant sources of climate variability and inter-model spread. The importance of VolMIP is enhanced as the specification of the volcanic stratospheric aerosol for the CMIP6 *~~Historical~~ historical* experiment is based on "time-dependent observations" (Eyring et al., ~~2015~~2016), and some modeling groups may therefore perform the simulations using online calculation of volcanic radiative forcing based on SO_2 emissions.

160   This paper is organized as follows. First, in Section 2 we provide a general description of the individual experiments included in the VolMIP protocol. Then, Section 3 provides details about the volcanic forcing for each experiment, including implementation and the forcing input data to be employed, for which this paper also serves as a reference. We discuss the limitations of VolMIP and potential follow-up research in Section 4, before summarizing the most relevant aspects of this initiative in Section 5.

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3.2.   Experiments: rationale and general aspects

The VolMIP protocol consists of a set of idealized volcanic perturbation experiments based on historical eruptions. In this context, "idealized" means that the volcanic forcing is derived from radiation or source parameters of documented eruptions but the experiments generally do not include information about
170   the actual climate conditions when these events occurred. The experiments are designed as ensemble simulations, with sets of initial climate states sampled from the CMIP6-DECK ~~PiControl~~ piControl (i.e., preindustrial control) simulation describing unperturbed preindustrial climate conditions (Eyring et al., ~~2015~~2016), unless specified otherwise.

VolMIP experiments are designed based on a ~~twofold~~ multifold strategy. A first set of experiments
175   (~~VolcShort~~volc-pinatubo) focuses on the systematical assessment of uncertainty and inter-model differences in the seasonal-to-interannual climatic response to an idealized 1991 Pinatubo-like eruption, chosen as representative of the largest magnitude of volcanic events that occurred during the observational period. ~~VolcShort~~volc-pinatubo experiments highlight the role of internal interannual variability for volcanic events characterized by a rather low signal-to-noise ratio in the response of global-average surface
180   temperature. The short-term dynamical response is sensitive to the particular structure of the applied forcing (Toohey et al., 2014). Using carefully constructed forcing fields and sufficiently large simulation ensembles, VolMIP allows us to investigate the inter-model robustness of the short-term dynamical response to volcanic forcing, and elucidate the mechanisms through which volcanic forcing leads to changes in atmospheric dynamics. The proposed set of ~~VolcShort~~volc-pinatubo experiments includes
185   sensitivity experiments designed to determine the different contributions to such uncertainty that are due to the direct radiative (i.e., surface cooling) and to the dynamical (i.e., stratospheric warming) response.

A second set of experiments (~~VolcLong~~volc-long) is designed to systematically investigate inter-model differences in the long-term (up to the decadal time scale) dynamical climate response to volcanic eruptions that are characterized by a high signal-to-noise ratio in the response of global-average surface
190   temperature. A third set of experiments (volc-cluster) is designed to investigate the climatic response to a close succession of strong volcanic eruptions. The main goal of ~~VolcLong~~ volc-long and volc-cluster

experiments is to assess how volcanic perturbation signals propagate within the simulated climates, e.g., into the ~~deep~~ subsurface ocean, the associated determinant processes and their representation across models.

The VolMIP protocol defines criteria for sampling desired initial conditions whenever this is necessary to ensure comparability across different climate models. Desired initial conditions and hence ensemble size are determined based on the state of dominant modes of climate variability, which are specifically defined for each experiment. The ensemble size must be sufficiently large to account for the range of climate variability concomitantly depicted by such modes. As a general rule, three initialization states are determined for each given mode based on an index describing its temporal evolution. Specifically, the predetermined ranges for the sampling are: the lower tercile (i.e., the range of values between the minimum and the 33rd percentile) for the negative/cold state, the mid-tercile (i.e., the range of values between the 33rd and 66th percentiles) for the neutral state, and the upper tercile (i.e., the range of values between the 66th percentile and the maximum) for the positive/warm state. If n modes are sampled concomitantly, this yields an ensemble with 3^n members. For instance, in the case of two modes, an ensemble of at least nine simulations is requested. The choice of the climate modes to be considered for initialization essentially depends on the timescales of interest: seasonal to interannual modes for ~~VolcShort~~ *volc-pinatubo* experiments, and interannual and decadal modes for ~~VolcLong~~ *volc-long* experiments (selection of initialization states are less important for *volc-cluster* experiments). The sampled years refer to the second integration year of the VolMIP experiment, when the volcanic forcing is generally strongest. Therefore, if, for instance, year Y of the control integration matches the desired conditions for the sampling, then the corresponding VolMIP simulation should start with restart data from year Y-1 of the control, for the day of the year specified for the experiment. Restart files from ~~PiControl~~ *piControl* must be accordingly selected and documented in the metadata of each simulation. If no restart data ~~is~~ are available for the day of the year when the experiment starts, the control simulation must be re-run based on the first (backward in time) available restart file until the start date of the VolMIP experiment. All experiments except the decadal prediction experiment (section 2.1.4) and the millennium cluster experiment (section 2.4.4) maintain the same constant boundary forcing as the ~~PiControl~~ *piControl* integration, except for the volcanic forcing.

VolMIP has defined a new group of variables (Volcanic Instantaneous Radiative Forcing, or VIRF, see Table 4), which includes additional variables that were not in the CMIP5 data request and are necessary to generate the volcanic forcing for the *volc-pinatubo-surf*/*strat* experiments (see section 3.3). In particular, all VIRF diagnostics are instantaneous 6h data, so some interpolation in time may be required.

Some experiments are designed in cooperation with the Dynamics and Variability of the Stratosphere–Troposphere System MIP (DynVarMIP) (Gerber and Manzini, 2016, this issue). DynVarMIP defines requirements for diagnosing the atmospheric circulation and variability in the context of CMIP6. DynVar diagnostics include a refinement of the vertical resolution of standard variables archived as daily and monthly means, zonal mean diagnostics focused on the transport and exchange of momentum within the atmosphere and between the atmosphere and surface, and zonal mean diagnostics describing the interaction between radiation, moisture and the circulation. For a detailed description of these diagnostics and the output format requested by DynVarMIP see Gerber and Manzini (2016).

The data request is at: https://www.earthsystemcog.org/projects/wip/CMIP6DataRequest.

An overview of the experimental design of the proposed experiments is provided in Tables 1, 2, and 3, where they are summarized according to their prioritization: Tier 1 experiments are mandatory; Tier 2 and Tier 3 experiments have decreasing priority. The experiments are individually described in the following sub-sections. Figure 2 sketches how the different experiments included in CMIP6 tackle different aspects of the climate response to volcanic forcing. The codes for the naming conventions of the experiments are in Tables 1-3.

2.1   VolcShortvolc-pinatubo

2.1.1 VolcShortvolc-pinatubo-Eq-full

Tier 1 experiment based on a large ensemble of short-term "Pinatubo" climate simulations aimed at accurately estimating simulated responses to volcanic forcing that may be comparable to the amplitude of internal interannual climate variability (Table 1). Initialization is based on equally-distributed predefined states of ENSO (cold/neutral/warm states) and of the North Atlantic Oscillation (NAO, negative/neutral/positive states). Sampling of an eastern phase of the Quasi Quasi-Biennial Oscillation (QBO), as observed after the 1991 Pinatubo eruption, is preferred for those models that spontaneously generate such mode of stratospheric variability. VIRF diagnostics must be calculated for this experiment for the whole integration and for all ensemble members, as these are required for the *volc-pinatubo-strat/surf* experiments (see section 2.1.2). For models participating in DynVarMIP, DynVar diagnostics shall be calculated for all simulations and for the whole integration period. A minimum length of integration of three years is requested.

255   The recommended ENSO index is the Northern Hemisphere (NH) winter (DJF, with January as reference for the year) Nino3.4 sea-surface temperature index, defined as the spatially averaged, winter-average sea-surface temperature over the region bounded by 120°W-170°W and 5°S- 5°N. The recommended NAO index is the, calculated based on the latitude-longitude 2-box method by Stephenson et al. (2006) applied on Z500 data, *i.e.*, as the pressure difference between spatial averages over [20-55ºN;
260   90ºW-60ºE] and [55-90ºN; 90ºW-60ºE].principal component associated to the first empirical orthogonal function of winter-average geopotential heights at 500 hPa over the North Atlantic-European region bounded by 90°W- 40°E and 20- 70°N.

2.1.2 VolcShortvolc-pinatubo-Eq-surf and VolcShortvolc-pinatubo-Eq-strat

265   Tier 1 simulations aimed at investigating the mechanism(s) connecting volcanic forcing and short-term climate anomalies (Table 1). These experiments aim to disentangle the dynamical responses to the two primary thermodynamic consequences of aerosol forcing: stratospheric heating (*VolcShortvolc-pinatubo-Eq*-strat) and surface cooling (*VolcShortvolc-pinatubo-Eq*-surf). Both experiments are built upon *VolcShortvolc-pinatubo-Eq*-full- and use the VIRF designed in cooperation with the Dynamics and
270   Variability of the Stratosphere–Troposphere System (DynVar) project. Therefore, DynVar diagnostics calculated from the different realizations of this experiment must be calculated for *VolcShort-Eq-full/surf/strat*. Integration length, ensemble size and restart files are the same as for *volc-pinatubo-full*. For models participating in DynVarMIP, DynVar diagnostics shall be calculated for both experiments, for all simulations and for the whole integration period.

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2.1.3 VolcShortvolc-pinatubo-Eq-slab

Non-mandatory slab-ocean experiment, which is proposed to clarify the role of coupled atmosphere-ocean processes (most prominently linked to ENSO) in determining the dynamical response (Table 3). A reference simulation (*control-slab*) shall be set up using the mixed layer depth climatology of the coupled
280   model, which should include a minimum of 20-year spin-up followed by a 10-year control integration. A minimum length of integration of three years and at least 25 ensemble members are requested for *volc-pinatubo-slab*. VIRF diagnostics shall be calculated for all simulations and for the whole integration period. For models participating in DynVarMIP, DynVar diagnostics shall be calculated for all simulations and for the whole integration period.

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2.1.4 VolcShortvolc-pinatubo-Eq-ini

Non-mandatory experiment to address the impact of volcanic forcing on seasonal and decadal climate predictability (Table 3). The experiment will address the climatic implication of a future Pinatubo-like eruption. The experiment is designed in cooperation with ~~the decadal climate prediction panel DCPP~~(DCPP), and is the same as DCPP experiment C3.4 (Boer et al., 2016). It complies with the VolMIP protocol about the forcing and its implementation. The experiment is initialized on 1st November 2015, or any other date in November or December for which initialized hindcasts are available (depending on the modeling center). Ten decadal simulations are requested for this experiment. Calculation of DynVar diagnostics is recommended for the first three years of integration for at least one realization, but preferably for all of them. DCPP diagnostics must be calculated for all realizations and for the whole integration period.

2.2 ~~VolcLong~~volc-long

2.2.1 ~~VolcLong~~volc-long-~~Single-Eq~~eq

Tier 1 experiment designed to understand the long-term response to a single volcanic eruption with radiative forcing comparable to that estimated for the 1815 eruption of Mt Tambora, Indonesia (e.g., Oppenheimer, 2003) (Table 1). A recent review paper (Raible et al., 2016) describes the 1815 Tambora eruption as a test case for high impacts on the Earth system. Initialization spans cold/neutral/warm states of ENSO and weak/neutral/strong states of the Atlantic Meridional Overturning Circulation (AMOC), resulting in a 9-member ensemble. A minimum length of integration of 20 years is requested to cover the typical duration of the simulated initial post-eruption AMOC anomaly (e.g., Zanchettin et al., 2012). Longer integration times (50 years) are recommended to capture the later AMOC evolution (Swingedouw et al., 2015; Pausata et al., 2015b) and related climate anomalies. The recommended AMOC index is defined as the annual-average time series of the maximum value of the zonally-integrated meridional streamfunction in the North Atlantic Ocean in the latitude band 20°N-60°N. VIRF diagnostics shall be calculated for the first three years of integration and for just one realization. For models participating in DynVarMIP, DynVar diagnostics shall be calculated for the first three years of integration and for all realizations.

2.2.2 ~~VolcLong~~volc-long-~~Single-HL~~hlN and volc-long-hlS

Non-mandatory experiment~~s~~ that ~~applies~~ apply the same approach as *~~VolcLong~~volc-long-* *~~Single-Eq~~eq* and extends the investigation to the case of ~~an~~ idealized strong high-latitude volcanic eruption~~s~~ (Table~~s~~ 2 and 3). *~~This~~ Volc-long-hlN* and *volc-long-hlS* experiment ~~is~~ are designed as a ~~Northern Hemisphere~~ NH and

a Southern Hemisphere (SH) extra-tropical eruption, respectively, both with SO$_2$ injection equal to half the total amount injected for the ~~VolcLong~~*volc-long-*~~Single-Eq~~*eq* experiment. This choice was based on the assumption that for an equatorial eruption the injected mass is roughly evenly distributed between the two hemispheres, increasing comparability between ~~VolcLong~~*volc-long-*~~Single-Eq~~*eq* and ~~VolcLong~~*volc-long-*~~Single-HL~~*hlN/hlS* as both should yield similar forcing over the ~~Northern Hemisphere~~eruption's hemisphere (but see Section 3.3). The initialization procedure and required integration length are the same as for ~~VolcLong~~*volc-long-*~~Single-Eq~~*eq*. Both experiments are expected to contribute to ~~outstanding~~ open questions about the magnitude of the climatic impact of high-latitude eruptions, especially concerning the inter-hemispheric response. VIRF diagnostics shall be calculated for the first three years of integration and for just one realization. For models participating in DynVarMIP, DynVar diagnostics shall be calculated for the first three years of integration, for all realizations.

