Application for a Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP) as CMIP6-Endorsed MIP

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VolMIP

Name of MIP: "VolMIP - Model Intercomparison Project on the climatic response to Volcanic forcing"

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WCRP webpage:
http://www.wcrp-climate.org/index.php/modelling-wgcm-mip-catalogue/modelling-wgcm-mips/505-modelling-wgcm-volmip
Official webpage: under construction

- Goal of the MIP and a brief overview

VolMIP focuses on one of the three broad CMIP questions: How does the Earth system respond to external forcing? It is motivated by the large uncertainties regarding the climatic responses to strong volcanic eruptions identified in CMIP5 simulations (e.g., Driscoll et al., 2012; Ding et al., 2014) and the apparent mismatch between simulated and reconstructed post-eruption surface cooling for volcanic eruptions reconstructed for the last millennium (Mann et al., 2012, 2013; Anchukaitis et al., 2012; D'Arrigo et al., 2013; Schurer et al., 2013). Therefore, VolMIP will assess to what extent responses of the coupled ocean-atmosphere system to 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 the models' treatment of physical processes. For these purposes, VolMIP defines a common protocol to improve comparability of results across different earth system models and coupled general circulation models, and accordingly subjects them to the same set of idealized volcanic perturbations under similar background climate conditions (Zanchettin et al., in prep, 2014a).

VolMIP experiments will be designed based on a twofold strategy. First, coupled climate model experiments will be based on a limited set of historical and prehistoric volcanic eruptions as well as of volcanic clusters, i.e., close successions of strong volcanic eruptions. These will be used to systematically investigate inter-model differences in the interannual and decadal dynamical response of the coupled ocean-atmosphere system. Available instrumental and climate proxy data for such events will allow for a comparative assessment of simulated and observed/reconstructed responses, with a strong focus on regional features. Then, idealized volcanic perturbation experiments will be used to tackle specific issues related to uncertainties in the direct radiative and short-term dynamical atmospheric responses. In particular, sensitivity experiments separating the short- and long-wave impacts of volcanic aerosols will be used to investigate the individual climatic imprints of volcanically-forced surface cooling and stratospheric warming.

VolMIP will contribute towards advancing our understanding of the dominant mechanisms behind simulated post-eruption climate evolution, but also more generally enhance our understanding of climate dynamics and decadal variability. Volcanic eruptions offer the opportunity to assess the climate system's dynamical response to changes in radiative forcing, a major uncertainty in future climate projections. Careful sampling of initial climate conditions and consideration of volcanic eruptions of different strengths (e.g., Fröhlicher et al, 2012; Muthers et al., 2014a,b; Pausata et al., 2014; Zanchettin et al., 2014b) will allow a better understanding of the relative role of internal and externally-forced climate variability during periods of strong volcanic activity, hence improving the evaluation of climate models and enhancing our ability to accurately simulate past, as well as future, climates.

VolMIP will be a protocol-driven international multi-model project with data production and data sharing as integral components.

➢ An overview of the proposed experiments

VolMIP will entail two types of experiments: historical eruption experiments (Type-I) and mechanistic volcanic forcing experiments (Type-II).

Type-I: Historical eruption experiments

VolMIP will use a set of volcanic forcing data sets for individual historical eruptions reconstructed from observations and aerosol-climate model simulations. While the volcanic forcing will be as realistic as possible, with eruption details (including SO_2 emission strength, location, duration and season) based on observations and documentation, the experiments will not account for the actual climate conditions when these events occurred (e.g., presence and strength of additional forcing factors). Instead, the experiments for each volcanic event are designed to span very different initial climate states to systematically assess uncertainties in the post-eruption behavior that are related to background climate conditions. Candidate events currently under consideration are: 1815 Tambora, 1783-84 Laki and 74kya Toba.

Additionally, VolMIP will propose a set of "volcanic cluster" experiments to investigate the climate response to close successions of strong volcanic eruptions. Candidate events currently under consideration are: the 13th century volcanic cluster (including Samalas/1257) and the early 19th century volcanic cluster (including the 1809 eruption of unknown location and the 1815 Tambora and 1835 Cosigüina eruptions).

