Final scientific report

Project: FUPSOL-2 **CRSII2_147659**
Project duration: 01.01.2014 – 31.03.2017

1. Summary of the research and its results

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

The work on the project is conducted in the framework of the four subprojects, which are carried out at four institutions working in close collaboration by the means of data exchange, intensive discussions, and science meetings.

The **subproject A** (“*Calculating the time variable spectral solar irradiance for past and future based on solar activity proxies* ”) started in February 2014. We (A. Shapiro, PMOD/WRC) applied the available version of COde for the Solar Irradiance calculation (COSI) to extend the solar irradiance dataset from 2100 to 2200 using previously published scenarios of the solar magnetic activity level (**Milestone A-A**). This data set was provided for the **subproject B** team and used for the calculation of future climate and ozone layer state. The spectral solar irradiance (SSI) calculated using the same approach for the cases with strong decrease of the solar activity was provided for the **subproject C** team and used for the study of the interactive chemistry contribution. In parallel we have been working on improving our approach and compiled the CHRONOS (Code for the High spectral ResolutiOn recoNstructiOn of Solar irradiance) model by introduction of additional solar components (umbra and penumbra), implementation of the activity belts for the calculation of the active region contribution to solar irradiance, application of the new approach to calculate of the long-term variability of the irradiance from the quiet Sun and application of the NESSI code for the calculation of the irradiance from different solar components. We compared CHRONOS results with the available observed and modelled by other groups total and spectral solar irradiance time series and demonstrated a good performance of our new model. We applied CHRONOS to produce the SSI data covering 1600-2010 (**Milestone A-B**) and provided these data for the **subproject B** team to simulate climate and ozone layer evolution during 20th century. In collaboration with A.I. Shapiro (MPS, Gottingen, Germany) we also reconstructed SSI for the time period 850-1850 using the solar activity proxy based on time series of ^{14}C isotope provided by I. Usoskin (Oulu University, Finland). The coordinators of the PMIP-3 project (https://pmip3.lsce.ipsl.fr/) requested this data set as an alternative scenario of solar irradiance variability for paleoclimate simulations. The results have been published (Jungclaus et al., 2016). Finally, we exploited three of the most recent solar modulation potential reconstructions based on cosmogenic isotopes time series to drive CHRONOS and produced the final SSI data set covering 1600-2200 (**Milestone A-C**). The application of multiple solar modulation potential time series allows estimating the uncertainty of the SSI reconstruction. The TSI changes between the Maunder Minimum and present day minimum in 1996 range between 3.7 and 4.5 W/m^2, which is slightly smaller than our previous estimates. The final data set is available for the community by request and will be made available on-line after the paper by Egorova et al, 2017, submitted to A&A) describing CHRONOS and SSI data set is published.

The **subproject B** (“*Long-term simulations of the future climate with the standard and improved versions of the AOCCM*”) started in March 2014. During the first year, we focused on model improvements and the extension of climate simulations performed in the framework of FUPSOL-1 for the time 2100-2200 using solar irradiance provided by **subproject A** team. For that purpose, we extended the time series of greenhouse gases and ozone depleting substances concentrations, emissions of ozone precursors, aerosol burdens, and the quasi-biennial oscillation. For concentrations of greenhouse gases and ozone depleting substances we followed RCP4.5 scenario. We performed three sets of two-member ensemble simulations for period 2000-2200 using three different solar forcing scenarios. For the reference experiment, we repeated solar cycles 22 and 23 until the year 2200, for the solar magnetic activity minimum case we applied weak and strong decrease of solar irradiance (characterized by the 4 and 6 W/m^2 drop in total solar irradiance). Other forcings were kept constant in all experiments. We found that a strong decline in solar irradiance reduces the average global surface temperature by up to 0.6 K at the end of the 22nd century compared to the constant solar forcing case and leads to a delay or even a full cancelation of the global mean total column ozone recovery. The results are described by Arsenovic et al. (2017a, submitted to ACP).