The eruption strength is about 4 times stronger than that estimated for the Mt Katmai/Novarupta eruption in 1912 (Oman et al., 2005). The eruption used in ~~VolcLong~~*volc-long-*~~Single-HL~~*hlN* should not be considered directly comparable to the 1783-84 Laki eruption – one of the strongest high-latitude eruptions that occurred in historical times – since the experiment does not try to reproduce the very specific characteristics of Laki, including multistage releases of large SO$_2$ mass paced at short temporal intervals (e.g., Thordarson and Self, 2003; ~~Oman et al., 2006;~~ Schmidt et al., 2010; Pausata et al., 2015b).

volc-long-hlN (Tier 2) has a higher priority than *volc-long-hlS* (Tier 3).

2.3 volc-cluster

~~2.2.3~~ 2.3.1 ~~VolcLong~~*volc-*~~Cluster~~*cluster-*~~Ctrl~~*ctrl*

~~A~~ This non-mandatory ~~"volcanic cluster"~~ experiment ~~to~~ investigates the climatic response to a close succession of strong volcanic eruptions, so-called "volcanic cluster" (Table 2). The experiment is motivated by the large uncertainties in the multidecadal and longer-term climate repercussions of multiple eruptions, including volcanic double events (e.g., Toohey et al., 2016b) and prolonged periods of strong volcanic activity (e.g., Miller et al., 2012; Schleussner and Feulner, 2013; Zanchettin et al., 2013a; Moreno-Chamarro et al., 2016). The proposed experiment is designed to realistically reproduce the volcanic forcing generated by the early 19th century volcanic cluster, which included the 1809 eruption of unknown location and the 1815 Tambora and 1835 Cosigüina eruptions. The early 19th century is the coldest period in the past 500 years (Cole-Dai et al., 2009) and therefore of special interest for interdecadal climate variability (Zanchettin et al., 2015a; Winter et al., 2015). In addition, long-term repercussions may be relevant for the initialization of CMIP6 *historical* simulations.

At least an ensemble of three 50-year long simulations is requested. Due to the long-term focus of the experiment, selection of initialization states is of second-order importance. Nonetheless, it is recommended to sample initial states pacing them at a minimum 50-year intervals. Initial states ~~should~~ shall be sampled from the *~~PiControl~~ piControl* for consistency with the *~~VolcLong~~ volc-long-Single* experiments.

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2.~~2~~3.~~4~~2   *~~VolcLong~~ volc--~~Cluster~~ cluster-~~Mill~~ mill*

A parallel experiment to *~~VolcLong~~ volc-~~Cluster~~ cluster-~~Ctrl~~ ctrl* using restart files from PMIP-*past1000* instead of from *~~PiControl~~ piControl* (see Table ~~2~~3). Starting from a climate state that experienced

360 realistic past ~~volcanic~~ natural forcing, this experiment allows to explore the sensitivity of the ocean response to the initial state ~~, which has been highlighted to be significant particularly for preindustrial controls that do not include background volcanic aerosols~~ [e.g., Gregory, 2010; Zanchettin et al., 2013a]. *~~VolcLong~~ Volc--~~Cluster~~ cluster-- ~~Mill~~ mill* is more suitable for a direct comparison with early instrumental data and paleoclimate reconstructions, and allows one to explore the role of ocean initial conditions on sea ice response, ocean response and surface temperature response by comparison with *~~VolcLong~~ volc--

365 ~~Cluster~~ cluster-~~Ctrl~~ ctrl*.

This non-mandatory experiment requires that at least one PMIP-*past1000* realization has been performed. One simulation is requested, but an ensemble of three simulations is recommended. The proper experiment starts in year 1809 as *~~VolcLong~~ volc-~~Cluster~~ cluster-~~Ctrl~~ ctrl*. However, the simulation must be initialized in January 1st 1790 to avoid interferences due to the decadal drop of solar activity associated

370 with the Dalton Minimum. Hence, the experiment proper lasts 50 -years as *~~VolcLong~~ volc-~~Cluster~~ cluster-~~Ctrl~~ ctrl*, but a total of 69 years for each ensemble member are actually requested. Different members of the *~~VolcLong~~ volc-~~Cluster~~ cluster-~~Mill~~ mill* ensemble can be obtained by either using restart files from different ensemble members of PMIP-*past1000*, if available, or through introducing small perturbations to the same restart file. All external forcings, except volcanic forcing, are set as a perpetual repetition of the year 1790

375 for the full duration of the experiment.

2.3.3 volc-cluster-21C

A parallel experiment to *volc-cluster-ctrl* using restart files from the end of the *historical* simulation instead of from *piControl*, and boundary conditions from the 21st century SSP2-4.5 scenario experiment of

380 ScenarioMIP (O'Neill et al., 2016), except for volcanic forcing during the volcanic cluster period (see Table 3). The experiment is designed to explore the climate response to volcanic eruptions under warmer background conditions compared to preindustrial climates and to investigate the potential uncertainties in

future climate projections due to volcanic activity. The experiment uses the same volcanic forcing used in *volc-cluster-ctrl/-mill*, with the first eruption of the cluster (i.e., the 1809 eruption) placed on year 2015. Simulations shall be run to the end of the 21st century for full comparability with the corresponding scenario simulation. At the end of the volcanic cluster, volcanic forcing input shall be kept constant at the same constant value prescribed for the *piControl* simulation for consistency with the SSP2-4.5 scenario experiment.

We encourage modeling groups that are interested in both VolMIP and ScenarioMIP to also coordinate experiments where the same volcanic cluster is placed later on in the scenario integration (e.g., with the first eruption in year 2050).

4.3. Forcing

3.1 Implementation: general aspects

VolMIP identifies a volcanic forcing dataset for each experiment included in the protocol. The forcing parameters can are either be provided in terms of aerosol optical properties and distributions in time and space, as for the case when available data were identified as consensus reference, or can be calculated based on the tool and guidelines described in the protocol. The latter is the case for the *volc-long* and *volc-cluster* experiments that using use forcing input data specifically created generated for VolMIP.

In addition, the implementation of the forcing (e.g., spectral interpolation) is constrained to ensure that the imposed radiative forcing is consistent across the participating models. Surface albedo changes due to tephra deposition and indirect cloud radiative effects are neglected in all the experiments.

VolMIP has defined a new group of variables (Volcanic Instantaneous Radiative Forcing, or VIRF, see Table 4), which includes additional variables that were not in the original set provided by CMIP and are necessary to generate the volcanic forcing in some experiments. In particular, all VIRF diagnostics used for *VolcShort-Eq-full/surf/strat* are instantaneous 6h data, so some interpolation in time may be required. The data request is at: https://www.earthsystemcog.org/projects/wip/CMIP6DataRequest.

3.2 VolcShortvolc-pinatubo

VolcShortvolc-pinatubo-Eq-full will use the CMIP6 stratospheric aerosol data set (Thomason et al., 2016) for the volcanic forcing of the 1991 Pinatubo eruption, which is set upcompiled for the CMIP6 *historical* simulationexperiment. Specifically, the reference stratospheric aerosol forcing dataset for the CMIP6 *historical* experiment includes model-specific data for aerosol extinction, single scattering albedo and asymmetry factor, all as a function of latitude, height and the spectral bands of the model (see

415 ftp://iacftp.ethz.ch/pub_read/luo/CMIP6 and https://pcmdi.llnl.gov/projects/input4mips). We recommend to follow the same protocol for implementation of the forcing in the *historical* experiment, and therefore recommend to replace forcing input data below the model tropopause by the climatological or other values of tropospheric aerosol used by the models.

420 *VolcShort*volc-pinatubo Eq-surf and *VolcShort*volc-pinatubo Eq-strat will not account for forcing based on imposed aerosol optical properties as is the usual approach in VolMIP. Instead, they will use output from the corresponding *VolcShort*volc-pinatubo Eq-full experiment. Specifically, *VolcShort*volc-pinatubo Eq-surf will specify a prescribed perturbation to the shortwave flux to mimic the attenuation of solar radiation by volcanic aerosols, and therefore the cooling of the surface. The goal is to isolate the

425 impact of shortwave reflection from the impact of aerosol heating in the stratosphere. The changes must be prescribed at the top of atmosphere (TOA) under clear sky conditions (variable swtoafluxaerocs of VIRF). Similarly, *VolcShort*volc-pinatubo Eq-strat will specify a prescribed perturbation to the total (long-wave plus short-wave) radiative heating rates, seeking to mimic the local impact of volcanic aerosol (variables zmlwaero and zmswaero of VIRF). This must be implemented by adding an additional temperature

430 tendency. VolMIP does not enforce the same perturbation across all models in *VolcShort*volc-pinatubo Eq-surf and *VolcShort*volc-pinatubo Eq-strat, as for both mechanistic experiments priority is given to the consistency with the corresponding *VolcShort*volc-pinatubo Eq-full experiment.

3.3 ~~VolcLong~~volc-long and volc-cluster

435 These experiments are based on pre-industrial volcanic events for which no direct observation is available. VolMIP recognizes the need to overcome the uncertainties and the limitations of currently available volcanic forcing datasets for the pre-industrial period (see Figure 1a), which poses the need to identify a single, consensus forcing dataset for each one of the *VolcLong*volc-long and *volc-cluster* experiments. Therefore, for the *VolcLong*volc-long Single Eq-eq experiment, coordinated climate

440 simulations of the 1815 eruption of Mt. Tambora (see Table 5) were performed with different climate models including modules for stratospheric chemistry and aerosol microphysics and chemistry (chemistry climate models). The imposed SO_2 injection of 60 Tg at the equator used in these simulations is deduced from reanalysis of bipolar ice-core data used in recent volcanic forcing reconstructions (Stoffel et al., 2015; Gao et al., 2008) and calculations based on geological data (Self et al., 2004). The easterly QBO phase and

445 altitude of injection are based on satellite and lidar observations of QBO, SO_2, and sulfate after the Pinatubo eruption (McCormick and Veiga, 1992; Read et al., 1993; Herzog and Graf, 2010). The results

show large uncertainties in the estimate of volcanic forcing parameters derived from different state-of-the-art chemistry climate models perturbed with the same sulfur injections (Figure 3a). How these results are traced back to the different treatment of aerosol microphysics and climate physical processes in the

450 different models is the subject of a dedicated study. Here, we only conclude that existing uncertainties prevent the identification, within the time constraints of the CMIP6 schedule, of a single consensus forcing estimate for a given volcanic eruption based on a multi-model ensemble with current chemistry climate models.

Therefore, VolMIP proposes for the ~~VolcLong~~*volc-long* and *volc-cluster* experiments forcing data

455 sets constructed with the Easy Volcanic Aerosol (EVA) module (Toohey et al., 2016a). EVA provides an analytic representation of volcanic stratospheric aerosol forcing, prescribing the aerosol's radiative properties and primary modes of spatial and temporal variability. It creates volcanic forcing from a given eruption sulfur injection and latitude with an idealized spatial and temporal structure, constructed so as to produce good agreement with observations of the aerosol evolution following the 1991 Pinatubo eruption.

460 Scaling to larger eruption magnitudes is performed in a manner ~~consistent with~~similar to the forcing reconstruction of Crowley and Unterman (2013). EVA is also used to construct the volcanic forcing dataset used for the PMIP-*past1000* experiment~~the last-millennium experiment of the Paleoclimate MIP (PMIP-past1000)~~ (Kageyama et al., 2016). This augments the comparability between PMIP and VolMIP results concerning those eruptions that are featured by both MIPs. The EVA module outputs data resolved for

465 given latitudes, heights and wavelength bands. It therefore is an improvement compared to previously available volcanic forcing datasets for the pre-observational period. The forcing sets produced with EVA have the same format as the CMIP6 standard forcing files, i.e., aerosol extinction, single scattering albedo and asymmetry factor, all as a function of latitude, height and the spectral bands of the model. The aerosol forcing produced by EVA decays to zero around the tropopause. Therefore, differently from the forcing

470 used in the *volc-pinatubo* experiments, no clipping of the forcing is necessary at the tropopause for experiments using EVA forcing. Toohey et al. (2016a) provide technical details about EVA.

VolMIP requests that all modeling groups use EVA to generate the specific forcing input dataset for their model, using the same sulfur emission estimates to be specified for use in the PMIP-*past1000* experiment. Figure 3 provides an overview of the EVA forcing for an estimated SO_2 injection for the 1815

475 Tambora eruption of 56.2 Tg to be used in ~~VolcLong~~*volc-long*-~~Single~~Single-~~Eq~~*eq*., ~~VolcLong~~*volc*-~~Cluster~~*cluster*-~~Ctrl~~*ctrl* and ~~VolcLong~~*volc*--~~Cluster~~*cluster*-~~Mill~~*mill* include all eruptions represented in the PMIP-past1000 experiment for the overlapping period.

