Final scientific report

Project: 200021_169241 (**Volcanic Eruptions and their impact on future Climate, VEC)**

Time: 1.10.2016-30.11.2018

1. Summary of the research plan and its results

1.1 Research work conducted in relation to the objectives, milestones and hypotheses mentioned in the research plan.

The main goals of the project VEC were to create a new coupled atmosphere-ocean-aerosol-chemistry-climate model, to verify its representation of volcanic activity, and to apply it to investigate the influence of different volcanic eruptions on future climate.

1.1.1 SOCOLv4 model development and validation.

We have developed the fourth version of the SOCOL model (SOCOLv4) as the combination of the MPI-Met Earth System Model consisting of ECHAM6 for the atmosphere, MPIOM for the ocean, JSBACH for the terrestrial biosphere and HAMOCC for the ocean´s biogeochemistry, as well as the latest versions of the chemical (MEZON) and sulfate aerosol microphysics (AER) modules used in previous SOCOL versions (see Figure 1). The model considers the majority of processes responsible for the behavior of the Earth climate system including gas-phase/heterogeneous chemistry and bin-resolved stratospheric sulfate aerosol and is able to simulate direct forcings and feedbacks important for climate, ozone and volcanic aerosol evolution. A publication describing the new model is in preparation for submission to the Geoscientific Model Development journal (Sukhodolov et al., 2019a).

1.1.2 Simulations of atmosphere and climate states for 1950-2015 period.

We applied SOCOLv4 to simulate the climate, ozone and stratospheric sulfate aerosol historical evolution from 1950 to 2015 and to evaluate the model against available observations. Figure 2 illustrates that SOCOLv4 already performs better than the previous SOCOL version in terms of reproducing ozone trends, especially after the Mt. Pinatubo eruption in 1991. Before applying the model for future climate studies, it was necessary to examine the behaviour of the aerosol module following large volcanic eruptions. For this task, we simulated the effects of the strongest directly observed eruption of Mt. Pinatubo in 1991. Our results, published in Geoscientific Model Development journal (Sukhodolov et al., 2018), showed that the aerosol module AER can predict the most important global-scale atmospheric effects following volcanic eruptions. A more accurate model evaluation is not possible because of the large uncertainties in observational data, which we addressed in our other paper (Revell et al., 2017).
We participated in the international model evaluation activity (VolMIP) providing the sulfate aerosol response to the Tambora eruption in 1815. Our model showed the closest agreement with ice-core observations in terms of start and end dates of the volcanic aerosol deposition, which confirms a good representation of stratospheric volcanic cloud evolution in our model (Marshall et al., 2018; Clyne et al., 2019). Based on these publications, we improved the treatment of water uptake by sulfate aerosol particles, corrected the aerosol mass conservation, revised natural and anthropogenic sulfur emissions, and significantly improved dry and wet deposition schemes. The updated version shows similar levels of agreement with stratospheric aerosol observations, while achieving superior agreement to tropospheric sulfur observations, e.g. wet deposition fluxes. A paper discussing the tropospheric sulfur budget and changes in the model is in preparation for submission to the Geoscientific Model Development journal (Feinberg et al., 2019). We then used this model version to study the role of small volcanic eruptions in the aerosol layer evolution over the early 21st century. We performed ensemble experiments by switching on and off different sulfur emission sources and by using different volcanic emission databases. The modelled and observed evolution of the stratospheric aerosol burden is presented in Figure 3. We found that, even though there are increasing trends in all the main sources of sulfur emission, the observed trend in the sulfate aerosol layer is most likely defined by volcanic activity. However, we also demonstrated that the volcanic emission data are quite uncertain and need further clarification.

1.1.3 Simulations of atmosphere and climate states in the future.

To estimate the influence of small eruptions on the future climate we performed ensemble experiments simulating the end of 21st century under the IPCC RCP6.0 scenario. For this we applied the volcanic SO_2 emissions observed during 2000-2015 from the database by Carn et al. (2015). To estimate possible uncertainties, we repeated this experiment using enhanced frequency and magnitude of volcanic eruptions for the years 2085-2100. Our results showed a small effect of volcanic eruptions on global mean climate even for enhanced activity case. However, small volcanos can have some influence on the ozone layer (up to 5 %), climate/extreme weather events on regional/seasonal time scales (the influence of daily minimum temperature is shown in Figure 4).