Type-II: Mechanistic volcanic forcing experiments

VolMIP will carry out highly idealized forcing experiments aimed at investigating the mechanism(s) connecting volcanic forcing and short-term dynamical climate anomalies. Specifically, the experiments will separate the roles of increased stratospheric long-wave absorption and decreased surface short-wave absorption in the presence of a stratospheric volcanic aerosol cloud on atmospheric dynamics. The mechanistic volcanic forcing experiments will be carried out at first for an idealized tropical eruption of Pinatubo-like strength. More realistic Pinatubo simulations are planned for a later stage.

➢ An overview of the proposed evaluation/analysis of the CMIP DECK and CMIP6 experiments

VolMIP experiments will provide context to CMIP DECK simulations where volcanic forcing is among the dominant sources of climate variability. These include *historical* and *past1000* simulations.

➢ Proposed timing

2014 - 2015 – Experimental design phase and definition of consensus volcanic forcing input

2015 - 2016 – Execution of experiments

2016 – Public sharing and analysis of model output

➢ For each proposed experiment to be included in CMIP6

- the experimental design;

  In the following we distinguish between two different types of experiments:

  Type-I: historical eruptions, further separated in single event simulations (Type-IA) and simulations of volcanic clusters (Type-IB)

  Type-II: mechanistic volcanic forcing experiments

  - **Length of integration**
    - (Type-IA): for each simulation: at least 20 years, but preferably longer (30-40 years) to cover the multi-decadal oceanic response;

- (Type-IB): at least 100 years to determine stationarity of post-cluster climate;
- (Type-II): for each simulation: ten years, fully covering at least one decade.

▪ **Initial conditions**:
- (Type-I): predefined states describing different states of dominant modes of variability (see "ensemble size") sampled from an unperturbed control integration, under common constant boundary forcing across the different models (*PiControl* simulations from CMIP/PMIP). The VolMIP experiments should maintain the same constant boundary forcing as the control integration, except for the volcanic forcing;
- (Type-II): same as (Type-I).

▪ **Ensemble size**:
- (Type-IA): should be large to systematically account for the range of variability depicted by the dominant processes influencing interannual and decadal climate variability. VolMIP will accordingly identify a set of desired initial conditions. Nine simulations would allow spanning warm/cold/neutral and strong/weak/neutral states of El Niño Southern Oscillation (ENSO and of the Atlantic Meridional Overturning Circulation (AMOC), respectively;
- (Type-IB): at least an ensemble of three simulations;
- (Type-II): same rationale as for (Type-IA), but further taking into account also additional phenomena primarily contributing to internal atmospheric variability, such as the Quasi Biennial Oscillation (QBO), the characteristics of the polar vortex and the North Atlantic Oscillation (NAO). Up to 45 (core 20) members can be expected for each ensemble.

▪ **Forcing input:** For an event to be eventually included in the protocol, forcing data should be consistent across the participating models. Therefore, VolMIP will provide a self-consistent set of forcing parameters that can be used by all models, in order to ensure the best possible consistency between models in the resulting radiative forcing. Depending on the number of participating coupled climate models including modules for interactive stratospheric chemistry and aerosols microphysics, VolMIP may pose an additional focus on the simulated climatic response to given SO_2 emissions beyond the CMIP6 simulations. In this stage, VolMIP will benefit from global aerosol model studies conducted within the framework of SSiRC.

- (Type-I) The forcing input data will be in the form of aerosol optical properties (e.g., aerosol optical depth, effective radius, SSA, asymmetry factor), which will allow the applied forcing in the different models to be constrained. Coupled climate models including modules for stratospheric chemistry and aerosol microphysics will be selected and used to generate forcing input;
- (Type-II): Mechanistic forcing experiments will either follow a similar approach as for Type-I experiments or an analytical description of aerosol optical depth, SSA and asymmetry factor following the Easy Aerosol protocol (http://www.wcrp-climate.org/index.php/gc-clouds-circulation-activities/gc4-clouds-initiatives/368-gc-clouds-inititative3-easy-aerosol).

- the science question and/or gap being addressed with this experiment:

▪ The large uncertainties in both short-and long-term dynamical climatic responses to strong volcanic eruptions (e.g., Driscoll et al., 2012; Ding et al., 2014). On the one hand, observed volcanic events are few and of limited magnitude, and the dynamical response is very noisy (e.g., Hegerl et al., 2011). On the other hand, coupled climate simulations produce a considerable range of dynamical responses to volcanic forcing likely depending on various aspects of model formulation, on the simulated background internal climate variability, and also on eruption details including magnitude, latitude and season. This will be addressed by Type-IA experiments.

