Final scientific report

Project: 200020_182239 (Past and future of the Ozone Layer Evolution, POLE)

Time: 1.01.2019-31.08.2023

1. Summary of the research work and its results

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

The overall goals of the project POLE were to understand the past and make future predictions of the ozone layer state. To address the main goals, we completed the development and documentation of the Earth System model SOCOLv4 (Sukhodolov et al., 2021). We applied the model to study past ozone layer evolution. We performed several model experiments in the ensemble mode for the period 1980-2018 using different sets of boundary conditions to elucidate the role of different forcing agents. In parallel to the modeling studies, we also continued observational data analysis to confirm our previous findings about the continuous ozone depletion in the tropical lower stratosphere. We performed several ensemble runs for the period 1980-2100 using IPCC scenarios SSP5-85 (business as usual) and SSP2-45 (with some reduction of the anthropogenic emissions). We also repeated experiment with SSP2-45 scenario suggesting the absence of the Montreal Protocol limitations and also using an alternative scenario for the solar irradiance variability. For all experiments we introduced very short-lived and newly discovered halogen containing species. We modified and applied SOCOLv3 to estimate the possible influence of iodine-containing species on the ozone layer. Using the new version SOCOLv3-Iod we simulated the ozone layer state for the present day and doubled levels of iodine emissions. Special attention was paid to possible climate interventions. Using our model, we simulate the consequences of exploiting different kinds of aerosol particles or artificial gas phase SO_2 emissions to estimate the benefits of these measures for climate as well as potential problems with the ozone layer. This activity requested substantial validation and modification of the aerosol microphysical scheme and several experimental set-ups. We performed several specially designed numerical experiments requested by international ISA-MIP and VolRES projects. In particular, we executed several experiments simulating the influence of the recent unique Hunga Tonga–Hunga Ha‘apai_eruption on the atmosphere and ozone layer. We continue model validation by participating in the IGBP/SPARC CCMI-2 activity providing the output from the SOCOLv4 simulations for the period from 1960 to 2018. The project implementation was evolving generally in agreement with the proposed timeline. During the first year of project implementation, we (in agreement with milestone M1) completed the reference run, established the project webpage (https://www.pmodwrc.ch/en/research-development/climate-modelling/pole/) and started the runs planned for the experiments 2.3.3.1 (hindcast runs with different forcing sets), 2.3.3.2 (Montreal Protocol benefits) and 2.3.3.4 (evaluation of the aerosol module). We also analyzed the results of the first runs looking at the ozone trends in the past. During the second year of the project (milestone M2), we completed all intended runs for the experiments 2.3.3.1 and 2.3.3.2 and started work on the publications. The model was prepared for the ISA-MIP and VolRES project. Some runs covering the future (planned in 2.3.3.3 section of the proposal) were initiated. During the third year we started preparation of the papers based on experiment 2.3.3.4 (studies of the stratospheric aerosol effects). The papers based on ISA-MIP and VOL-MIP appeared. In parallel we started updating the aerosol module. During the fourth year we completed papers about future ozone trends, the role of the Montreal Protocol and the influence of possible solar irradiance decline scenario. Our PhD student successfully defended his thesis in 2022. During this year we also started several experiments devoted to climate intervention with artificial stratospheric aerosol.

1.2 Main research results and their relevance to the published research output.

- A new Earth’s system model SOCOLv4 containing original aerosol microphysics and chemistry modules was evaluated and documented (Sukhodolov et al., 2021).