1.1.4 Down propagation of stratospheric disturbances

To understand the mechanisms responsible for the downward propagation of stratospheric disturbances, we participated in the analysis of different model results. This activity is reflected in two published (Son et al., 2018 and Egorova et al., 2018) and one submitted (Gillett et al., 2019) papers.

1.1.5 Extreme climate indicators and food production model

To characterize the influence of volcanic aerosol on climate extremes we developed a simple post-processing tool for the calculation of indices describing extremes in temperature and precipitation fields described in Zhang et al., (2011). To estimate a volcanic influence on crop production we downloaded, installed and tested WOFOST (WOrld FOod STudies) model, which is freely available from https://github.com/ajwdewit/ WOFOST as open source Fortran code.

1.2 Main research results and their relevance to planned research outputs.

- A new atmosphere-ocean-aerosol-chemistry-climate model SOCOLv4 has been developed, tested and applied to study the influence of volcanic aerosol on climate;
- The new model allowed forming a methodological framework for our new ongoing SNSF project POLE looking at the ozone layer evolution.
- A comparison with observations has been made of the simulated past atmospheric evolution for volcanically quiet conditions, major eruptions, and recent small volcanic eruptions; SOCOLv4 showed good performance.
- We have simulated the influence of volcanic eruptions on the future climate using moderate and enhanced volcanic activity scenarios;
- We have shown that the sulfate aerosols from small volcanoes has a small effect on global mean climate and that even global cooling resulting from enhanced volcanic activity cannot compete with the climate warming effects from anthropogenic activity;
- We have shown that small volcanoes can have a substantial influence on climate and extreme weather events on regional/seasonal time scales;
- We found that enhanced levels of volcanic activity have implications for the future ozone layer state.

1.3 Major deviations from the research plan.

Since the initial proposal duration was cut by one third, we were not able to publish the latest results concerning the volcanic influence on future climate and perform necessary calculations with the food production model.

1.4 Contributions of the SNF-coworkers

Dr. Timofei Sukhodolov (PMOD/WRC) was employed as the named postdoc. He led the effort to develop and evaluate the SOCOLv4 model. Dr. Sukhodolov prepared necessary external boundary conditions and scenarios, performed simulations of the past and future climate, analyzed the results and participated in the preparation of the papers. Dr. Eugene Rozanov (PMOD/WRC) participated in the experimental design, analysis of the results and preparation of the papers. Prof. W. Schmutz (PMOD/WRC) participated in the analysis of the results and paper preparation.

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Marshall, L., A. Schmidt, M. Toohey, K. Carslaw, G. Mann, M. Sigl, M. Khodri, C. Timmreck, D. Zanchettin, W. Ball, S. Bekki, C. Johnson, J.-F. Lamarque, A. LeGrande, M. Mills, U. Niemeier, J. Pope, V. Poulain, A. Robock, E. Rozanov, A. Stenke, T. Sukhodolov, S. Tilmes, K. Tsigaridis, and F. Tummon, Multi-model comparison of the volcanic sulfate deposition from the 1815 eruption of Mt. Tambora, Atmos. Chem. Phys., 18, 2307–2328, 10.5194/acp-18-2307-2018, 2018.
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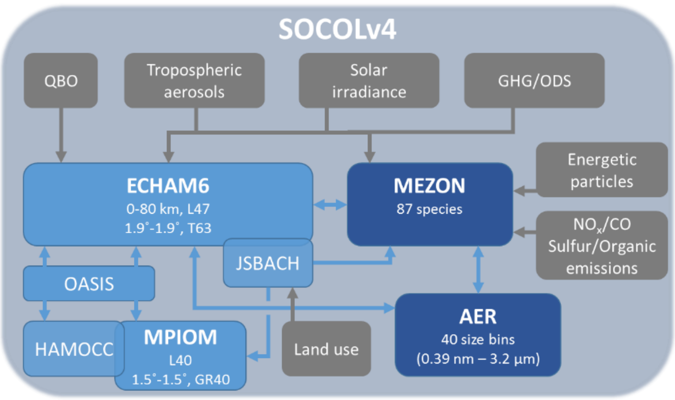

Figure 1. Main modules and information flow of the SOCOLv4.