- The apparent mismatch between simulated and reconstructed post-eruption surface cooling for volcanic eruptions reconstructed for the last millennium (e.g., Mann et al., 2012; Anchukaitis et al., 2012). VolMIP will provide new consensus forcing input data and related coupled climate simulations for some of the major volcanic eruptions that occurred during the pre-industrial period of the last millennium. Therefore, VolMIP will clarify how regional responses to volcanic forcing are affected by the background climate state, especially the phase of internal climate variability modes. As a consequence, VolMIP will improve our confidence in the attribution and dynamical interpretation of reconstructed post-eruption regional features. Inclusion of "volcanic cluster" experiments will allow the longer-term climate repercussions of periods of strong volcanic activity to be assessed (e.g., Miller et al., 2012; Schleussner and Feulner, 2013). This will be addressed by Type-IA and Type-IB experiments.
- The mismatch between observed and modeled short-term dynamical responses to volcanic eruptions (e.g., Driscoll et al., 2012, Charlton-Perez et al., 2013). Observations imply that volcanic eruptions are followed by strong Northern Hemisphere's winter polar vortex, and significant positive anomalies in the NAO and in the Northern Annular Mode. CMIP5 models do not reproduce these expected responses. The short-term dynamical response is now known to be sensitive to the particular structure of the applied forcing (Toohey et al., 2014). Using carefully constructed forcing fields, VolMIP will 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 surface dynamics. This will be addressed by Type-II experiments.

o possible synergies with other MIPs:

VolMIP is closely linked to and will co-operate with the following ongoing modeling activities and MIPs:

- **PMIP** (https://pmip3.lsce.ipsl.fr/) – VolMIP systematically assesses uncertainties in the climatic response to volcanic forcing associated with initial conditions and structural model differences. In contrast, the PMIP last-millennium experiments, i.e., the *past1000* simulations, describe 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.
- **GeoMIP** (http://climate.envsci.rutgers.edu/GeoMIP/)
- **RFMIP** – Radiative Forcing MIP
- **DAMIP** – Detection and Attribution MIP. Common interest is the assessment of the volcanic input over the historic past. In particular, VolMIP can address the substantial uncertainty associated with the effects of volcanism on the historical periods.
- **DCPP** – Decadal climate prediction panel
- **Easy Aerosol** (http://www.wcrp-climate.org/index.php/gc-clouds-circulation-activities/gc4-clouds-initiatives/gc4-clouds-projects/368-gc-clouds-easy-aerosol)
- **AeroCom** (http://aerocom.met.no/) – Aerosol Comparisons between Observations and Models
- **CCMI** (http://www.met.reading.ac.uk/ccmi/) – The IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) was established to coordinate future (and to some extent existing) IGAC and SPARC chemistry-climate model evaluation and associated modeling activities
- **WCRP Grand challenge Initiative on leveraging the past record**
- **SPARC DYNVAR (**http://www.sparcdynvar.org/) – The SPARC DynVar group aims to assess the impact of uncertainty in atmospheric dynamics on climate projections and is therefore highly interested in VolMIP's Type-II mechanistic experiments.
- **SPARC-SSiRC** (http://www.sparc-ssirc.org/) – The Stratospheric Sulfur and its Role in Climate Initiative (SSiRC) model intercomparison uses global aerosol models to understand the radiative forcing of stratospheric aerosols (background, volcanic) and to assess related parameter uncertainties. The SSiRC study "Pinatubo Emulation in Multiple models" (PoEMs)

will inter-compare and evaluate Pinatubo perturbation to stratospheric aerosol properties and radiative forcings across A-GCMs with prognostic stratospheric aerosol modules.

- Potential benefits of the experiment to (A) climate modeling community, (B) Integrated Assessment Modelling (IAM) community, (C) Impacts Adaptation and Vulnerability (IAV) community, and (D) policy makers.
  - (A) VolMIP will contribute towards identifying the causes that limit robust simulated behavior under strong volcanic forcing conditions. It will also clarify more general aspects of the dynamical climatic response to strong external forcing, especially differences in the models' treatment of physical processes. VolMIP will further evaluate the possibility of robustly identifying key climate feedbacks in coupled climate simulations following well-observed eruptions (e.g., Soden et al., 2002).
  - (B) VolMIP will contribute towards advancing our understanding of the dominant mechanisms behind simulated post-eruption climate evolution, but also more generally of climate dynamics, decadal variability and of past transitions between different multi-centennial climate states, such as the transition between the so-called Medieval Climate Anomaly and Little Ice Age. Careful and systematic sampling of initial climate conditions and consideration of volcanic eruptions of different strength will help in better understanding the relative role of internal and externally-forced climate variability during periods of strong volcanic activity, hence improving the evaluation of climate models and advancing our understanding of past climates.
  - (C) VolMIP will identify regions that are most robustly significantly affected by strong volcanic eruptions, and it will provide a framework for assessing the immediate as well as decadal climate repercussions of future volcanic events.
  - (D) VolMIP will contribute towards advancing our understanding of the relative role of internal and natural externally-forced climate variability, therefore providing relevant information to policy makers concerning how the latter may contribute to the spread of future climate scenarios (where volcanic forcing is presently not accounted for).