The reference SO_2 emission for the ~~*VolcLong*~~*volc-long*-~~*Single HL*~~*hlN/hlS* experiment~~s~~ is equal to one-half the Tambora value. The evolution of aerosol optical depth (AOD) by EVA for a NH high-latitude injection of 28.1 Tg of SO_2 is illustrated in Figure 4. The N~~orthern Hemisphere~~ average AOD for the ~~*VolcLong*~~*volc-long*-~~*Single HL*~~*hlN* and ~~*VolcLong*~~*volc-long*-~~*Single Eq*~~*eq* experiments are quite similar in magnitude and temporal structure. Differences occur mainly due ~~mainly~~ to the seasonal dependence of the tropical-to-extratropical transport parameterized in EVA. The reduced stratospheric transport into the Northern Hemisphere in the summer months after the April eruptions leads to a time lag in the peak N~~orthern Hemisphere~~ mean AOD for ~~*VolcLong*~~*volc-long*-~~*Single Eq*~~*eq* compared to ~~*VolcLong*~~*volc-long*-~~*Single HL*~~*hlN*. It also leads to generally somewhat less aerosol transported to the Northern compared to the Southern Hemisphere for ~~*VolcLong*~~*volc-long*-~~*Single Eq*~~*eq*, which explains the lower peak AOD for this experiment than for ~~*VolcLong*~~*volc-long*-~~*Single HL*~~*hlN*. Similar considerations stand for *volc-long-hlS*.

Formattato: Tipo di carattere: Corsivo

4. Follow-up research and synergies with other modeling activities

We expect the VolMIP experiments not only to generate broad interest within the climate modeling community but also to stimulate research across many different branches of climate sciences.

Cooperation between VolMIP and other ongoing climate modeling initiatives and MIPs increases VolMIP's relevance for climate model evaluation. In particular, synergies between VolMIP and the WCRP/SPARC Stratospheric Sulfur and its Role in Climate (SSiRC) coordinated multi-model initiative (Timmreck et al., 2016b) as well as between VolMIP and the Radiative Forcing MIP (RFMIP) (Pincus et al., 2016, this issue) will help to building a scientific basis to distinguish between differences in volcanic radiative forcing data and differences in climate model response to volcanic forcing. VolMIP provides a well-defined set of forcing parameters in terms of aerosol optical properties and is thus complementary to SSiRC, which uses global aerosol models to investigate radiative forcing uncertainties associated with given SO_2 emissions. Precise quantification of the forcing to which models are subject is central for both RFMIP and VolMIP: RFMIP has planned transient volcanic and solar forcing experiments with fixed preindustrial sea-surface temperature to diagnose volcanic and solar effective forcing, instantaneous forcing and adjustments, which is complementary to the ~~*Short*~~*pinatubo* experiments of VolMIP.

VolMIP has synergies with the Geoengineering Model Intercomparison Project (GeoMIP; Kravitz et al., 2015), which includes proposals to simulate a long-duration stratospheric aerosol cloud to counteract global warming. Furthermore, PMIP and VolMIP provide complementary perspectives on one of the most important and less understood factors affecting climate variability during the last millennium. Specifically, VolMIP systematically assesses uncertainties in the climatic response to volcanic forcing associated with

different initial conditions and structural model differences. In contrast, the PMIP *past1000* experiment describes the climatic response to volcanic forcing in long transient simulations where related uncertainties are due to the reconstruction of past volcanic forcing, the implementation of volcanic forcing within the models, initial conditions, the presence and strength of additional forcings, and structural model differences. The *past1000_volc_cluster* experiment of PMIP consists of an ensemble of full-forcing simulations covering the early 19th century whose design is aligned with VolMIP *volc-cluster* experiments (Jungclaus et al., 2016, this issue). This hierarchy of volcanic cluster experiments will allow to investigate the interactions between different natural forcing factors and the role of background climate conditions during one of coldest periods of the last millennium, when discrepancies exist between information from available climate simulations and reconstructions (e.g., Winter et al., 2015; Zanchettin et al., 2015a). Modeling groups who participate in both VolMIP and PMIP are encouraged to output the VIRF diagnostics for the following tropical eruptions simulated in the *past1000* experiment: 1257 Samalas, 1453 Kuwae, 1600 Huaynaputina, 1809 Unidentified, and 1815 Tambora. VIRF diagnostic~~s~~ ~~should~~ shall be calculated for a period of five years starting from the eruption year, and ~~would~~ will be useful for future studies to expand the investigation based on *~~VolcShort~~volc-pinatubo ~~-Eq~~-strat* and *~~VolcShort~~volc-pinatubo ~~-Eq~~-surf*.

VolMIP and the Detection and Attribution MIP (DAMIP) (Gillet et al., 2016) share the CMIP6 science theme of characterizing forcing. The experiments *histALL*, *histNAT*, *histVLC* and *histALL_~~aerocone~~ estAER2* of DAMIP include the 1991 Pinatubo eruption within transient climate situations and therefore provide context to the *~~VolcShort~~volc-pinatubo* set of VolMIP experiments. The experiment *volc-cluster-21C* is built on and complement to the SSP2-4.5 scenario experiment of ScenarioMIP.

VolMIP and DCPP are closely working together on the impact of volcanic eruptions on seasonal and decadal predictions, and have designed a common experiment (*~~VolcShort~~volc-pinatubo ~~-Eq~~-ini* and the DCPP experiment *C3.4~~2~~* are different labels for the same experiment). ~~The~~ DynVar ~~activity~~MIP puts a particular emphasis on the two-way coupling between the troposphere and the stratosphere, and it is therefore deeply involved in the design and analysis of the *~~VolcShort~~volc-pinatubo-full/-strat/-surf* ~~mechanistic~~ experiments.

We envisage follow-up research stimulated by VolMIP's links to the Grand Challenges of the World Climate Research Program (Brasseur and Carlson, 2015) on:

- "Clouds~~ and atmospheric~~, circulation and climate sensitivity~~,~~," in particular through improved characterization of volcanic forcing and improved understanding of how the hydrological cycle and the large-scale circulation respond to volcanic forcing. Volcanic sulfate aerosols can affect clouds

also by acting as cloud condensation nuclei (Graf et al., 1997; see also: Mather et al., 2004; Seifert et al., 2011; Schmidt et al., 2012; Meyer et al., 2015), thereby affecting regional precipitation (e.g., Zhao et al., 2012). Volcanic eruptions are among the natural aerosol sources producing the strongest simulated cloud albedo effect (Rap et al., 2013). Assessments of cloud responses to volcanic forcing in VolMIP must take into account that in all experiments only the radiative effects of volcanic aerosols are represented (see section 3). VolMIP further contributes to the initiative on leveraging the past record through planned experiments describing the climate response, in an idealized context, to historical eruptions that are not (or not sufficiently) covered by CMIP6-DECK, *historical* or other MIPs.in particular through improved characterization of volcanic forcing and improved understanding of how the hydrological cycle and the large-scale circulation respond to volcanic forcing. VolMIP further contributes to the initiative on leveraging the past record through planned experiments describing the climate response, in an idealized context, to historical eruptions that are not (or not sufficiently) covered by CMIP6-DECK, *historical* or other MIPs.

- "Climate extremes," in particular through a more systematical assessment of regional climate variability – and associated predictability and prediction – during periods of strong volcanic forcing at both intraseasonal-to-seasonal (e.g., post-eruption Northern Hemisphere's winter warming) and interannual-to-decadal (e.g., post-eruption delayed winter warming, Zanchettin et al., 2013b; Timmreck et al., 2016b2016a) time scales.

- "Water availability," in particular through the assessment of how strong volcanic eruptions affect the monsoon systems and the occurrence of extensive and prolonged droughts.

- "Rapid cryosphere changesMelting ice and global consequences," in particular concerning the onset of volcanically forced long-term feedbacks involving the cryosphere which is suggested by recent studies (e.g., Miller et al., 2012, Berdahl and Robock, 2013; Zanchettin et al., 2014).

Ocean heating and circulation, annual to decadal timescales, and short-lived climate forcers were identified among those areas where the WCRP's grand challenges seem most in need of broadened or expanded research (Brasseur and Carlson, 2015). VolMIP is expected to advance knowledge in all such areas.

VolMIP is designed based on a limited number of idealized volcanic forcing experiments. We recognize that an eruption's characteristics are a major source of uncertainty for its climatic impacts. We encourage modeling groups interested in performing sensitivity experiments based on the experiments proposed here and concerning, e.g., the magnitude and the season of the eruption, to use VolMIP as a

platform for coordinating such efforts within a multi-model framework. The flexibility of the EVA module is, to this regard, a valuable advantage.

575 Follow-up research must take ~~also~~ into account ~~the following considerations.~~

~~T~~that ~~t~~he design of the simulations reflects necessary constraints on the overall resources required to perform the whole set of mandatory experiments. This implies limitations such as the possibly insufficient representation of the whole range of variability of climate modes not explicitly accounted in the design. This includes, for instance, the S~~outhern~~ Hemispheric annular mode (e.g., Karpechko et al., 2010;

580 Zanchettin et al., 2014) and modes of internal stratospheric variability like the QBO. VolMIP's experiments are designed based on observed or reconstructed forcing characteristics of historical volcanic eruptions (1815 Tambora and 1991 Pinatubo for the Tier 1 experiments). Comparison with observational or reconstructed evidence must, however, take into account the idealized character of VolMIP's experiments, including the simplified setting for generating volcanic forcing parameters provided by the EVA module.

585 Specifically, the evolution of the volcanic aerosol cloud in EVA does not account for the meteorological conditions at the time of the eruption, and cannot represent the aerosol properties at anything other than the largest scales. Eccentricities of the aerosol evolution, due to variations in stratospheric transport such as the QBO, mid-latitude mixing, and the polar vortex, cannot be reliably included in any reconstruction of aerosol forcing which relies only on sparse proxy records. ~~Observations~~Additionally, observations-

590 simulations assessments ~~cannot also leave aside~~need to include the identification of the origins and consequences of systematic model biases affecting the dynamical climate response to volcanic forcing.

5. Summary

VolMIP is a coordinated climate modeling activity to advance our understanding of how the climate

595 system responds to volcanic forcing. VolMIP contributes to identifying the causes that limit robustness in simulated volcanically-forced climate variability, especially concerning differences in models' treatment of physical processes. It further allows for the evaluation of key climate feedbacks in coupled climate simulations following relatively well-observed eruptions.

The protocol detailed in this paper aims at improving comparability across the participating climate

600 models by (i) constraining the applied radiative forcing, ~~proposing~~prescribing for each experiment a consensus set of forcing parameters to be employed, and (ii) constraining the background climate conditions upon which the volcanic forcing is applied. The protocol entails ~~two~~three main sets of experiments: the first focusing on the short-term (seasonal to interannual) atmospheric response, ~~and~~ the second focusing on the long-term (interannual to decadal) response of the coupled ocean-atmosphere

system, and the third focusing on the climate response to close successions of volcanic eruptions (so-called volcanic clusters). Both Experiments are further prioritized into three tiers of experiments. Careful sampling of initial climate conditions and the opportunity to consider volcanic eruptions of different strengths will allow a better understanding of the relative role of internal and externally-forced climate variability during periods of strong volcanic activity, hence both improving both the evaluation of climate models and enhancing our ability to accurately simulate past and future climates.

Data Availability

The model output from the all simulations described in this paper will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. As in CMIP5, the model output will be freely accessible through data portals after registration. In order to document CMIP6's scientific impact and enable ongoing support of CMIP, users are obligated to acknowledge CMIP6, the participating modelling groups, and the ESGF centrers (see details on the CMIP Panel website at http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip). Further information about the infrastructure supporting CMIP6, the metadata describing the model output, and the terms governing its use are provided by the WGCM Infrastructure Panel (WIP) in their invited contribution to this Special Issue. Along with the data itself, the provenance of the data will be recorded, and DOI's will be assigned to collections of output so that they can be appropriately cited. This information will be made readily available so that published research results can be verified and credit can be given to the modelling groups providing the data. The WIP is coordinating and encouraging the development of the infrastructure needed to archive and deliver this information. In order to run the experiments, datasets for volcanic forcing are required, which are described in the present paper. In order to run the experiments, data sets for natural and anthropogenic forcings defined for the DECK and the CMIP6 historical simulations are required. These forcing data sets are described in separate invited contributions to this special issue. In addition, specific volcanic forcings are required for the VolMIP experiments that are described in this paper. The forcing datasets or, alternatively, dedicated tools to derive them will be made available through the ESGF with version control and DOIs assigned.

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References

Anchukaitis, K., Breitenmoser, P., Briffa K., Buchwal, A., Büntgen, U., Cook E., D'Arrigo, R., Esper, J., Evans, M., Frank, D., Grudd ,H., Gunnarson, B., Hughes, M., Kirdyanov ,A., Körner, C., Krusic, P., Luckman, B., Melvin, T., Salzer, M., Shashkin, A., Timmreck, C., Vaganov, E., Wilson, R...: Tree-rings and volcanic cooling, Nature Geoscience, 5, 836-837, doi:10.1038/ngeo1645, 2012.

Anet, J. G., Muthers, S., Rozanov, E. V., Raible, C. C., Stenke, A., Shapiro, A. I., Brönnimann, S., Arfeuille, F., Brugnara, Y., Beer, J., Steinhilber, F., Schmutz, W., and Peter, T.: Impact of solar versus volcanic activity variations on tropospheric temperatures and precipitation during the Dalton Minimum, Clim. Past, 10, 921-938, doi:10.5194/cp-10-921-2014, 2014.

Bekki, S., Pyle, J. A., Zhong,W., Tourni, R., Haigh, J. D., Pyle, D. M.: The role of microphysical and chemical processes in prolonging the climate forcing of the Toba Eruption, Geophys. Res. Lett. 23, 2669–2672, 1996.