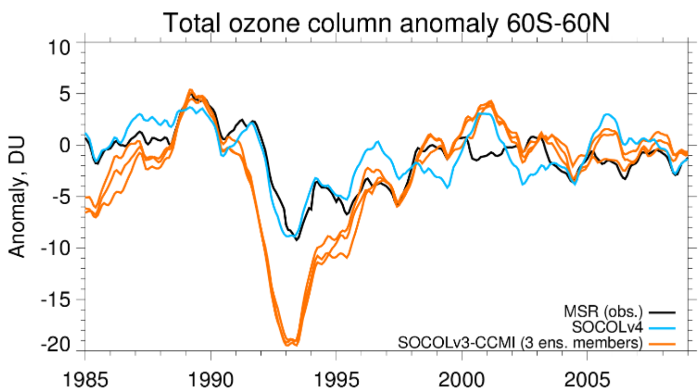

Figure 2. Total ozone column anomaly averaged over 60˚S-60˚N from the observational composite MSR (black), previous SOCOLv3-CCMI (orange) and the SOCOLv4 (blue) models.

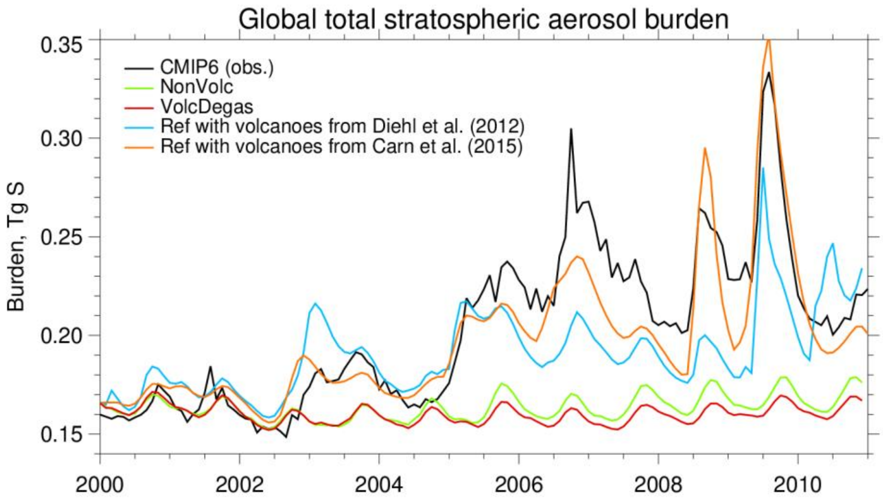

Figure 3. Time evolution of the globally averaged stratospheric aerosol burden from the observational composite CMIP6 (black) as well as from the four model experiments where only non-volcanic sulfur emissions are transient (NonVolc, green), only degassing volcanic emissions are transient (VolcDegas, red), and all emissions are transient (Ref, blue and orange). Blue and red lines represent different volcanic emission scenarios.