- If possible, a prioritization of the suggested experiments, including any rationale

Type-I: Historical eruptions experiments

Name	**Experiment**	**Description**	**Priority**
VS100EQ	Type -IA	Idealized equatorial eruption corresponding to an initial emission of 100 Tg of SO_2 initialized on June 1. This eruption has a magnitude roughly corresponding to the 1815 Tambora eruption, the largest historical tropical eruption, which was linked to the so-called “year without a summer” in 1816	TOP
VS100HL	Type – IB	Idealized high-latitude (60N) eruption emitting 100 Tg of SO_2 initialized on June 1. The eruption strength and length roughly correspond to the 1783-84 Laki eruption. It is especially interesting due to its unique eruption style (large SO_2 mass releases and close temporal spacing); outstanding questions about the magnitude of the climatic impact of high-latitude eruptions and results may have implications for sulfate aerosol geo-engineering	TOP
VC19thC	Type -IB	Early 19th century cluster of strong tropical volcanic eruptions, including the 1809 event of unknown location, and the 1815 Tambora and 1835 Cosigüina eruptions. The early 19th century is the coldest period in the past 500 years	TOP
VC13thC	Type -IB	The 13th century cluster of strong volcanic eruptions. This	MID

		cluster of volcanic eruptions constitutes the strongest over the last two millennia at least, having possibly played a role on the onset of the Little Ice Age. Samalas/1257 is critical as it is among the most debated events concerning its climatic impacts because of the large discrepancy between simulated and reconstructed responses	
VS1700EQ	Type-IA	Idealized equatorial eruption emitting 1700 Tg of SO_2 initialized on June 1. The eruption strength roughly corresponds to estimates for the 74kya Toba eruption, which is the most recent “super-eruption”. This experiment allows us to assess the climatic responses under exceptionally strong conditions, pushing the simulated climates to their extreme	LOW

Legend for experiment names: V = Volcano, S = Single, C = Cluster, XXX = approx. amount of Tg of SO_2 release, HL = high latitude, EQ = equator

Type-II: Mechanistic volcanic forcing experiments

Name	**Experiment**	**Description**	**Priority**
F20EQfull	Type-II	Highly idealized equatorial volcanic eruption initialized on June 1 and corresponding to a Pinatubo-like global aerosol peak AOD loading of 0.1	TOP
F20EQsurf	Type-II	As F20EQfull, but with prescribed surface cooling patterns or net flux changes at the top of the atmosphere	TOP
F20EQstrat	Type-II	As F20EQfull, but with prescribed aerosol heating in the stratosphere	TOP
FA20EQini	Type II	As F20EQfull, but as decadal prediction runs	Medium
TbD	Type-II	Idealized volcanic eruptions for different strengths and locations	LOW

Legend for experiment names: F = Forcing, XXX = approx. amount of Tg of SO_2 release, HL = high latitude, EQ = equator, full= full-forcing, surf = surface forcing only (cooling), strat= stratospheric heating only, ini= initialized runs

- All model output archived by CMIP6-Endorsed MIPs is expected to be made available under the same terms as CMIP output. Most modeling groups currently release their CMIP data for unrestricted use. If you object to open access to the output from your experiments, please explain the rationale.
  - No objection
- List of output and process diagnostics for the CMIP DECK/CMIP6 data request:
  VolMIP output is planned to be converted into the standard format using the CMOR package, following the same criteria adopted for *past1000* and *historical* simulations. Additional output is needed for Type-II experiments. This includes key diagnostics of parameterized and resolved wave forcings, radiative and latent heating rates. A daily temporal resolution of output data for the stratosphere is desirable.

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