- Continuous improvement of the model quality led to a better representation of the stratospheric aerosol (Brodowsky et al., 2021), sulphate cycles (Feinberg et al., 2019) and halogen chemistry (Karagodin-Doyennell et al., 2021).
- Our analysis of the observed and simulated ozone trends in the lower tropical stratosphere (Ball et al., 2019; 2020) pointed to a disagreement between persistent negative trends in the satellite data and model output.
- The model version with iodine chemistry demonstrated that doubling the present-day emission of the iodine-containing species does not present substantial danger for the future state of the ozone layer (Karagodin-Doyennell et al., 2021).
- We showed that the model accurately reproduces trends in the upper stratosphere demonstrating ozone depletion before 1998 followed by the ozone recovery until 2018. In the tropical lower stratosphere, the model simulates weak negative tendencies related to the intensified meridional transport and does not completely agree with the discovered earlier large trends in the tropical lower stratosphere (Karagodin-Doyennell et al., 2022).
- Simulated evolution of the future ozone layer state reveals stabilization and recovery on a global scale. However, we expect continuous depletion of the total ozone over the tropical area and extensive (above 1980 level) increase over the northern midlatitude. The model results point to the increasing role of the tropospheric ozone. We demonstrated that the sign of future ozone column changes is still unclear in some regions and largely depends on the pattern of the future human activities (Karagodin-Doyennell et al., 2023).
- Simulation of the future ozone and climate in case of the absence of Montreal Protocol limitations confirmed the vital importance of these limitations not only for the ozone layer, but also for climate changes (Egorova et al., 2023).
- Using different scenarios for the future solar irradiance changes we show that the ozone layer state is not sensitive to the suggested decline of the solar magnetic activity if traditional treatment of the quiet Sun radiation is applied (Sedlacek et al., 2023). However, the application of an alternative treatment of solar irradiance changes led to substantial solar influence on the ozone during the early 20^{th} century (Egorova et al., 2020).
- We demonstrated that the dependence of the ozone layer state on the level of oxygen concentration is driven not only by chemical, but also by dynamical/transport processes. Our model shows that the total ozone reaches its maximum for the present-day level of oxygen (Józefiak et al., 2023).
- We actively participated in several international programs such as IGBP/SPARC CCMI-2022, ISA-MIP, Vol-MIP, and Vol-RES devoted to the comparison and validation of chemistry-climate models. Our data helped to establish the importance of the interactive chemistry for the calculation of the atmospheric state (Morgenstern et al., 2022), climate (Friedel et al., 2023) as well as to elucidate main problems in the simulation of the Tambora eruption and background stratospheric aerosol influence on the atmosphere (Clyne et al., 2021; Brodowsky et al., 2023).

1.3 Major deviations from the research plan.

There were no major deviations from the research plan. Some problems with the presentation of the results at major international conferences appeared due to the COVID-19 pandemic. These problems were fixed using cost-neutral extension of the project by 8 months.

1.4 Contributions made by the project staff.

Model development and exploitation were conducted by E. Rozanov, T. Sukhodolov, T. Egorova, A. Doyennel, and J. Sedlácek.

E. Rozanov, T. Sukhodolov, T. Egorova, A. Doyennel, J. Sedlácek, C. Brodowsky, and I. Józefiak were involved in the analysis of the results and preparation of the research output. W. Ball worked on the analysis of the observation and model simulated data. M. Gyo was dealing with the visualization of the results and preparation of the figures for the publications.

1.5 Important events (e.g., change of personnel, delayed start of project etc.)

There were no such important events.

2. Research output

Here we present the planned or submitted research output. Research output that has already been published (e.g., publications accepted, published or in press) is available from the "output data" container and described in the 1.2 section). Results directly or highly relevant to the project were presented in 29 papers published in peer-reviewed journals and talks at 38 international workshops and conferences.

2.1 The Montreal protocol limitations and regional climate.

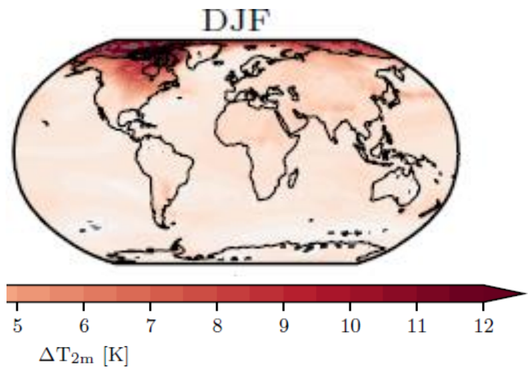

Figure 1. Global surface temperature response to the CFC increase during 2080-2099 relative to reference case.

