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

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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 Model Intercomparison Project (CMIP5). In order to better understand the sources of these model diversities, the model intercomparison project on the climate 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 differences in the applied volcanic forcing, and defines a set of initial conditions to determine 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.

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1. Introduction

Volcanic eruptions that eject substantial amounts of sulfur dioxide (SO_2) into the atmosphere have been the dominant natural cause 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 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 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). There is also large uncertainty across CMIP5 models concerning the short-term dynamical atmospheric response, 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. 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) 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). 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 to 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), 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). 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 hardly 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, 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

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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 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 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) and the *past1000* simulations of the Paleoclimate MIP (PMIP) 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 experiment is based on "time-dependent observations" (Eyring et al., 2015), and some modeling groups may therefore perform the simulations using online calculation of volcanic radiative forcing based on SO_2 emissions.

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.

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 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* (i.e., preindustrial control) simulation describing unperturbed preindustrial climate conditions (Eyring et al., 2015), unless specified otherwise.

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VolMIP experiments are designed based on a twofold strategy. A first set of experiments (*VolcShort*) 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 magnitude of volcanic events that occurred during the observational period. *VolcShort* 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 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* experiments includes 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*) 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 temperature. The main goal of *VolcLong* experiments is to assess how volcanic perturbation signals propagate within the simulated climates, e.g., into the deep 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 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*

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experiments, interannual and decadal modes for *VolcLong* 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 must be accordingly selected and documented in the metadata of each simulation. If no restart data is 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 integration, except for the volcanic forcing.

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 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 VolcShort

2.1.1 **VolcShort-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 Biennial Oscillation (QBO), as observed after the 1991 Pinatubo eruption, is preferred for those models that spontaneously generate such mode of stratospheric variability. A minimum length of integration of three years is requested.

The recommended ENSO index is the 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 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.

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2.1.2 VolcShort-Eq-surf and VolcShort-Eq-strat

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 (*VolcShort-Eq-strat*) and surface cooling (*VolcShort-Eq-surf*). Both experiments are built upon *VolcShort-Eq-full* and designed in cooperation with the Dynamics and Variability of the Stratosphere–Troposphere System (DynVar) project. Therefore, DynVar diagnostics must be calculated for *VolcShort-Eq-full/surf/strat*.

2.1.3 VolcShort-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 minimum length of integration of three years and at least 25 ensemble members are requested.

2.1.4 VolcShort-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) (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.

2.2 VolcLong

2.2.1 VolcLong-Single-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 (Table 1). 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 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.

2.2.2 VolcLong-Single-HL

Non-mandatory experiment that applies the same approach as *VolcLong-Single-Eq* and extends the investigation to the case of an idealized strong high-latitude volcanic eruption (Table 2). This experiment is designed as a Northern Hemisphere extra-tropical eruption with SO_2 injection equal to half the total amount injected for the *VolcLong-Single-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-Single-Eq* and *VolcLong-Single-HL* as both should yield similar forcing over the Northern Hemisphere (but see Section 3.3). The initialization procedure and required integration length are the same as for *VolcLong-Single-Eq*. Both experiments are expected to contribute to outstanding questions about the magnitude of the climatic impact of high-latitude eruptions, especially concerning the inter-hemispheric response.

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-Single-HL* 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).

2.2.3 VolcLong-Cluster-Ctrl

A “volcanic cluster” experiment to investigate the climatic response to a close succession of strong volcanic eruptions (Table 2). The experiment is motivated by the large uncertainties in the multidecadal and longer-term climate repercussions of prolonged periods of strong volcanic activity (e.g., Miller et al., 2012; Schleussner and Feulner, 2013; Zanchettin et al., 2013a). 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.

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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 be sampled from the PiControl for consistency with the *VolcLong-Single* experiments.

2.2.4 VolcLong-Cluster-Mill

A parallel experiment to *VolcLong-Cluster-Ctrl* using restart files from PMIP-past1000 instead of from PiControl (see Table 2). Starting from a climate state that experienced realistic past volcanic forcing, this experiment allows to explore the sensitivity of ocean response to the initial state, which has been highlighted to be significant particularly for preindustrial controls that do not include background volcanic aerosols [Gregory, 2010]. *VolcLong-Cluster- 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-Cluster-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-Cluster-Ctrl*. However, the simulation must be initialized in January 1st 1790 to avoid interferences due to the decadal drop of solar activity associated with the Dalton Minimum. Hence, the experiment proper lasts 50-years as *VolcLong-Cluster-Ctrl*, but a total of 69 years for each ensemble member are actually requested. Different members of the *VolcLong-Cluster-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 for the full duration of the experiment.