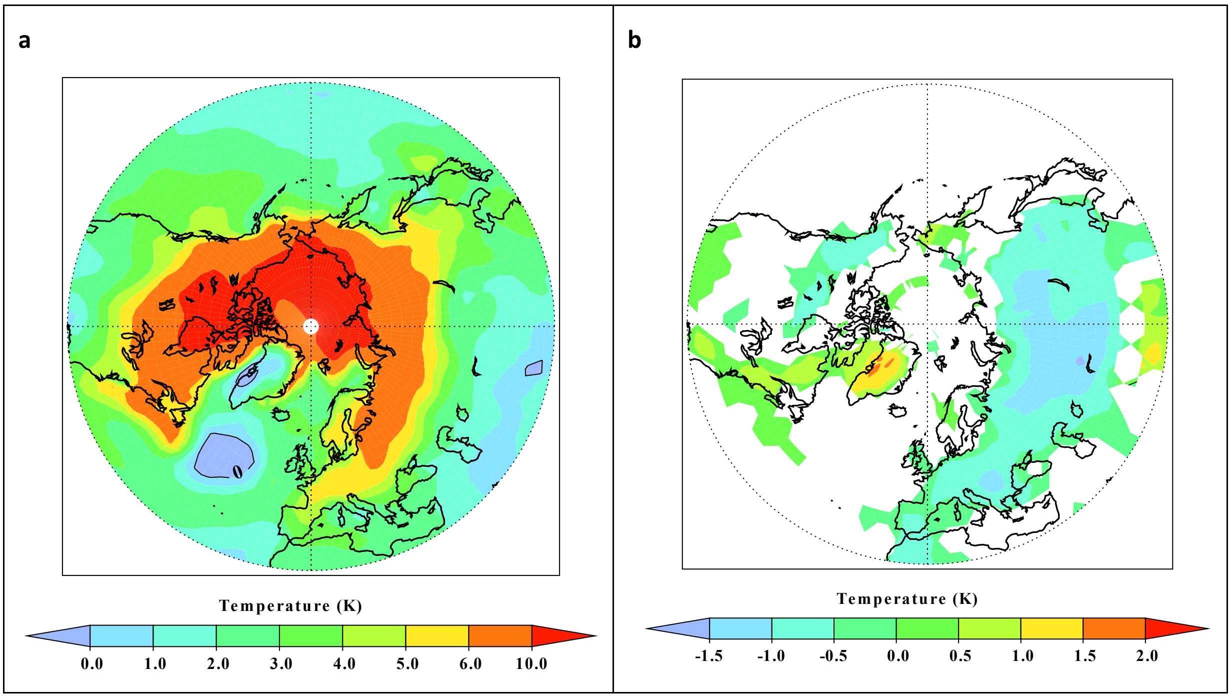

Figure 4. (a) Changes of the December daily minimum temperature (K) between future and present caused by greenhouse gas emissions according to IPCC RCP6.0 scenario. (b) changes of the December daily minimum temperature (K) in the future caused by enhanced volcanic activity.

2. Research output

Here we list the planned or submitted research output. Research output that has already been published (e.g. publications accepted, published or in press) are available from the "output data" container. Results directly or highly relevant to the project were presented in 7 papers published in peer-reviewed journals and talks at 14 international workshops and conferences.

Papers in preparation:

Clyne et al.: Incomplete Model Physics and Chemistry Leading Cause of Inter-Model Disagreement Within the VolMIP-Tambora Pre-Study (in preparation for Atmospheric Chemistry and Physics).

Gillett, J. Arblaster, A. Dittus, M. Deushi, P. Jöckel, D. Kinnison, O. Morgenstern, Plummer, L. Revell, E. Rozanov, R. Schofield, A. Stenke, K. Stone, and S. Tilmes, Evaluating the relationship between interannual variations in the Antarctic Ozone Hole and Southern Hemisphere surface climate in chemistry-climate models, (Submitted to Journal of Climate).

Feinberg, A. et al.: SOCOL-AERv2: improving the representation of the tropospheric sulfur cycle in an aerosol-chemistry-climate model (in preparation for Geoscientific Model Development journal).

Sukhodolov T. et al.: Earth system model SOCOLv4.0 with interactive chemistry and sulfate aerosol modules (in preparation form Geoscientific Model Development journal).

Rozanov E. et al., Influence of small volcanic eruptions on the future climate and ozone layer, (in preparation).

Sukhodolov T. et al.: Contribution of volcanic SO2 emissions to stratospheric aerosol burden evolution during early 21st century (in preparation for Journal of Geophysical Research: Atmospheres).