Detailed investigation of the model experiment using the hypothetical absence of the Montreal Protocol limitations allowed to emphasize the influence of halogen-containing species on the regional scale which can be as high as 12 K over Eastern Canada and Western Arctic (Zilker et al., 2023). Figure 1 illustrates the surface temperature increase for the period 2080-2099 due to the halogen-containing ozone depleting substances (CFC) enhancement caused by the absence of the Montreal Protocol limitations.

2.2 Improvement of the microphysical module.

In preparation for the climate intervention studies we explored how changing the timesteps and sequencing of microphysical processes in the sectional aerosol module affect climate and ozone layer impacts and under an extreme level of the stratospheric aerosol the accurate calculations should be performed with less than 2 minutes time step or with the application of nucleation- condensation order of operations (Vattioni et al., 2023).

2.3 Stratospheric sulfur budget in chemistry-climate models.

In the framework of the international ISA-MIP project we analyze the atmospheric burden, seasonal cycle, and vertical and meridional distribution of the main sulfur species simulated by nine global atmospheric chemistry-climate-aerosol models that are widely used in the stratospheric aerosol research community. We found out that the differences in the atmospheric sulfur budget among the models arise from the representation of both chemical and dynamical processes, whose interplay complicates the bias attribution. We pointed to several problematic points related to the specifics of the chemistry schemes, model resolution, and representation of cross-tropopause transport in extra-tropics, which requires further investigations (Brodowsky et al., 2023).

2.4 Impacts of the Hunga Tonga-Hunga Ha'apai Eruption

We assessed the impacts of the Hunga Tonga-Hunga Ha'apai eruption on stratospheric composition and dynamics. Simulated with the SOCOLv4 and observed with AURA/MLS sensor H_2O mixing ratio at 26.1 hPa are shown in Figure 2 for the year 2022. The model results resemble an observed pattern, but they look less diffusive in horizontal direction. The model also points to noticeable ozone layer depletion over the southern high latitudes during the austral spring years 2023-2024. The manuscript about this experiment is under preparation.

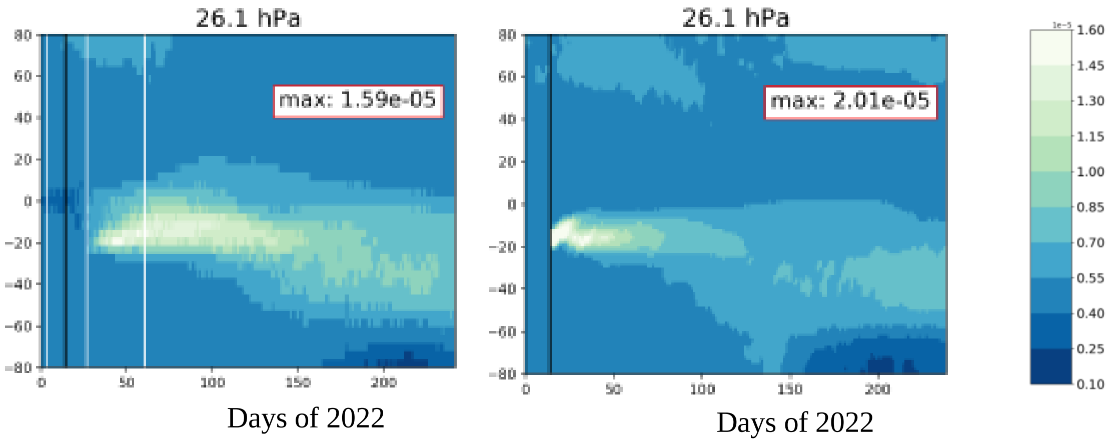

Figure 2. Observed (MLS, left) and simulated (SOCOLv4, right) time-latitude cross-section of the H_2O mixing ratio (ppmv) at 26.1 hPa in 2022.