3. Forcing

3.1 Implementation: general aspects

VolMIP identifies a volcanic forcing dataset for each experiment included in the protocol. The forcing parameters can 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 calculated based on the tool and guidelines described in the protocol. The latter is the case for experiments using forcing input data specifically created for VolMIP.

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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 VolcShort

VolcShort-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 up for the CMIP6 historical simulation. *VolcShort-Eq-surf* and *VolcShort-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-Eq-full* experiment. Specifically, *VolcShort-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 impact of shortwave reflection from the impact of aerosol heating in the stratosphere. The changes must be prescribed at the top of atmosphere under clear sky conditions (variable swtoafluxaerocs of VIRF). Similarly, *VolcShort-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 tendency. VolMIP does not enforce the same perturbation across all models in *VolcShort-Eq-surf* and *VolcShort-Eq-strat*, as for both mechanistic experiments priority is given to the consistency with the corresponding *VolcShort-Eq-full* experiment.

3.3 VolcLong

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* experiments. Therefore, for the *VolcLong-Single-Eq* experiment, coordinated climate simulations of the 1815 eruption of Mt. Tambora (see Table 5) were performed with different climate models including modules for stratospheric chemistry and

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aerosol microphysics (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 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 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* experiments forcing data sets constructed with the Easy Volcanic Aerosol (EVA) module (Toohey et al., 2016). 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 given eruption sulfur injection and latitude with idealized spatial and temporal structure, constructed so as to produce good agreement with observations of the aerosol evolution following the 1991 Pinatubo eruption. Scaling to larger eruption magnitudes is performed in a manner consistent with the forcing reconstruction of Crowley and Unterman (2013). EVA is also used to construct the volcanic forcing dataset used for 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 given latitudes, heights and wavelength bands. It therefore is an improvement compared to previously available volcanic forcing datasets for the pre-observational period. Toohey et al. (2016) 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 Tambora eruption of 56.2 Tg to be used in *VolcLong-Single-Eq*. *VolcLong-Cluster-Ctrl* and *VolcLong-Cluster-Mill* include all eruptions represented in the PMIP-past1000 experiment for the overlapping period.

The reference SO_2 emission for the *VolcLong-Single-HL* experiment is equal to one-half the Tambora value. The evolution of aerosol optical depth (AOD) by EVA for a high-latitude injection of 28.1 Tg of SO_2

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is illustrated in Figure 4. The Northern Hemisphere average AOD for the *VolcLong-Single-HL* and *VolcLong-Single-Eq* experiments are quite similar in magnitude and temporal structure. Differences occur 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 Northern Hemisphere mean AOD for *VolcLong-Single-Eq* compared to *VolcLong-Single-HL*. It also leads to generally somewhat less aerosol transported to the Northern compared to the Southern Hemisphere for *VolcLong-Single-Eq*, which explains the lower peak AOD for this experiment than for *VolcLong-Single-HL*.

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 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) 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* 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. 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 be calculated for a period of five years starting from the eruption year, and would be useful for future studies to expand the investigation based on *VolcShort-Eq-strat* and *VolcShort-Eq-surf*.

VolMIP and the Detection and Attribution MIP (DAMIP) share the CMIP6 science theme of characterizing forcing. The experiments *histALL*, *histNAT*, *histVLC* and *histALL_aerconc* of DAMIP include the 1991 Pinatubo eruption within transient climate situations and therefore provide context to the *VolcShort* set of VolMIP experiments.

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-Eq-ini* and the DCPP experiment *C2* are different labels for the same experiment). The DynVar activity 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* 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," 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., 2016b) 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.

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- “Rapid cryosphere changes,” 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.

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

The design of the simulations reflects necessary constrains 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 Southern Hemispheric annular mode (e.g., Karpechko et al., 2010; 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. 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-simulations assessments cannot also leave aside 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 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 models by (i) constraining the applied radiative forcing, proposing 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 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. Both 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 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 centres (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. 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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Figures