Bekki, S.: Oxidation of volcanic SO2: a sink for stratospheric OH and H2O, Geophys. Res. Lett., 22(8), 913-916, 1995.

Berdahl, M., and Robock, A.: Northern Hemispheric cryosphere response to volcanic eruptions in the Paleoclimate Modeling Intercomparison Project 3 last millennium simulations, J. Geophys. Res. Atmos., 118, 12,359–12,370, doi:10.1002/2013JD019914, 2013.

Boer, G. J., Smith, D. M., Cassou, C., Doblas-Reyes, F., Danabasoglu, G., Kirtman, B., Kushnir, Y., Kimoto, M., Meehl, G. A., Msadek, R., Mueller, W. A., Taylor, K., and Zwiers, F.: The Decadal Climate Prediction Project, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-78, in review, 2016.

Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte, V., Abe-Ouchi, A., Otto-Bliesner, B., and Zhao, Y.: Evaluation of climate models using palaeoclimatic data, Nature Climate Change, 2, 417–424, doi:10.1038/nclimate1456, 2012.

Brasseur, G. and Carlson, D.: Future directions for the World Climate Research Programme, Eos, 96, doi:10.1029/2015EO033577, 2015

Charlton-Perez, A. J., Baldwin, M. P., Birner, T., Black, R. X., Butler, A. H., Calvo, N., Davis, N. A., Gerber, E. P., Gillett, N., Hardiman, S., Kim, J., Krüger, K., Lee, Y.-Y., Manzini, E., McDaniel, B. A., Polvani, L., Reichler, T., Shaw, T. A., Sigmond, M., Son, S.-W., Toohey, M., Wilcox, L., Yoden, S., Christiansen, B., Lott, F., Shindell, D., Yukimoto, S. and Watanabe, S.: On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models, J. Geophys. Res. Atmos., 118(6), 2494–2505, doi:10.1002/jgrd.50125, 2013.

Cole-Dai, J., Ferris, D., Lanciki, A., Savarino, J., Baroni, M., and Thiemens, M. H.: Cold decade (AD 1810–1819) caused by Tambora (1815) and another (1809) stratospheric volcanic eruption, Geophys. Res. Lett., 36, L22703, doi:10.1029/2009GL040882, 2009.

Corona, C., Guiot, J., Edouard, J. L., Chalié, F., Büntgen, U., Nola, P., and Urbinati, C.: Millennium-long summer temperature variations in the European Alps as reconstructed from tree rings, Clim. Past, 6, 379-400, doi:10.5194/cp-6-379-2010, 2010.

Crowley, T. J. and Unterman, M. B.: Technical details concerning development of a 1200 yr proxy index for global volcanism, Earth Syst. Sci. Data, 5(1), 187–197, doi:10.5194/essd-5-187-2013, 2013

D'Arrigo, R., Wilson R., and A. Tudhope, A.: The impact of volcanic forcing on tropical temperatures during the past four centuries, Nature Geoscience, 2, 51 – 56, doi:10.1038/ngeo393, 2009.

Devine, J. D., Sigurdsson, H., Davis, A. N., Self, S.: Estimates of sulfur and chlorine yield to the atmosphere from volcanic eruptions and potential climatic effect, J. Geophys. Res., 89, 6309–6325, 1984.

Dhomse, S. S., Emmerson, K. M., Mann, G. W., Bellouin, N., Carslaw, K. S., Chipperfield, M. P., Hommel, R., Abraham, N. L., Telford, P., Braesicke, P., Dalvi, M., Johnson, C. E., O'Connor, F., Morgenstern, O., Pyle, J. A., Deshler, T., Zawodny, J. M., and Thomason, L. W.: Aerosol microphysics simulations of the Mt. Pinatubo eruption with the UM-UKCA composition-climate model, Atmos. Chem. Phys., 14, 11221–11246, doi: 10.5194/acp-14-11221-2014, 2014

Ding, Y., Carton, J. A., Chepurin, G. A., Stenchikov, G., Robock, A., Sentman, L. T., and Krasting, J. P.: Ocean response to volcanic eruptions in Coupled Model Intercomparison Project5 (CMIP5) simulations, J. Geophys. Res., Ocean, 119, 5622–5637, doi:10.1002/2013JC009780, 2014

Driscoll, S., Bozzo, A., Gray, L. J., Robock, A., and Stenchikov, G.: Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions, J. Geophys. Res. Atmos., 117, D17105, doi:10.1029/2012JD017607, 2012

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937-1958, doi:10.5194/gmd-9-1937-2016, 2016.

Frank, D. C., Esper, J., Raible, C. C., Büntgen, U., Trouet, V., B. Stocker, B., Joos, F.: Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate, Nature, 463, 527–530, doi:10.1038/nature08769, 2010.

Gao, C., Robock, A., and Ammann, C.: Volcanic forcing of climate over the past 1500 years: an improved ice core-based index for climate models, J. Geophys. Res., 113, D23111, doi:10.1029/2008JD010239, 2008.

Gennaretti, F., Arseneault, D., Nicault, A., Perreault, L., and Begin, Y.: Volcano-induced regime shifts in millennial tree-ring chronologies from northeastern North America, Proceedings of the National Academy of Sciences, 111: 10077-10082, 2014.

Gerber, E. P. and Manzini, E.: DynVarMIP: Assessing the Dynamics and Variability of the Stratosphere-Troposphere System, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-80, in review, 2016.

Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D., and Tebaldi, C.: Detection and Attribution Model Intercomparison Project (DAMIP), Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-74, in review, 2016.

Graf, H.-F., Feichter, J., and Langmann, B.: Volcanic sulfur emissions: estimates of source strength and its contribution to the global sulfate burden, J. Geophys. Res., 102, 10,727–10,738, 1997.

Gregory, J. M.: Long-term effect of volcanic forcing on ocean heat content, Geophys. Res. Lett., 37, L22701, doi:10.1029/2010GL045507, 2010.

Hegerl, G. C., Crowley, T. J., Baum, S. K., Kim, K.-Y., and Hyde W. T.: Detection of volcanic, solar and greenhouse gas signals in paleo-reconstructions of Northern Hemispheric temperature, Geophys. Res. Lett., 30 (5), doi:10.1029/2002GL016635, 2003.

Hegerl, G., Luterbacher, J., González-Rouco, F., Tett, S. F. B., Crowley, T. and Xoplaki E.: Influence of human and natural forcing on European seasonal temperatures, Nat. Geosc., 4, 99-103, doi:10.1038/NGEO1057, 2011.

Herzog, M., and Graf, H.-F.: Applying the three-dimensional model ATHAM to volcanic plumes: dynamic of large co-ignimbrite eruptions and associated injection heights for volcanic gases, Geophys. Res. Lett., 37, L19807, doi:10.1029/2010GL044986, 2010.

Hofer, D., Raible, C. C., and Stocker, T. F.: Variations of the Atlantic meridional overturning circulation in control and transient simulations of the last millennium, Clim. Past, 7, 133-150, doi:10.5194/cp-7-133-2011, 2011

Iles, C. and Hegerl, G.C.: The global precipitation response to volcanic eruptions in the CMIP5 models, Environm. Res. Lett., 9, 104012, 2014.

Jungclaus, J. H., et al: The PMIP4 simulations of the last millennium (PMIP past1000), In preparation for Climate of the Past. 2016.

Kageyama, M., Braconnot, P., Harrison, S. P., Haywood, A. M., Jungclaus, J., Otto-Bliesner, B. L., Peterschmitt, J.-Y., Abe-Ouchi, A., Albani, S., Bartlein, P. J., Brierley, C., Crucifix, M., Dolan, A., Fernandez-Donado, L., Fischer, H., Hopcroft, P. O., Ivanovic, R. F., Lambert, F., Lunt, D. J., Mahowald, N. M., Peltier, W. R., Phipps, S. J., Roche, D. M., Schmidt, G. A., Tarasov, L., Valdes, P. J., Zhang, Q., and Zhou, T.: PMIP4-CMIP6: the contribution of the Paleoclimate Modelling Intercomparison Project to CMIP6, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-106, in review, 2016.

Karpechko, A. Y., Gillett, N. P., Dall'Amico, M., and Gray, L. J.: Southern Hemisphere atmospheric circulation response to the El Chichón and Pinatubo eruptions in coupled climate models, Q. J. Roy. Meteorol. Soc., 136, 1813–1822, doi:10.1002/qj.683, 2010.

Kravitz, B., Robock, A., Tilmes, S., Boucher, O., English, J. M., Irvine, P. J., Jones, A., Lawrence, M. G., MacCracken, M., Muri, H., Moore, J. C., Niemeier, U., Phipps, S. J., Sillmann, J., Storelvmo, T., Wang, H., and Watanabe, S.: The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): simulation design and preliminary results, Geosci. Model Dev., 8, 3379-3392, doi:10.5194/gmd-8-3379-2015, 2015.

785   Lehner, F., Schurer, A. P., Hegerl, G. C., Deser, C., Frölicher, T. L.: The importance of ENSO phase during volcanic eruptions for detection and attribution, Geophys. Res. Lett., doi:10.1002/2016GL067935, 2016.

Luterbacher J., Werner, J. P., Smerdon, J. E., Fernández-Donado, L., González-Rouco, F. J., Barriopedro, D., Ljungqvist, F. C., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J. H., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R., Camuffo, D., Dobrovolný, P., Gagen, M., García-Bustamante, E., Ge, Q., Gómez-Navarro, J. J., Guiot, J., Hao, Z., Hegerl, G. C., Holmgren, K., Klimenko, V. V., Martín-Chivelet, J., Pfister, C., Roberts, N., Schindler, A., Schurer, A., Solomina, O., von Gunten, L., Wahl, E., Wanner, H., Wetter, O., Xoplaki, E., Yuan, N., Zanchettin, D., Zhang, H., and Zerefos, C.: European summer temperatures since Roman times, Environmental Research Letters 11, 024001, doi: 10.1088/1748-9326/11/1/024001, 2016.

Mann, M. E., Rutherford, S., Schurer, A., Tett, S. F., and ~~and~~ Fuentes, J. D.: Discrepancies between the modeled and proxy-reconstructed response to volcanic forcing over the past millennium: Implications and possible mechanisms, J. Geophys. Res. Atmos~~.~~., 118(14), 7617-7627, 2013.

Mann, M. E., Fuentes J. D., and Rutherford S.: Underestimation of volcanic cooling in tree-ring based reconstructions of hemispheric temperatures, Nature Geosciences, doi 10.1038/ngeo1394, 2012.

~~Mather, T. A., Oppenheimer, C., Allen, A. G., and McGonigle, A.J. S. : Aerosol chemistry of emissions from three contrasting volcanoes in Italy, Atm. Environ., 38, 5637–5649, doi:10.1016/j.atmosenv.2004.06.017, 2004~~

Marotzke, J., and Forster, P. M.: Forcing, feedback and internal variability in global temperature trends, Nature, 517, 565-570, doi:10.1038/nature14117, 2015.

Mather, T. A., Oppenheimer, C., Allen, A. G., and McGonigle, A. J. S.: Aerosol chemistry of emissions from three contrasting volcanoes in Italy, Atm. Environ., 38, 5637–5649, doi:10.1016/j.atmosenv.2004.06.017, 2004

McCormick, M. P., and Veiga, R. E.: SAGE II measurements of early Pinatubo aerosols, Geophys. Res. Lett~~.~~., 19 (2~~).~~), 155–158, doi:10.1029/91GL02790, 1992.

Meyer, A., Vernier, J.-P., Luo, B., Lohmann, U., and Peter, T.: Did the 2011 Nabro eruption affect the optical properties of ice clouds?, J. Geophys. Res. Atmos., 120, 9500–9513, doi:10.1002/2015JD023326, 2015.

Mignot, J., Khodri, M., Frankignoul, C., and Servonnat, J.: Volcanic impact on the Atlantic Ocean over the last millennium, Clim. Past, 7, 1439-1455, doi:10.5194/cp-7-1439-2011, 2011.

815   Miller, G. H., Geirsdóttir, Á., Zhong, Y., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Björnsson, H., and Thordarson, T.: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, Geophys.Res. Lett., 39, L02708, doi:10.1029/2011GL050168, 2012.

Minnis, P., Harrison, E. F., Stowe, L. L., Gibson, G.G., Denn, F. M., Doelling, D. R., Smith Jr., W. L.:
820   Radiative Climate Forcing by the Mount Pinatubo, Eruption. Science, 259(5100): 1411-1415, doi:10.1126/science.259.5100.1411, 1993.

Mills, M. J., Schmidt, A., Easter, R., Solomon, S., Kinnison, D. E., Ghan, S. J., Neely III, R. R., Marsh, D. R., Conley, A., Bardeen, C. G., and Gettelman, A.: Global volcanic aerosol properties derived from emissions, 1990–2014, using CESM1(WACCM). J. Geophys. Res. Atmos.,
825   doi:10.1002/2015JD024290 ,2016.

Minnis, P., Harrison, E. F., Stowe, L. L., Gibson, G.G., Denn, F. M., Doelling, D. R., Smith Jr., W. L.: Radiative Climate Forcing by the Mount Pinatubo, Eruption. Science, 259(5100): 1411-1415, doi:10.1126/science.259.5100.1411, 1993.

Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., and Jungclaus, J. H.: An abrupt weakening of the
830   subpolar gyre as trigger of Little Ice Age--type episodes. Clim. Dyn., doi:10.1007/s00382-016-3106-7, 2016.