2.5 Climate intervention

We explore the ozone layer and climate response to the artificial stratospheric aerosol injections using the ESM SOCOLv4. We applied additional injection of 5 Tg S to our previously performed SSP5-8.5 experiment described by Karagodin-Doyennel et al. (2023). The aerosol formed from the introduced artificial sulfur injections allowed to compensate about 1.5 K global warming in the SSP5-8.5 relative to the SSP2-4.5 experiment all over the word except Eurasian middle to high-latitudes (see Figure 3).

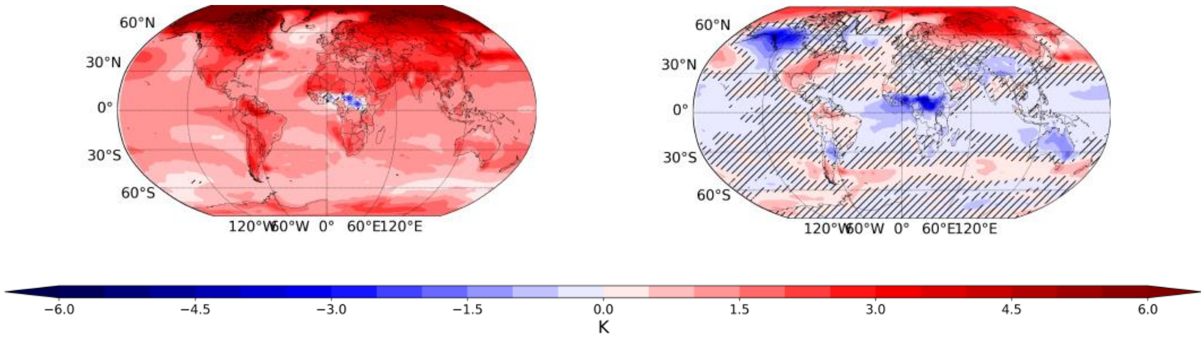

Figure 3. Surface temperature difference between SSP5-8.5 with (right) and without (left) artificial sulfur emissions and SSP2-4.5 experiments.

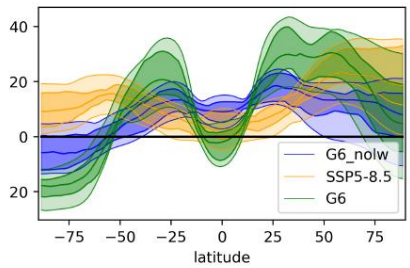

Figure 4. Zonal and annual mean total column ozone difference (DU) between SSP5-8.5 with (G6 and G6_nolw) and without (SSP5-8.5) artificial aerosol emissions and SSP2-4.5 experiments.

The ozone anomalies relative to SSP2-4.5 experiments are illustrated in Figure 4. The model shows that the introduced stratospheric aerosol intervention led to positive ozone changes everywhere except slight decrease in equatorial area and substantial (around 20 DU or 6%) depletion over the high southern latitudes. This problem can be solved by the application of aerosol with lower absorption coefficient in the longwave spectrum (see G6_nolw line). The search for such material is ongoing.

References

Ball, W. T., Chiodo, G., Abalos, M., et al.: Inconsistencies between chemistry–climate models and observed lower stratospheric ozone trends since 1998, Atmos. Chem. Phys., 20, 9737–9752, 2020, doi:10.5194/acp-20-9737-2020.

Ball, W. T., Alsing, J., Staehelin, et al.: Stratospheric ozone trends for 1985–2018: sensitivity to recent large variability, Atmos. Chem. Phys., 19, 12731–12748, 2019, doi:10.5194/acp-19-12731-2019.

Brodowsky, C., Sukhodolov, T., Feinberg, et al.: Modeling the sulfate aerosol evolution after recent moderate volcanic activity, 2008–2012. Journal of Geophysical Research: Atmospheres, 126, e2021JD035472. 2021. doi: 10.1029/2021JD03547

Brodowsky, C., T. Sukhodolov, G. Chiodo et al.: Analysis of the global atmospheric background sulfur budget in a multi-model framework, 2023, under review, doi:10.5194/egusphere-2023-1655.