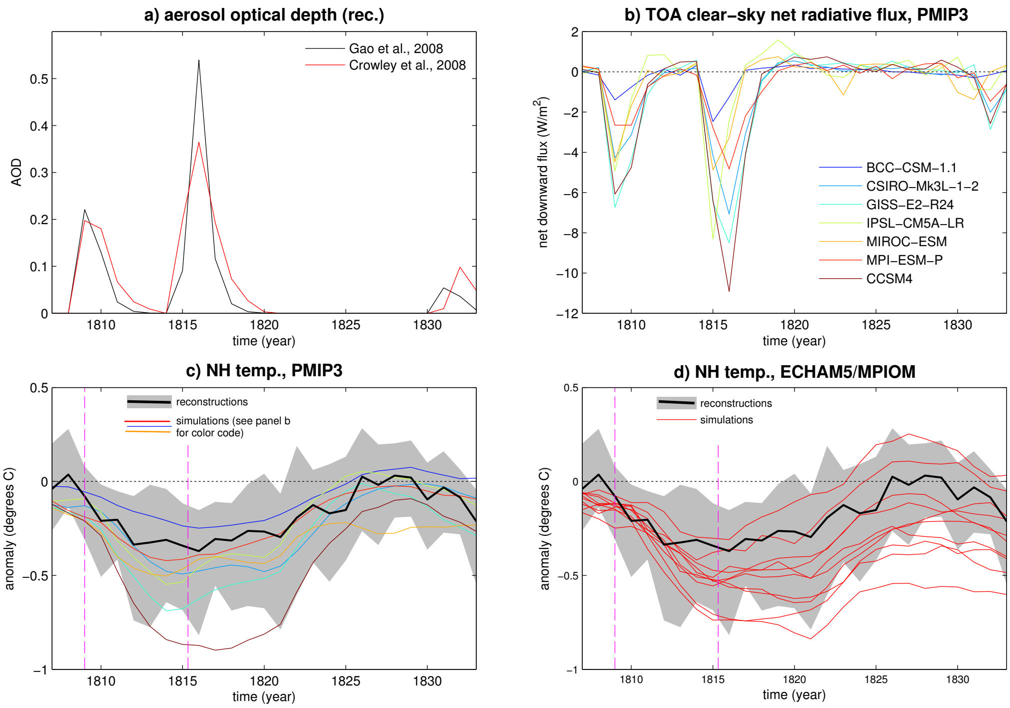

Figure 1: Uncertainty in radiative forcing and climate response for the early-19th-century eruptions. (**a**) two estimates of annual-average global aerosol optical depth at 550 nm (AOD); (**b**) top-of-atmosphere annual-average net clear-sky radiative flux anomalies for a multi-model ensemble of last-millennium 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].

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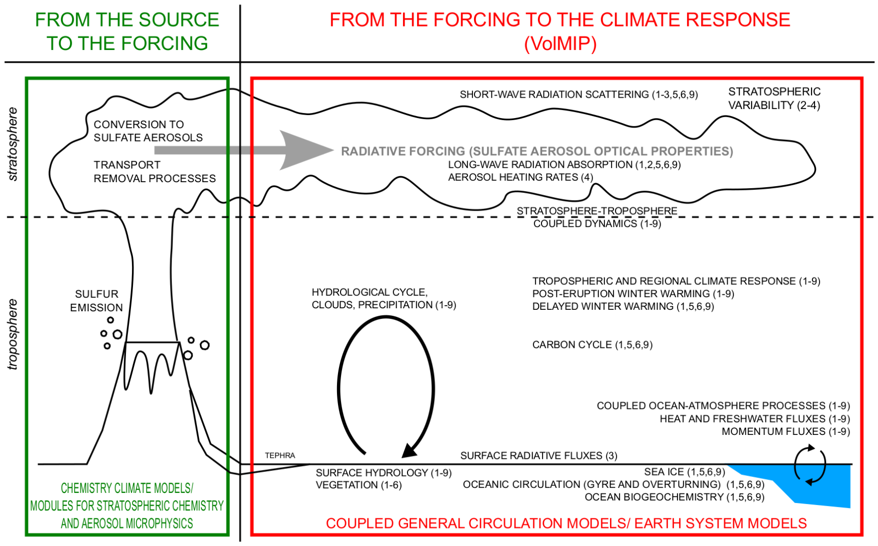

Figure 2: Illustrating the dominant processes linking volcanic eruptions and climate response, with an overview of VolMIP experiments: 1: VolcLong-Single-Eq, 2: VolcShort-Eq-full, 3: VolcShort-Eq-surf, 4: VolcShort-Eq-strat, 5: VolcLong-Single-HL, 6: VolcLong-Cluster-Ctrl, 7: VolcShort-Eq-slab, 8: VolcShort-Eq-ini, 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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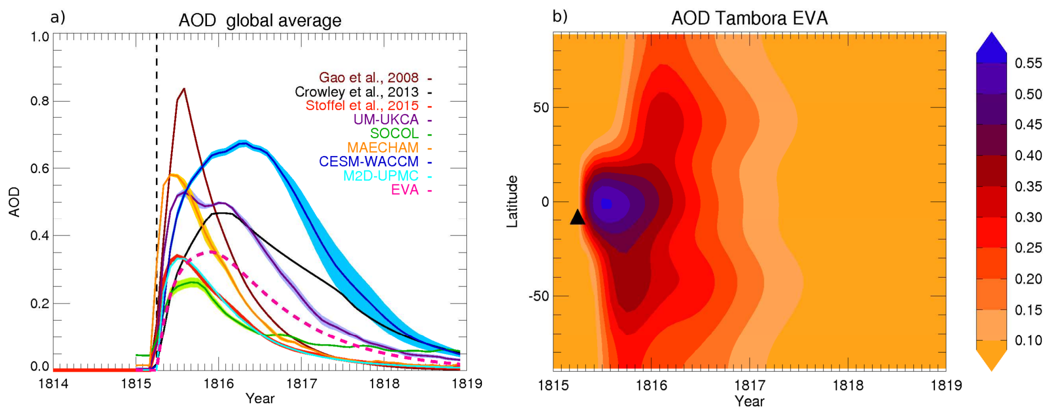