Muthers, S., Anet, J. G., Raible, C. C., Brönnimann, S., Rozanov, E., Arfeuille, F., Peter, T., Shapiro, A. I., Beer, J., Steinhilber, F., Brugnara, Y., and Schmutz, W.: Northern hemispheric win-ter warming pattern after tropical volcanic eruptions: sensitiv-ity to the ozone climatology, J. Geophys. Res.,
835   110, 1340–1355,doi:10.1002/2013JD020138, 2014..

Muthers, S., Arfeuille, F., Raible, C. C., and Rozanov, E.: The impacts of volcanic aerosol on stratospheric ozone and the Northern Hemisphere polar vortex: separating radiative-dynamical changes from direct effects due to enhanced aerosol heterogeneous chemistry, Atmos. Chem. Phys., 15, 11461-1147611,461-11,476, doi:10.5194/acp-15-11461-2015, 2015.

840   Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J. F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and natural radiative forcing, in: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Nauels,

845   A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Niemeier, U., Timmreck, C., Graf, H.-F., Kinne, S., Rast, S., and Self, S.: Initial fate of fine ash and sulfur from large volcanic eruptions, Atmos. Chem. Phys., 9, 9043-9057, doi:10.5194/acp-9-9043-2009, 2009.

850 Oman, L., Robock, A. Stenchikov, G., Schmidt, G. A., and Ruedy, R.: Climatic response to high-latitude volcanic eruptions, Geophys. Res. Lett., 110, D13, doi:10.1029/2004JD005487, 2005.

O'Neill, B. C., Tebaldi, C., van Vuuren, D., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, J., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev. Discuss., doi:10.5194/gmd-

855   2016-84, in review, 2016.

Oppenheimer, C.: Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815, Progress in Physical Geography, 27, 2:, 230–259, 2003.

Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C. C., M. Casado, M., Yiou, P.: A multi-proxy model-tested NAO reconstruction for the last millennium, Nature, 523, 71-75, 2015.

860 Pausata, F. S. R., Grini, A., Caballero, R., Hannachi, A., Seland, Ø.: High-latitude volcanic eruptions in the Norwegian Earth System Model: the effect of different initial conditions and of the ensemble size, Tellus B, 67, 26728, http://dx.doi.org/:10.3402/tellusb.v67.26728, 2015a.

Pausata, F. S. R., Chafik, L., Caballero, R., Battisti, D. S.: Impacts of high-latitude volcanic eruptions on ENSO and AMOC. Proc. Nat. Ac. Sc., doi:10.1073/pnas.1509153112, 2015b.

865 Pincus, R., Forster, P. M., and Stevens, B.: The Radiative Forcing Model Intercomparison Project (RFMIP): Experimental Protocol for CMIP6, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-88, in review, 2016.

Raible, C. C., Brönnimann, S., Auchmann, R., Brohan, P., Frölicher, T. L., Graf, H.-F., Jones, P., Luterbacher, J., Muthers, S., Neukom, R., Robock, A., Self, S., Sudrajat, A., Timmreck, C.,

870   Wegmann, M.: Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects. WIREs Clim Change, 7: 569-589, doi: 10.1002/wcc.407, 2016

Rap, A., Scott, C. E., Spracklen, D. V., Bellouin, N., Forster, P. M., Carslaw, K. S., Schmidt, A., Mann, G.: Natural aerosol direct and indirect radiative effects, Geophys. Res. Lett., 40, 3297–3301, doi:10.1002/grl.50441, 2013.

875   Read, W. G., Froidevaux, L., and Waters, J. W.: Microwave limb sounder measurement of stratospheric SO2 from the Mount Pinatubo volcano, Geophys. Res. Lett., 20, 1299–1302, doi:10.1029/93GL00831, 1993

Santer, B. D., Bonfils, C., Painter, J. F., Zelinka, M. D., Mears, C., Solomon, S., Schmidt, G. A., Fyfe, J. C., Cole, J. N. S., Nazarenko, L., Taylor, K. E., and Wentz, F. J.: Volcanic contribution to decadal
880   changes in tropospheric temperature, Nat. Geosci., 7, 185–189, doi:10.1038/ngeo2098, 2014.

Schleussner, C. F., and Feulner, G.: A volcanically triggered regime shift in the subpolar North Atlantic Ocean as a possible origin of the Little Ice Age, Clim. Past, 9, 1321–1330, doi:10.5194/cp-9-1321-2013, 2013.

Schurer, A. P., Tett, S. F. B., -and Hegerl, G. C.: Small influence of solar variability on climate over the past
885   millennium, Nature Geosci. 7, 104–108, doi:10.1038/ngeo2040, 2014.

Schmidt, A., Carslaw, K. S., Mann, G. W., Rap, A., Pringle, K. J., Spracklen, D. V., Wilson, M., and Forster, P. M. : Importance of tropospheric volcanic aerosol for indirect radiative forcing of climate, Atmos. Chem. Phys., 12, 7321-7339, doi:10.5194/acp-12-7321-2012, 2012.

Seifert, P., Ansmann, A., Groß, S., Freudenthaler, V., Heinold, B., Hiebsch, A., Mattis, I., Schmidt, J.,
890   Schnell, F., Tesche, M., Wandinger, U., and Wiegner, M.: Ice formation in ash-influenced clouds after the eruption of the Eyjafjallajökull volcano in April 2010, J. Geophys. Res., 116, D00U04, doi:10.1029/2011JD015702, 2011.

Self, S., Gertisser, R., Thordarson, T., Rampino, M. R., and Wolff, J. A.: Magma volume, volatile emissions, and stratospheric aerosols from the 1815 eruption of Tambora, Geophys. Res. Lett. 31, L20608,
895   doi:10.1029/2004GL020925, 2004

Sheng, J.-X., Weisenstein, D. K., Luo, B.-P., Rozanov, E., Stenke, A., Anet, J., Bingemer, H., and Peter, T.: Global atmospheric sulfur budget under volcanically quiescent conditions: aerosol–chemistry–climate model predictions and validation, J. Geophys. Res.-Atmos., 120, 256–276, doi:10.1002/2014JD021985, 2015

900   Sigl, M., Mcconnell, J. R., Toohey, M., Curran, M., Das, S. B., Edwards, R., Isaksson, E., Kawamura, K., Kipfstuhl, S., Krüger, K., Layman, L., Maselli, O. J. Motizuki, Y., Motoyama, H., and Pasteris, D. R.: Insights from Antarctica on volcanic forcing during the Common Era, Nature Climate Change, 4, 693–697, doi:10.1038/nclimate2293, 2014.

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O. J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D.R., Pilcher, J. R., Salzer, M., Schüpbach, S., Steffensen, J. P.,Vinther, B. M., and Woodruff, T. E.: Timing and climate forcing of volcanic eruptions for the past 2,500 years, Nature, 523, 543–549, doi:10.1038/nature14565, 2015.

Stephenson, D. B., Pavan, V., Collins, M., Junge, M. M., and Quadrelli, R.: North Atlantic Oscillation response to transient greenhouse gas forcing and the impact on European winter climate: a CMIP2 multi-model assessment, Clim. Dyn., 27, 401–420, doi:10.1007/s00382-006-0140-x, 2006.

Stoffel, M., Khodri, M., Corona, C., Guillet, S., Poulain, V., Bekki, S., Guiot, J., Luckman, B. H., Oppenheimer, C., Lebas, N., Beniston, M. and Masson-Delmotte, V.: Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years, Nat. Geosci., advance on, doi:10.1038/ngeo2526, 2015.

Swingedouw D., Ortega P., Mignot E., Guilyardi E., Masson-Delmotte V., Butler P.G., Khodri M., and Seferian R.: Bidecadal North Atlantic ocean circulation variability controlled by timing of volcanic eruptions, Nature Comm., 6, 6545, doi: 10.1038/ncomms7545, 2015.

Thomas, M. A., Timmreck, C., Giorgetta, M. A., Graf, H.-F., and Stenchikov, G.: Simulation of the climate impact of Mt. Pinatubo eruption using ECHAM5 – Part 1: Sensitivity to the modes of atmospheric circulation and boundary conditions, Atmos. Chem. Phys., 9, 757-769, doi:10.5194/acp-9-757-2009, 2009.

Thomason, L., Vernier, J.-P., Bourassa, A., Arfeuille, F., Bingen, C., Peter, T., and Luo, B.: Stratospheric Aerosol Data Set (SADS Version 2) Prospectus. In preparation for Geosc. Model Dev. Discuss., 2016.

Thordarson, T., and Self, S.: Atmospheric and environmental effects of the 1783–1784 Laki eruption: A review and reassessment, J. Geophys. Res., 108(D1), 4011, doi: 10.1029/2001JD002042, 2003.

Timmreck, C.: Modeling the climatic effects of large volcanic eruptions, WIREs Clim. Change, 3, 545–564, doi:10.1002/wcc.192, 2012.

Timmreck, C., Pohlmann, H., Illing, S., and Kadow, C.: The impact of stratospheric volcanic aerosol on decadal-scale climate predictions, Geophys. Res. Lett., 43(2), 834–842, doi:10.1002/2015GL067431, ~~2016~~2016a.

Timmreck, C., Mann, G. W., Aquila, V., Brühl, C., Chin, M., Dhomse, S.S., English, J. M., Lee, L. A., Mills, M. J., Hommel, R., Neely, R., Sheng, J.-X., Toohey, M. and Weisenstein, D.: The Stratospheric Sulphur and its Role in Climate (SSIRC) Model intercomparison project. Geophysical Research Abstracts 18, EGU2016-13766, 2016 EGU General Assembly 2016, 2016b

Toohey, M., Stevens, B., Schmidt, H., and Timmreck, C.: Easy Volcanic Aerosol (EVA v1.0): An idealized forcing generator for climate simulations, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-83, in review, 2016.

Toohey, M., Krüger, K., Bittner, M., Timmreck, C., and Schmidt, H.: The impact of volcanic aerosol on the Northern Hemisphere stratospheric polar vortex: mechanisms and sensitivity to forcing structure, Atmos. Chem. Phys., 14, 13063-13079, doi:10.5194/acp-14-13063-2014, 2014.

Toohey, M., Stevens, B., Schmidt, H., and Timmreck, C.: Easy Volcanic Aerosol (EVA v1.0): An idealized forcing generator for climate simulations, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-83, in review, 2016a.

Toohey, M., Krüger, K., Sigl, M., Stordal, F. and Svensen, H.: Climatic and societal impacts of a volcanic double event at the dawn of the Middle Ages, Clim. Change, 136(3-4), 401–412, doi:10.1007/s10584-016-1648-7, 2016b.

Winter, A., Zanchettin, D., Miller, T., Kushnir, Y., Black, D., Lohmann, G., Burnett, A., Haug, G. H., Estrella-Martínez, J., Breitenbach, S. F. M, Beaufort, L., Rubino, A., and Cheng, H. : Persistent drying in the tropics linked to natural forcing, Nature Communications 6, 7627, doi:10.1038/ncomms8627, 2015.

Zanchettin D., Timmreck, C., O. Bothe, O., Lorenz, S. J., Hegerl, G., Graf, H.-F., Luterbacher, J., and . Jungclaus, J. H.: Delayed winter warming: a robust decadal response to strong tropical volcanic eruptions? Geophys. Res. Lett. 40, doi:10.1029/2012GL054403, 2013b.

Zanchettin, D., Bothe, O., Lehner, F., Ortega, P., Raible, C. C., and Swingedouw, D.: Reconciling reconstructed and simulated features of the winter Pacific/North American pattern in the early 19th century, Clim. Past, 11, 939-958, doi:10.5194/cp-11-939-2015, 2015a.

Zanchettin, D., Timmreck, C., Graf, H.-F., Rubino, A., Lorenz, S., Lohmann, K., Krueger, K., and Jungclaus, J. H.: Bi-decadal variability excited in the coupled ocean–atmosphere system by strong tropical volcanic eruptions, Clim. Dynam., 39, 419–444, doi:10.1007/s00382-011-1167-1, 2012.

Zanchettin, D., Timmreck, C., Khodri, M., Robock, A., Rubino, A., Schmidt A., and Toohey, M.: A coordinated modeling assessment of the climate response to volcanic forcing. PAGES Magazine, 32(2): 54-55, 2015b.

Zanchettin, D., Bothe, O., Timmreck, C., Bader, J., Beitsch, A., Graf, H.-F., Notz, D., and Jungclaus, J. H.: Inter-hemispheric asymmetry in the sea-ice response to volcanic forcing simulated by MPI-ESM (COSMOS-Mill), Earth Syst. Dynam., 5, 223-242, doi:10.5194/esd-5-223-2014, 2014.

Zanchettin, D., Bothe, O., Graf, H. F., Lorenz, S. J., Luterbacher, J., Timmreck, C., and Jungclaus, J. H.: Background conditions influence the decadal climate response to strong volcanic eruptions, J. Geophys. Res.-Atmos., 118, 4090–4106, doi:10.1002/jgrd.50229, 2013a.

Zhao, Z., Pritchard, M. S., Russell, L. M.: Effects on precipitation, clouds, and temperature from long-range transport of idealized aerosol plumes in WRF-Chem simulations. J. Geophys. Res., 117, D05206, doi:10.1029/2011JD016744, 2012.