Clyne, M., J.-F. Lamarque, M. Mills, et al.: Model physics and chemistry causing intermodel disagreement within the VolMIP-Tambora Interactive Stratospheric Aerosol ensemble, ACP, 2021, doi: 10.5194/acp-21-3317-2021.

Egorova, T., E. Rozanov, P. Arsenovic, and T. Sukhodolov, Ozone Layer Evolution in the Early 20th Century, Atmosphere, 11, 169, 2020, doi: 10.3390/atmos11020169.

Egorova, T., J. Sedlacek, J., T. Sukhodolov, et al.: Montreal Protocol's impact on the ozone layer and climate, Atmos. Chem. Phys., 23, 5135–5147,2023, doi:10.5194/acp-23-5135-2023.

Feinberg, A., T. Sukhodolov, B.-P. Luo, et al.: Improved tropospheric and stratospheric sulfur cycle in the aerosol–chemistry–climate model SOCOL-AERv2, Geosci. Model Dev., 12, 2019, 3863–3887, doi: 10.5194/gmd-12-3863-2019.

Friedel, M., Chiodo, G., Sukhodolov, T. et al.: Weakening of springtime Arctic ozone depletion with climate change, Atmos. Chem. Phys., 23, 10235–10254, doi:10.5194/acp-23-10235-2023, 2023.

Józefiak I, Sukhodolov T, Egorova T, et al.: Stratospheric dynamics modulates ozone layer response to molecular oxygen variations. Front. Earth Sci. 11:1239325, 2023, doi: 10.3389/feart.2023.1239325

Karagodin-Doyennel, A., E. Rozanov, T. Sukhodolov et al: Iodine chemistry in the chemistry–climate model SOCOL-AERv2-I, Geosci. Model Dev., 14, 6623–6645, 2021. doi: 10.5194/gmd-14-6623-2021.

Karagodin-Doyennel, A., E. Rozanov, T. Sukhodolov et al.: The historical ozone trends simulated with the SOCOLv4 and their comparison with observations and reanalyses, Atmospheric Chemistry and Physics, 22, 23, 15333-15350, 2022. doi:10.5194/acp-22-15333-2022.

Karagodin-Doyennel, A., E. Rozanov, T. Sukhodolov et al.: The future ozone trends in changing climate simulated with SOCOLv4, Atmos. Chem. Phys., 23, 4801–4817, doi:10.5194/acp-23-4801-2023, 2023.

Morgenstern, O., Kinnison, D. E., Mills, et al.: Comparison of Arctic and Antarctic stratospheric climates in chemistry versus no-chemistry climate models. Journal of Geophysical Research: Atmospheres, 127, e2022JD037123, 2022, doi:10.1029/2022JD037123

Sedlacek, J., Sukhodolov, T., Egorova, et al.: Future climate under CMIP6 solar activity scenarios. Earth and Space Science, 10, e2022EA002783, 2023, doi:/10.1029/2022EA0027830

Sukhodolov, T., T. Egorova, A. Stenke et al.: Atmosphere-Ocean-Aerosol-Chemistry-Climate Model SOCOLv4.0: description and evaluation, Geosci. Model Dev., 14, 5525-5560, 2021, doi: 10.5194/gmd-14-5525-2021.

Vattioni, S., A. Stenke, Beiping Luo et al.: Importance of microphysical settings for climate forcing by stratospheric SO2 injections as modelled by SOCOL-AERv2, 2023, under review, doi:10.5194/egusphere-2023-1726.

Wunderlin, E., G. Chiodo, T. Sukhodolov et al.: Side effects of sulfur-based geoengineering due to absorptivity of sulfate aerosols, 2023, in preparation for GRL.

Zilker, F., T. Sukhodolov, G. Chiodo et al.: Stratospherically induced tropospheric circulation changes under the extreme conditions of the No-Montreal-Protocol scenario, 2023, under review, doi:10.5194/egusphere-2023-326.