Figure 3: (**a**) Uncertainty in estimates of radiative forcing parameters for the 1815 eruption of Mt Tambora: global-average aerosol optical depth (AOD) in the visible band from an ensemble of simulations with chemistry climate models forced with a 60 Tg SO_2 equatorial eruption, from the Easy Volcanic 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). (**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-Single-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 et al., 1995, 1996). For models producing an ensemble of simulations, the line and shading are the ensemble mean and ensemble standard deviation, respectively.

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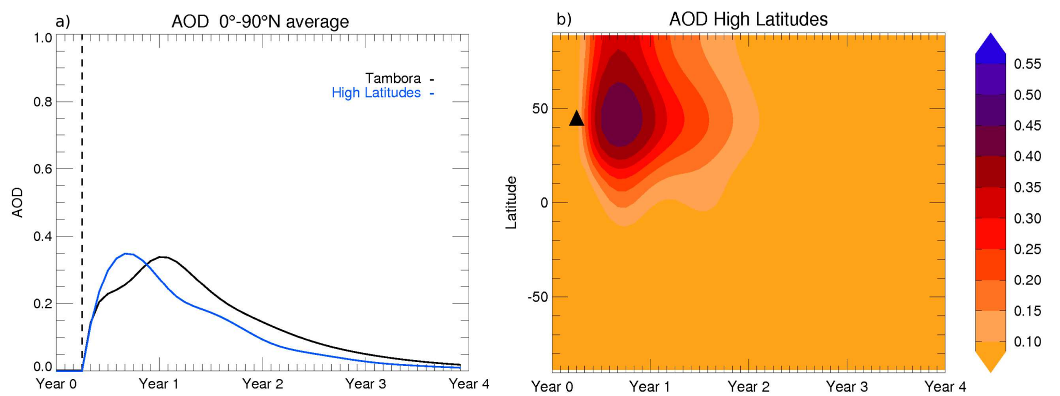

Figure 4: Consensus forcing for the *VolcLong-Single-HL* experiment. (**a**) Northern Hemisphere-average aerosol optical depth (AOD) at 550 nm produced by the Easy Volcanic Aerosol module (EVA) for a 56.2 Tg equatorial eruption (*VolcLong-Single-Eq*, black line) and for a 28.1 Tg SO_2 Northern Hemisphere extra-tropical eruption (*VolcLong-Single-HL*, 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-Single-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, which was linked to the so-called "year without a summer" in 1816.	*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-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, 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-Eq-surf	As VolcShort-Eq-full, but with prescribed perturbation to the shortwave flux to mimic the attenuation of solar radiation by volcanic aerosols	*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-Eq-strat.
VolcShort-Eq-strat	As VolcShort-Eq-full, but with prescribed perturbation to the total (LW+SW) radiative heating rates	*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-Eq-surf.

Volc = Volcano, Long = long-term simulation, Short = short-term simulation, 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-Single-HL	Idealized 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.
VolcLong-Cluster-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 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 = Volcano, Long = long-term simulation, HL = high latitude, Ctrl = initial state from control simulation

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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
VolcShort-Eq-slab	As VolcShort-Eq-full, but with a slab ocean	*PiControl June 1st*	25	3	75	Effects of volcanic eruptions on ENSO dynamics.
VolcShort-Eq-ini/ DCPP C2	As VolcShort-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	10(5)	5	50	Influence of large volcanic eruptions in future climate. Influence of large volcanic eruptions on seasonal and decadal climate predictability
VolcLong-Cluster-Mill	Parallel experiment to VolcLong-Cluster-Ctrl, but with initial conditions taken from last millennium simulation in order to avoid ocean drifts due to a climate not in equilibrium with volcanic forcing	*PMIP-Past1000, 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 = Volcano, Long = long-term simulation, Short = short-term simulation, Eq = equator, slab = slab ocean simulation, ini = simulation initialized for decadal prediction, Mill = initial conditions from full forcing transient simulation of the last millennium

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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 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

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Table 5 - Protocol for the chemistry climate model experiment to assess volcanic forcing uncertainty for the *VolcLong-Single-Eq* 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