Anchukaitis K, Breitenmoser P , Briffa K, Buchwal A, Büntgen U, Cook E, D'Arrigo R, Esper J, Evans M, Frank D, Grudd H, Gunnarson B, Hughes M, Kirdyanov A, Körner C, Krusic P , Luckman B, Melvin T, Salzer M, Shashkin A, Timmreck C, Vaganov E, Wilson R. (2012) Tree-rings and volcanic cooling. NatureGeoscience, 5: 836-837doi:10.1038/ngeo1645

Bekki, S., Pyle J.A., Zhong W., Tourni R., Haigh J.D., Pyle D.M., 1996. The role of microphysical and chemical processes in prolonging the climate forcing of the Toba Eruption. Geophys. Res. Lett. 23, 2669–2672

Bekki, S., 1995. Oxidation of volcanic SO2: a sink for stratospheric OH and H2O. Geophys. Res. Lett., 22(8), 913-916

Berdahl, M., and A. Robock (2013) Northern Hemispheric cryosphere response to volcanic eruptions in the Paleoclimate Modeling Intercomparison Project 3 last millennium simulations, J. Geophys. Res. Atmos., 118, 12,359–12,370, doi:10.1002/2013JD019914

Boer, G. J., D. M. Smith, Christophe Cassou, Franciscano Doblas-Reyes, Gokhan Danabasoglu, Ben Kirtman, Yochanan Kushnir, Kimoto Masahide, Jerry Meehl, Rym Msadek, Wolfgang A. Mueller, Karl Taylor, Francis Zwiers, The Decadal Climate Prediction Project, to be submitted to CMIP special issue in Geosc. Model Dev. Discuss.

Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte, V., Abe-Ouchi, A., Otto-Bliesner, B., and Zhao, Y. (2012) Evaluation of climate models using palaeoclimatic data, Nature Climate Change, 2, 417–424, doi:10.1038/nclimate1456

Brasseur, G. and Carlson, D. (2015) Future directions for the World Climate Research Programme, Eos, 96, doi:10.1029/2015EO033577

Charlton-Perez, A., Baldwin, M. P., Birner, T., Black, R. X., Butler, A. H., Calvo, N., Davis, N. A., Gerber, E. P., Gillett, N., Hardiman, S., Kim, J., Krüger, K., Lee, Y.-Y., Manzini, E., McDaniel, B. A., Polvani, L., Reichler, T., Shaw, T. A., Sigmond, M., Son, S.-W., Toohey, M., Wilcox, L., Yoden, S., Christiansen, B., Lott, F., Shindell, D., Yukimoto, S. and Watanabe, S. (2013) On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models. Journal of Geophysical Research: Atmospheres, 118 (6). pp. 2494-2505. ISSN 2169-8996 doi: 10.1002/jgrd.50125

Cole-Dai J., D. Ferris, A. Lanciki, J. Savarino , M. Baroni, MH Thiemens (2009) Cold decade (AD 1810-1819) caused by Tambora (1815) and another (1809) stratospheric volcanic eruption, Geophys. Res. Lett., 36,L22703 doi:10.1029/2009GL04088.

Crowley, T. J. and Unterman, M. B. (2013) Technical details concerning development of a 1200 yr proxy index for global volcanism, Earth Syst. Sci. Data, 5, 187–197, doi:10.5194/essd-5-187-2013

Devine, J. D., H. Sigurdsson, A. N. Davis, and S. Self (1984) Estimates of sulfur and chlorine yield to the atmosphere from volcanic eruptions and potential climatic effect. J. Geophys. Res. 89:6309–6325.

Dhomse, S. S., Emmerson, K. M., Mann, G. W., Bellouin, N., Carslaw, K. S., Chipperfield, M. P., Hommel, R., Abraham, N. L., Telford, P., Braesicke, P., Dalvi, M., Johnson, C. E., O'Connor, F., Morgenstern, O., Pyle, J. A., Deshler, T., Zawodny, J. M., Thomason, L. W. (2014) Aerosol microphysics

simulations of the Mt.Pinatubo eruption with the UM-UKCA composition-climate model, Atmospheric Chemistry and Physics, 14, 20, 11221--11246, doi :10.5194/acp-14-11221-2014.

Ding, Y., J. A. Carton, G. A. Chepurin, G. Stenchikov, A. Robock, L. T. Sentman, and J. P. Krasting (2014) Ocean response to volcanic eruptions in Coupled Model Intercomparison Project 5 (CMIP5) simulations. J. Geophys. Res., 119, 5622-5637, doi:10.1002/2013JC009780.

Driscoll, S., Bozzo, A., Gray, L. J., Robock, A., & Stenchikov, G. (2012) Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions. Journal of Geophysical Research: Atmospheres, 117, D17105, doi:10.1029/2012JD017607.

Eyring, V., S. Bony, G. A. Meehl, C. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor (2015) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. Discuss., 8, 10539–10583

Frank, D. C., J. Esper, C. C. Raible, U. Büntgen, V. Trouet, B. Stocker, and F. Joos (2010), Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate, Nature, 463, 527–530, doi:10.1038/nature08769

Gao, C., A. Robock, C. Ammann (2008) Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. J. Geophys. Res., 113, D23, doi:10.1029/2008JD010239

Gregory, J. M. (2010) Long-term effect of volcanic forcing on ocean heat content. Geophys. Res. Lett., 37, L22701, doi:10.1029/2010GL045507

Hegerl, G. C., T. J. Crowley, S. K. Baum, K. Y. Kim, and W. T. Hyde (2003) Detection of volcanic, solar and greenhouse gas signals in paleo-reconstructions of Northern Hemispheric temperature. Geophys. Res. Lett. 30 (5), doi:10.1029/2002GL016635

Hegerl, G., J. Luterbacher, F. González-Rouco, S. F. B. Tett, T. Crowley and E. Xoplaki (2011) Influence of human and natural forcing on European seasonal temperatures. Nat. Geosc. 4:99-103, doi:10.1038/NGEO1057

Herzog, M. and Graf, H. F. (2010) Applying the three-dimensional model ATHAM to volcanic plumes: dynamic of large co-ignimbrite eruptions and associated injection heights for volcanic gases. Geophys. Res. Lett., 37, L19807, doi:10.1029/2010GL044986

Hofer, D., C. C. Raible, and T. F. Stocker (2011) Variation of the Atlantic meridional overturning circulation in control and transient simulations of the last millennium. Clim. Past, 7, 133-150, 2011

Iles C. and Hegerl G.C. (2014) The global precipitation response to volcanic eruptions in the CMIP5 models. Environm. Res. Lett., 9, 104012

Kageyama et al., in preparation for the CMIP special issue in Geosc. Model Dev. Discuss.

Karpechko A. Y., N. P. Gillett, M. Dall'Amico, and L. J. Gray (2010) Southern Hemisphere atmospheric circulation response to the El Chichón and Pinatubo eruptions in coupled climate models. Quart. J. Royal Meteor. Soc. 136(652), 1813–1822, doi:10.1002/qj.683

Kravitz, Ben, Alan Robock, Simone Tilmes, Olivier Boucher, Jason M. English, Peter J. Irvine, Andy Jones, Mark G. Lawrence, Michael MacCracken, Helene Muri, John C. Moore, Ulrike Niemeier, Steven J. Phipps, Jana Sillmann, Trude Storelvmo, Hailong Wang, and Shingo Watanabe (2015) The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): Simulation design and preliminary results. Geosci. Model Dev., 8, 3379–3392, doi:10.5194/gmd-8-3379-2015

Lehner, F., A. P. Schurer, G. C. Hegerl, C. Deser 3 , and T. L. Frölicher (2016) The importance of ENSO phase during volcanic eruptions for detection and attribution. Geophys. Res. Lett., doi:10.1002/2016GL067935

Mann, M. E., Rutherford, S., Schurer, A., Tett, S. F., & Fuentes, J. D. (2013) Discrepancies between the modeled and proxy-reconstructed response to volcanic forcing over the past millennium: Implications and possible mechanisms. Journal of Geophysical Research: Atmospheres, 118(14), 7617-7627

Mann, M.E., Fuentes, J.D., Rutherford, S. (2012) Underestimation of volcanic cooling in tree-ring based reconstructions of hemispheric temperatures. Nature Geosciences, doi 10.1038/ngeo1394

Marotzke, J., and Forster, P. M. (2015) Forcing, feedback and internal variability in global temperature trends. Nature, 517, 565-570. doi:10.1038/nature14117

McCormick, M. P., and R. E. Veiga (1992) SAGE II measurements of early Pinatubo aerosols. Geophys. Res. Lett. 19 (2): 155–158, doi:10.1029/91GL02790

Mignot, J., M. Khodri, C. Frankignoul, and J. Servonnat (2011), Volcanic impact on the Atlantic Ocean over the last millennium, Clim. Past, 7, 1439–1455, doi:10.5194/cp-7-1439-2011

Miller, G. H., Geirsdóttir, Á., Zhong, Y., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Björnsson, H., and Thordarson, T. (2012) Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea ice/ocean feedbacks, Geophys. Res. Lett., 39, L02708, doi:10.1029/2011GL050168

Mills, M. J., Schmidt, A., Easter, R., Solomon, S., Kinnison, D. E., Ghan, S. J., R. R. Neely III, D. R. Marsh, A. Conley, C. G. Bardeen, and A. Gettelman (2016) Global volcanic aerosol properties derived from emissions, 1990–2014, using CESM1(WACCM). J. Geophys. Res.-Atmos., doi:10.1002/2015JD024290

Myhre, G., D. Shindell, F. M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J. F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Niemeier, U. et al. (2009), Initial fate of fine ash and sulfur from large volcanic eruptions. Atmos. Chem. Phys., 9, 9043-9057.

Oman, L., A. Robock, G. Stenchikov, G. A. Schmidt, R. Ruedy (2005) Climatic response to high-latitude volcanic eruptions. Geophys. Res. Lett., 110, D13, doi:10.1029/2004JD005487

Oman, L., A. Robock, G. L. Stenchikov, T. Thordarson, D. Koch, D. T. Shindell, and C. Gao, 2006: Modeling the distribution of the volcanic aerosol cloud from the 1783-1784 Laki eruption. J. Geophys. Res., 111, D12209, doi:10.1029/2005JD006899.

Pausata, F. S. R., A. Grini, R. Caballero, A. Hannachi and Ø. Seland (2015a) High-latitude volcanic eruptions in the Norwegian Earth System Model: the effect of different initial conditions and of the ensemble size. Tellus B,, 67, 26728, http://dx.doi.org/10.3402/tellusb.v67.26728

Pausata, F. S. R., L. Chafik, R. Caballero, and D. S. Battisti (2015b) Impacts of high-latitude volcanic eruptions on ENSO and AMOC. Proc. Nat. Ac. Sc., doi:10.1073/pnas.1509153112

Read, W. G., Froidevaux, L., and Waters, J. W. (1993) Microwave limb sounder measurement of stratospheric SO2 from the Mt. Pinatubo Volcano. Geophys. Res. Lett., 20, 1299–1302, doi:10.1029/93GL00831

Santer, B. D. et al. (2014) Volcanic contribution to decadal changes in tropospheric temperature. Nature Geosc., 7(3), 185–189, doi:10.1038/ngeo2098

1110   Schleussner, C. F. and Feulner, G. (2013) A volcanically triggered regime shift in the subpolar North Atlantic Ocean as a possible origin of the Little Ice Age. Clim. Past, 9, 1321–1330, doi:10.5194/cp-9-1321-2013

Schurer, A. P., S. F. B. Tett, and G. C. Hegerl (2014) Small influence of solar variability on climate over the vpast millennium. Nature Geosci. 7, 104–108, doi:10.1038/ngeo2040

1115   Self, S., R. Gertisser,, T. Thordarson, M. R. Rampino, and J. A. Wolff (2004) Magma volume, volatile emissions, and stratospheric aerosols from the 1815 eruption of Tambora. Geophys. Res. Lett. 31, L20608, doi:10.1029/2004GL020925

Sheng, J. X., D. K. Weisenstein, B. P. Luo, E. Rozanov, A. Stenke, J. Anet, H. Bingemer, and T. Peter (2015), Global atmospheric sulfur budget under volcanically quiescent conditions: Aerosol-

1120   chemistry-climate model predictions and validation, J. Geophys. Res. Atmos., 120, 256–276, doi:10.1002/2014JD021985

Sigl, M., J.R. McConnell, M. Toohey, M. Curran, S.B. Das, R. Edwards, E. Isaksson, K. Kawamura, S. Kipfstuhl, K. Krueger, L. Layman, O.J. Maselli, Y. Motizuki, H. Motoyama, D.R. Pasteris and M. Severi (2014): Insights from Antarctica on volcanic forcing during the Common Era. Nature Climate

1125   Change, 4, 693–697.

Sigl, M., M. Winstrup, J. R. McConnell, K. C. Welten, G. Plunkett, F. Ludlow, U. Büntgen, M. Caffee, N. Chellman, D. Dahl-Jensen, H. Fischer, S. Kipfstuhl, C. Kostick, O. J. Maselli, F. Mekhaldi, R. Mulvaney, R. Muscheler,D. R. Pasteris, J. R. Pilcher, M. Salzer, S. Schüpbach, J. P. Steffensen, B. M. Vinther, T. E. Woodruff (2015) Timing and climate forcing of volcanic eruptions for the past

1130   2,500 years. Nature, 523:543–549, doi:10.1038/nature14565

Stoffel, M., M. Khodri, C. Corona, S. Guillet, V. Poulain, S. Bekki, J. Guiot, B. H. Luckman, C. Oppenheimer, N. Lebas, M. Beniston, and V. Masson-Delmotte (2015) Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years.   Nature Geoscience 8, 784–788, doi:10.1038/ngeo2526

1135   Swingedouw D., Ortega P., Mignot E., Guilyardi E., Masson-Delmotte V., Butler P.G., Khodri M., Seferian R. (2015) Bidecadal North Atlantic ocean circulation variability controlled by timing of volcanic eruptions, Nature Communications, 6, 6545, doi: 10.1038/ncomms7545.

Thomas, M. A.,C. Timmreck, M. Giorgetta, H. Graf, and G. Stenchikov (2009), Simulation of the climate impact of Mt. Pinatubo eruption using ECHAM5. Part-I: Sensitivity to the modes of atmospheric circulation and boundary conditions, Atmos. Chem. Phys, 9, 757-769, 2009.

Thomason, L., J. P. Vernier, A. Bourassa, F. Arfeuille, C. Bingen, T. Peter, B. Luo (2016) Stratospheric Aerosol Data Set (SADS Version 2) Prospectus. In preparation for Geosc. Model Dev. Discuss.

Thordarson, T., and S. Self (2003) Atmospheric and environmental effects of the 1783–1784 Laki eruption: A review and reassessment, J. Geophys. Res., 108(D1), 4011, doi: 10.1029/2001JD002042

Timmreck C. (2012) Modeling the climatic effects of volcanic eruptions, invited review paper Wiley Interdisciplinary Reviews: Climate Change, doi: 10.1002/wcc.192

Timmreck, C., H. Pohlmann, S. Illing and C. Kadow (2016a). The impact of stratospheric volcanic aerosol on decadal scale predictability. Geophys. Res. Lett, 43, doi: 10.1002/2015GL067431Timmreck, C. G. W. Mann, V. Aquila, C. Brühl, M. Chin, S. S. Dhomse, J. M. English, L. A. Lee, M. J. Mills, R. Hommel, R. Neely, J.-X. Sheng, M. Toohey and D. Weisenstein (2016b) The Stratospheric Sulphur and its Role in Climate (SSIRC) Model intercomparison project, Geophysical Research Abstracts Vol. 18, EGU2016-13766, 2016 EGU General Assembly 2016

Timmreck, C., H. Pohlmann, S. Illing and C. Kadow (2016a). The impact of stratospheric volcanic aerosol on decadal scale predictability. Geophys. Res. Lett, 43, doi: 10.1002/2015GL067431

Toohey, M., B. Stevens, H. Schmidt, and C. Timmreck (2016) Easy Volcanic Aerosol: an idealized forcing generator for climate simulations. To be submitted to Geosc. Model Dev. Discuss.

Toohey M, K. Krüger, M. Bittner, C. Timmreck, H. Schmidt (2014) The impact of volcanic aerosol on the Northern Hemisphere stratospheric polar vortex: mechanisms and sensitivity to forcing structure, Atmos. Chem. Phys., 14, 13063-13079, doi:10.5194/acp-14-13063-2014

Winter, A., D. Zanchettin, T. Miller, Y. Kushnir, D. Black, G. Lohmann, A. Burnett, G. H. Haug, J. Estrella-Martínez, S. F. M. Breitenbach, L. Beaufort, A. Rubino, and H. Cheng. Persistent drying in the tropics linked to natural forcing. Nature Communications 6, 7627, doi:10.1038/ncomms8627, 2015

Zanchettin D., C. Timmreck, O. Bothe, S.J. Lorenz, G. Hegerl, H.-F. Graf, J. Luterbacher, and J.H. Jungclaus. Delayed winter warming: a robust decadal response to strong tropical volcanic eruptions? (2013b) Geophys. Res. Lett. 40, doi:10.1029/2012GL054403

Zanchettin, D., Bothe, O., Lehner, F., Ortega, P., Raible, C. C., and Swingedouw, D. (2015a) Reconciling reconstructed and simulated features of the winter Pacific/North American pattern in the early 19th century, Clim. Past, 11, 939-958, doi:10.5194/cp-11-939-2015

Zanchettin, D., C. Timmreck, H. F. Graf, A. Rubino, S. Lorenz, K. Lohmann, K. Krueger, and J. H. Jungclaus (2012) Bi-decadal variability excited in the coupled ocean-atmosphere system by strong tropical volcanic eruptions. Clim. Dyn., 39:1-2, 419-444, doi:10.1007/s00382-011-1167-1

Zanchettin, D., C. Timmreck, M. Khodri, A. Robock, A. Rubino, A. Schmidt and M. Toohey (2015b) A coordinated modeling assessment of the climate response to volcanic forcing. PAGES Magazine, 32(2): 54-55

Zanchettin, D., O. Bothe, C. Timmreck, J. Bader, A. Beitsch, H.-F. Graf, D. Notz and J. H. Jungclaus (2014) Inter-hemispheric asymmetry in the sea-ice response to volcanic forcing simulated by MPI-ESM (COSMOS-Mill). Earth Syst. Dynam., 5, 223–242, doi:10.5194/esd-5-223-2014

Zanchettin, D., O. Bothe, H. F. Graf, S. J. Lorenz, J. Luterbacher, C. Timmreck and J. H. Jungclaus (2013a) Background conditions influence the decadal climate response to strong volcanic eruptions, J. Geophys. Res. Atmos., 118, doi:10.1002/jgrd.50229

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Figures
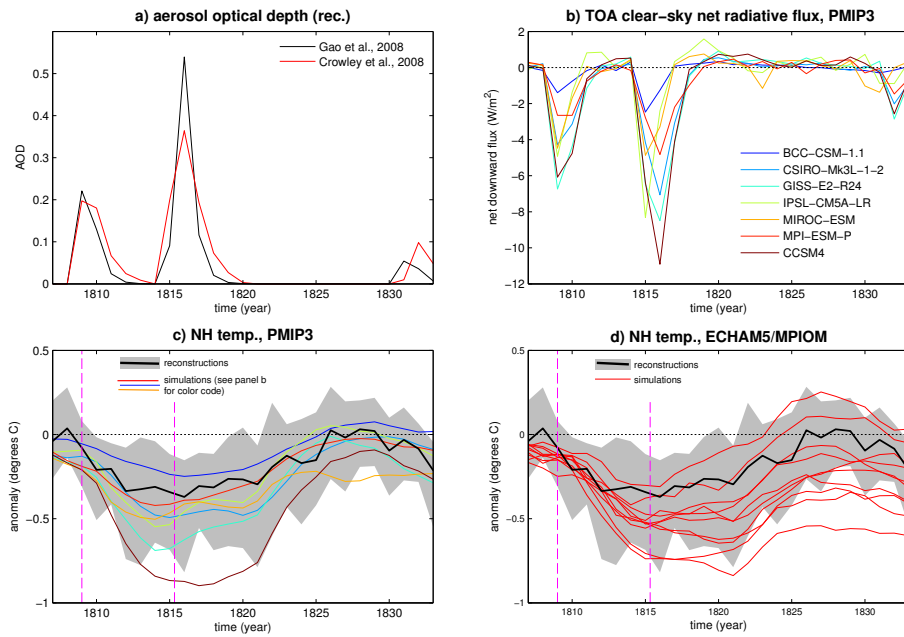
Figure 1: Uncertainty in radiative forcing and climate response for the early-19th-century eruptions. (**a**) two estimates of annual-average global aerosol optical depth at 550 nm (AOD); (**b**) top-of-atmosphere annual-average net clear-sky radiative flux anomalies for a multi-model ensemble of last-millennium simulations (PMIP3; see: Braconnot et al., 2012); (**c**) comparison between simulated (PMIP3, 11-year smoothing, colors) and reconstructed (black line: mean; shading: 5th-95th percentile range) Northern Hemisphere average summer temperature anomalies (relative to 1799-1808); (**d**) same as (**c**), but for a pre-PMIP3 single-model ensemble (ECHAM5/MPIOM; Zanchettin et al. 2013a,b). Reconstructed data are the full raw calibration ensemble by Frank et al. [2010].
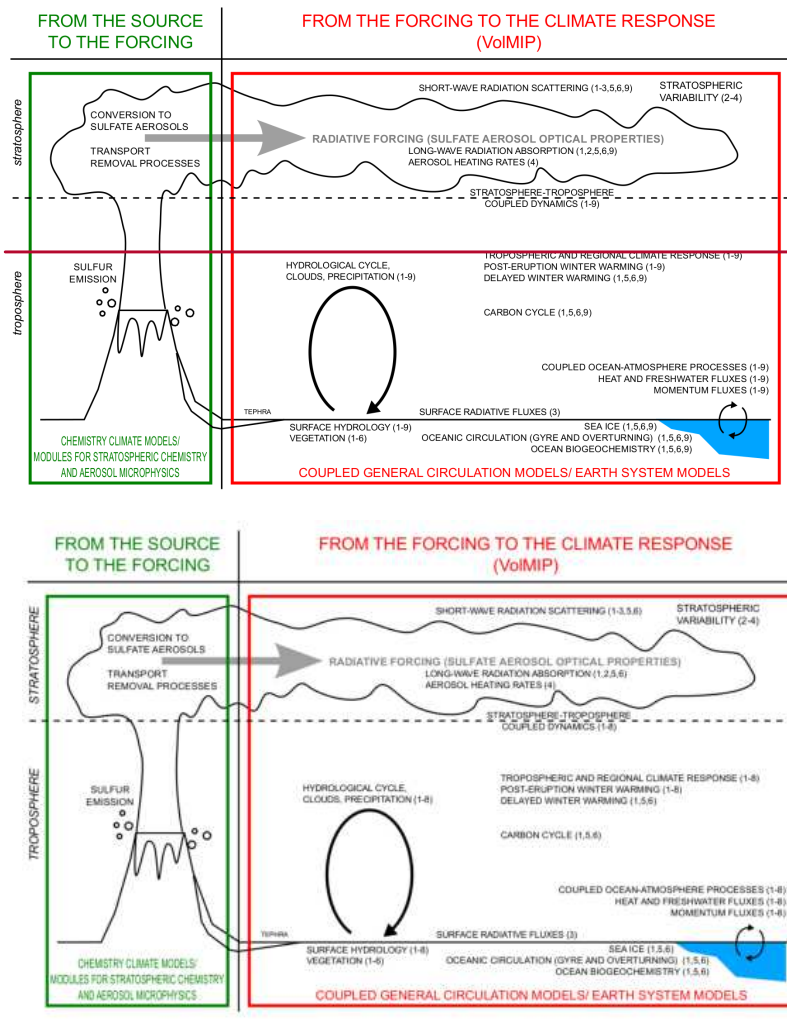
Figure 2: Illustrating the dominant processes linking volcanic eruptions and climate response, with an overview of VolMIP experiments: 1: ~~VolcLong~~volc-long ~~Single-Eq~~eq, 2: ~~VolcShort~~volc-pinatubo ~~Eq~~-full, 3: ~~VolcShort~~volc-pinatubo ~~Eq~~-surf, 4: ~~VolcShort~~volc-pinatubo ~~Eq~~-strat, 5: ~~VolcLong~~volc-long ~~Single-~~ ~~HL~~hlN/-hlS, 6: ~~VolcLong~~volc-~~Cluster~~cluster-~~Ctrl~~ctrl/-mill/-21C, 7: ~~VolcShort~~volc-pinatubo ~~Eq~~-slab, 8: ~~VolcShort~~volc-pinatubo ~~Eq~~-ini~~, 9: VolcLong-Cluster-Mill~~. The red box encompasses the processes related

to the climatic response to volcanic forcing that are accounted for in VolMIP; the green box encompasses the processes regarding volcanic forcing that are neglected by VolMIP.

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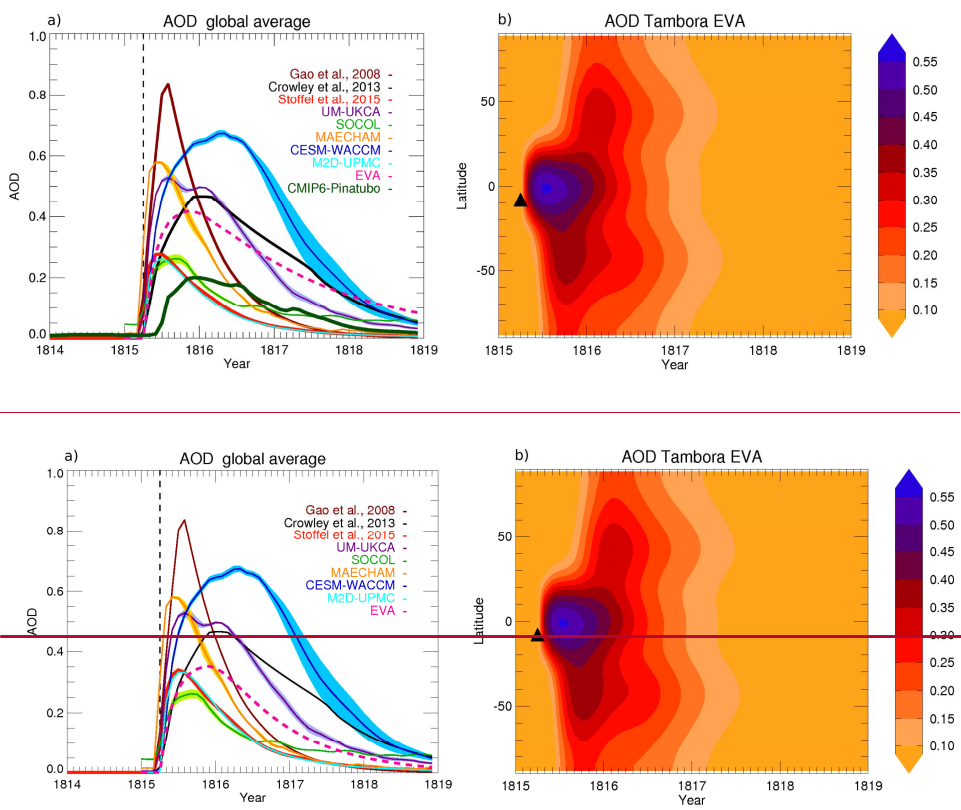
Figure 3: (**a**) Uncertainty in estimates of radiative forcing parameters for the 1815 eruption of Mt Tambora: global-average aerosol optical depth (AOD) in the visible band from an ensemble of simulations

1220   with chemistry climate models forced with a 60 Tg SO$_2$ equatorial eruption, from the Easy Volcanic Aerosol module (EVA) with 56.2 Tg SO$_2$ equatorial eruptions (magenta thick dashed line), from Stoffel et

al. (2015), from Crowley and Unterman (2013), and from Gao et al. (2008, aligned so that the eruption starts on April 1815). The estimate for the Pinatubo eruption as used in the CMIP6 *historical* experiment is also reported for comparison. (**b**) Time-latitude plot of the AOD in the visible band produced by EVA for a 56.2 Tg SO$_2$ equatorial eruption, illustrating the consensus forcing for the ~~VolcLong~~volc-long-~~Single~~-~~e~~Eq experiment. The black triangle shows latitudinal position and timing of the eruption.

Chemistry climate models are CESM (WACCM) (Mills et al., 2016), MAECHAM5-HAM (Niemeier et al., 2009), SOCOL (Sheng et al., 2015), UM-UKCA (Dhomse et al., 2014), CAMB-UPMC-M2D (Bekki, 1995; Bekki et al., ~~1995,~~ 1996). For models producing an ensemble of simulations, the line and shading are the ensemble mean and ensemble standard deviation, respectively.
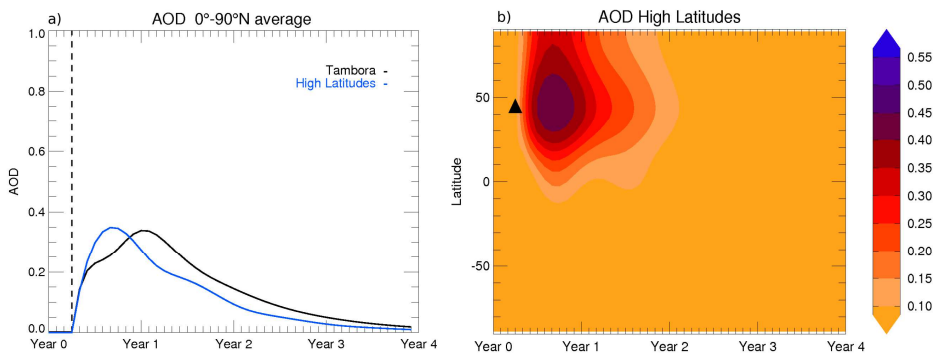
Figure 4: Consensus forcing for the ~~VolcLong~~volc-long-~~Single~~-hl~~N~~NH~~L~~ experiment. (**a**) Northern Hemisphere-average aerosol optical depth (AOD) at 550 nm produced by the Easy Volcanic Aerosol module (EVA) for a 56.2 Tg equatorial eruption (~~VolcLong~~volc-long-~~Single~~-~~e~~Eq, black line) and for a 28.1 Tg SO$_2$ Northern Hemisphere extra-tropical eruption (~~VolcLong~~volc-long-~~Single~~-hl~~N~~NH~~L~~, blue line). (**b**) Time-latitude plots of the AOD at 550 nm from EVA for the 28.1 Tg SO$_2$ Northern Hemisphere extra-tropical eruption. The black triangle shows latitudinal position and timing of the eruption.

Tables

Table 1 – Tier 1 VolMIP experiments

Name	Description	Parent experiment, start date	Ens. Size	Years per simulation (minimum)	Total years	Gaps of knowledge being addressed with this experiment
~~VolcLong~~volc-long ~~Single~~ ~~e~~Eq	Idealized equatorial eruption corresponding to an initial emission of 56.2 Tg of SO_2. The eruption magnitude corresponds to recent estimates for the 1815 Tambora eruption (Sigl et al., 2015), the largest ~~historical~~ tropical eruption of the last five centuries, which was linked to the so-called "year without a summer" in 1816.	*~~PiControl~~piControl, April 1st*	9	20	180	Uncertainty in the climate response to strong volcanic eruptions, with focus on coupled ocean-atmosphere feedbacks and interannual to decadal global as well as regional responses. The mismatch between reconstructed and simulated climate responses to historical strong volcanic eruptions, with focus on the role of simulated background internal climate variability.
~~VolcShort~~volc-pinatubo ~~Eq~~-full	1991 Pinatubo forcing as used in the CMIP6 *historical* simulations. Requires special diagnostics of parameterized and resolved wave forcings, radiative and latent heating rates. A large number of ensemble members is required to address internal atmospheric variability	*~~PiControl~~piControl, June 1st*	25	3	75	Uncertainty in the climate response to strong volcanic eruptions with focus on short-term response. Robustness of volcanic imprints on Northern Hemisphere's winter climate and of associated dynamics.
~~VolcShort~~volc-pinatubo ~~Eq~~-surf	As ~~VolcShort~~volc-pinatubo ~~Eq~~-full, but with prescribed perturbation to the shortwave flux to mimic the attenuation of solar radiation by volcanic aerosols	*~~PiControl~~piControl, June 1st*	25	3	75	Mechanism(s) underlying the dynamical atmospheric response to large volcanic eruptions, in particular in Northern Hemisphere's winters. The experiment considers only the effect of volcanically induced surface cooling. Complimentary experiment to ~~VolcShort~~volc-pinatubo ~~Eq~~-strat.
~~VolcShort~~volc-pinatubo ~~Eq~~-strat	As ~~VolcShort~~volc-pinatubo ~~Eq~~-full, but with prescribed perturbation to the total (LW+SW) radiative heating rates	*~~PiControl~~piControl June 1st*	25	3	75	Mechanism(s) underlying the dynamical atmospheric response to large volcanic eruptions, in particular in Northern Hemisphere's winter. The experiment considers only the effect of volcanically-induced stratospheric heating. Complimentary experiment to ~~VolcShort~~volc-pinatubo ~~Eq~~-surf.

Volc = Volcano, Long = long-term simulation, pinatubo~~Short~~ = short-term simulation of the 1991 Pinatubo eruption, ~~Eq~~ eq = equator, full = full-forcing simulation, surf = short-wave forcing only, strat = stratospheric thermal (long-wave) forcing only

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Table 2 – Tier 2 VolMIP experiments

Name	Description	Parent experiment, start date	Ens. Size	Years per simulation	Total years	Gaps of knowledge being addressed with this experiment
~~VolcLong~~volc-long ~~Single~~hlN~~HL~~	Idealized Northern Hemisphere high-latitude eruption emitting 28.1 Tg of SO_2.	~~PiControl~~ piControl April 1st	9	20	180	Uncertainty in climate response to strong high-latitude volcanic eruptions (focus on coupled ocean-atmosphere). Outstanding questions about the magnitude of the climatic impact of high-latitude eruptions.
~~VolcLong~~volc-~~C~~cluster-~~C~~ctrl	Early 19th century cluster of strong tropical volcanic eruptions, including the 1809 event of unknown location, and the 1815 Tambora and 1835 Cosigüina eruptions.	~~PiControl~~ piControl January 1st 1809	3	50	150	Uncertainty in the multi-decadal climate response to strong volcanic eruptions (focus on long-term climatic implications). Contribution of volcanic forcing to the climate of the early 19th century, the coldest period in the past 500 years. Discrepancies between simulated and reconstructed climates of the early 19th century.

~~Volc~~volc = ~~Volcano~~volcano, ~~Long~~long = long-term simulation, ~~HL~~hlN = Northern Hemisphere high latitude, ~~C~~ctrl = initial state from control simulation

Table 3 – Tier 3 VolMIP experiments

Name	Description	Parent experiment, start date	Ens. Size	Years per simulation	Total years	Gaps of knowledge being addressed with this experiment
control-slab	Slab ocean control run, necessary for volc-pinatubo-slab	-	1	30	30	-
VolcShortvolc-pinatubo-Eq-slab	As VolcShortvolc-pinatubo-Eq-full, but with a slab ocean	control-slabPiControl June 1st	25	3	75	Effects of volcanic eruptions on ENSO dynamics.
VolcShortvolc-pinatubo-Eq-ini/ DCPP C3.42	As VolcShortvolc-pinatubo-Eq-full, but as decadal prediction runs joint experiment with DCPP. Forcing input and implementation of the forcing fully comply with the VolMIP protocol.	2015 (initialization date depends on the system)	10(5)	5	50	Influence of large volcanic eruptions in on future climate. Influence of large volcanic eruptions on seasonal and decadal climate predictability
VolcLongvolc-Clustercluster-Millmill	Parallel experiment to VolcLongvolc-cCluster-cCtrl, but with initial conditions taken from last millennium simulation to account for the effects of a more realistic history of past natural forcing in order to avoid ocean drifts due to a climate not in equilibrium with volcanic forcing	PMIP-Past1000past1000, January 1st 1809	3(1)	69	207	Contribution of volcanic forcing to the climate of the early 19th century, the coldest period in the past 500 years. Discrepancies between simulated and reconstructed climates of the early 19th century. Effect of history of volcanic forcing on the response to volcanic eruptions.
volc-cluster-21C	Parallel experiment to volc-cluster-ctrl, using restart files from the end of the historical simulation instead of from piControl, and boundary conditions from the 21st century SSP2-4.5 scenario experiment of ScenarioMIP	historical, January 1st 2015	3(1)	85	255	Contribution of volcanic forcing uncertainty to uncertainty in future climate projections Long-term climate response to volcanic eruptions under warm background climate conditions
volc-long-hlS	Idealized Southern Hemisphere high-latitude eruption emitting 28.1 Tg of SO_2.	piControl April 1st	9	20	180	Uncertainty in climate response to strong high-latitude volcanic eruptions (focus on coupled ocean-atmosphere). Outstanding questions about the magnitude of the climatic impact of high-latitude eruptions.

Volc volc = Volcanovolcano, lLong = long-term simulation, Short pinatubo = short-term simulation of the 1991 Pinatubo eruption, Eq eq = equator, slab = slab ocean simulation, ini = simulation initialized for decadal prediction, Mill mill = initial conditions from full forcing transient simulation of the last millennium, 21C= 21st century scenario experiment, hlS = Southern Hemisphere high-latitude eruption

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Table 4 - **Definition of new variables requested by VolMIP. These have not been previously used in CMIP5, CCMI, CORDEX or SPECS. Shape is**
1295 **defined as time (T), longitude (X), latitude (Y) and height (Z)**

Short name	Standard name	units	description/comments	Shape	Levels	Time
aod550volso4	stratosphere optical thickness due to volcanic aerosol particles		aerosol optical thickness at 550 nm due to stratospheric volcanic aerosols	YZT	all	instantaneous
zmswaero	tendency of air temperature due to shortwave heating from volcanic aerosol particles	$K\ s^{-1}$	shortwave heating rate due to volcanic aerosols to be diagnosed through double radiation call, zonal average values required	YZT	all	instantaneous
zmlwaero	tendency of air temperature due to longwave heating from volcanic aerosol particles	$K\ s^{-1}$	longwave heating rate due to volcanic aerosols to be diagnosed through double radiation call, zonal average values required	XYT	1	instantaneous
swsffluxaero	surface downwelling shortwave flux in air due to volcanic aerosols	$W\ m^{-2}$	downwelling shortwave flux due to volcanic aerosols at the surface to be diagnosed through double radiation call	XYT	1	instantaneous
lwsffluxaero	surface downwelling longwave flux in air due to volcanic aerosols	$W\ m^{-2}$	downwelling longwave flux due to volcanic aerosols at the surface to be diagnosed through double radiation call	XYT	1	instantaneous
swtoafluxaerocs	toa outgoing shortwave flux due to volcanic aerosols assuming clear sky	$W\ m^{-2}$	downwelling shortwave flux due to volcanic aerosols at TOA under clear sky to be diagnosed through double radiation call	XYT	1	instantaneous
lwtoafluxaerocs	toa outgoing longwave flux due to volcanic aerosols assuming clear sky	$W\ m^{-2}$	downwelling longwave flux due to volcanic aerosols at TOA under clear sky to be diagnosed through double radiation call	XYT	1	daily mean

Table 5 - Protocol for the chemistry climate model experiment to assess volcanic forcing uncertainty for the
~~*VolcLong*~~*volc-long-*~~*Single-*~~*cEq* **experiment**

SO$_2$ emission	Eruption length	Latitude	QBO phase at time of eruption	SO$_2$ height injection	SST	Other radiative forcing	Duration	Ens. size
60 Tg SO$_2$	24 hours	Centered at the equator	Easterly phase (as for Pinatubo and El Chichón)	Same as Pinatubo. 100% of the mass between 22 and 26 km, increasing linearly with height from zero at 22 to max at 24 km, and then decreasing linearly to zero at 26 km.	Climatological from preindustrial control run	Preindustrial CO$_2$, other greenhouse gases, tropospheric aerosols (and O$_3$ if specified)	5-years long	5 members