We worked on the new model version based on ECHAM-6. In collaboration with PMOD team we have managed to check and correct the response of the heating rate parameterization to the solar irradiance variability (Sukhodolov et al., 2014). We have also carefully evaluated available codes for the photolysis rate calculations and define the most suitable scheme to be used in the new model version based on ECHAM-6 (Sukhodolov et al., 2016). These results were used to analyze the atmospheric response to solar irradiance variability caused by the Sun rotation (Sukhodolov et al., 2017). In the framework of international collaboration we participated in IPCC SOLMIP project aimed on the analysis of the atmosphere and climate response to the solar irradiance variability on decadal time scale. In collaboration with all FUPSOL teams we have also participated in the preparation of the detailed description of our AOCCM SOCOL-MPIOM. We have also continued the exploitation of the results obtained during FUPSOL-1 and analyzed the response of the climate to the decrease of the solar activity during Dalton Minimum. During the second year of the project we completed the planned model improvement. Firstly, the operational gravity wave drag (GWD) parameterization in ECHAM-5 has been replaced with the new ECHAM-6 GWD routine to introduce latitude dependent strength of the gravity wave source, which is missing in ECHAM-5. To evaluate the performance of the new GWD scheme we carried out two 9-years (2002-2010) 10-ensemble members model runs with different set-up for GWD scheme. The inclusion of the new GWD parameterization decreases the strength and increases the variability of the Northern Hemisphere polar vortex, but the obtained improvement is too small and only marginally significant. Secondly, we investigated the influence of Middle Range Energy Electrons (MEE, 30-300 keV) precipitation on the atmosphere using our AOCCM. We performed model simulations with and without MEE for the years from 2002 to 2010. For this time period we applied ionization rates from the AIMOS dataset. The results show that during geomagnetically active periods MEE lead to a significant increase of NO_y and HO_x in the polar winter mesosphere resulting in ozone decrease by up to 35 %. The results are published by Arsenovic et al. (2016). Despite of the MEE introduction the model still substantially underestimates observed NO_y above 50 km. To improve this, we applied new parameterization of NO_y influx from the thermosphere based on the recent analysis of the satellite data and demonstrated that the NO_y deficit completely disappeared in the Sothern Hemisphere, but weaker simulated downward transport in the Northern Hemisphere leads to some underestimation of the NO_y there. We also analyzed the simulated ozone depletion and found a good agreement with satellite data over the Southern high latitudes (Arsenovic et al., 2017b, submitted to GRL). The improved model (**Milestone B-A**) was applied for the simulations of 20th century climate. We performed several ensemble runs driven by different combinations of the forcings and compared the results with observed evolution of the surface air temperature. We showed that the anthropogenic forcing is responsible for 65% of the simulated annual and global mean early 20th century warming, while 35% is driven by solar irradiance. One of the conclusion from this work is that a weaker than observed warming trend can be fixed only by applying the larger solar forcing. This information was conveyed to **subproject A** team. The paper describing this experiment (Arsenovic et al., 2017c) and PhD thesis of P. Arsenovic are ready (**Milestone B-B and B-C**).

We also actively participated in the international projects SPARC CCMI and VolMIP aimed at the evaluation of chemistry-climate model performance in the simulation of ozone and climate response to different forcing (Morgenstern et al., 2017; Revell et al., 2016; Zanchettin et al., 2016) and HEPPA-II aimed at the evaluation of model performance in simulating downward NOx propagation after major sudden stratospheric warmings (Funke et al., 2017). We were also involved in the international collaboration aimed at the better understanding of precipitating energetic particle effects on the atmosphere. In collaboration with ISSI teams led by I. Mironova (S. Petersburg University, Russia) and K. Georgieva (Academy of Science, Bulgaria) we reviewed the recent progress in this area and defined the most promising directions to further studies (Mironova et al., 2015; Rozanov et al., 2016). In collaboration with scientist from Finland and Italy we simulated the effects of the strongest solar proton event in history on the atmosphere and deposition fluxes of ^{10}Be and nitrates. We simulated the ozone evolution during satellite era using different spectral solar irradiance (SSI) datasets to impose some constrains on possible changes of the solar forcing in the future. In collaboration with our colleagues from Czech Republic we analyzed the output of the CCM SOCOL runs performed in the framework of SPARC CCMI project using multiple regression analysis to extract the model response to the solar irradiance variability and evaluate its dependence on the other forcing agents (Kuchar et al., 2017, submitted to JGR).

In the framework of the **subproject C** ("Assessing the sensitivity of the atmosphere-ocean-chemistry system to different external forcing factors") we focused on a better understanding of the coupled atmosphere-ocean-chemistry-climate model SOCOL-MPIOM developed in the first phase of the FUPSOL project.

In a first study we analyzed the role of the interactive chemistry module for the simulated climate and its variability (Muthers et al. 2014). We performed several sensitivity runs (**Milestone C-A and C-B**) and identified a negative feedback mechanism related to the ozone chemistry, which leads to a slightly lower climate sensitivity to an instantaneous and transient doubling of the CO_2 concentrations, when chemistry-climate interactions are considered in the model. In general, the climate sensitivity of SOCOL-MPIOM compares well with other state of the art CMIP5 models.

A second study focused on the role of different processes, induced by the volcanic aerosols in the stratosphere, and chemical reactions on the surface of these aerosols in shaping the response of the atmospheric circulation to large volcanic eruptions (Muthers et al. 2015). Therefore, a large number of ensemble sensitivity simulations for different eruption sizes, climate states, and processes was performed. Results show that the radiative heating effect of the stratospheric aerosols leads to pronounced temperature changes in the stratosphere and is the main driver of the intensification of the Northern polar vortex during winter. Ozone changes due to heterogeneous chemical reactions on the surface of the aerosols cause a slight weakening of the polar vortex, when high loads of halogens are present in the stratosphere. This is the case in the present day simulations. Under preindustrial conditions, chemical effects are very small and have no significant effect on the atmospheric circulation.

A third study made use of the long-term simulations covering the period 1600 to 2100 from the first phase of the FUPSOL project. For these simulations, an Age of Air tracer was implemented in the model, which allows to estimate changes in the Brewer-Dobson circulation (BDC) over this time period and the contributions from different external forcings for BDC variations. We show that volcanic eruptions are an important driver of sub-decadal BDC variability. Long-term changes are related to the anthropogenic emission of CO_2 and ozone depleting halogens, which cause a pronounced intensification of the BDC in the late 20th and during the 21th century. The effect of the solar forcing on Age of Air is very weak. The simulations were analyzed in close collaboration with **subproject B** and the results are published in Muthers et al. (2016a).

Another objective of **subproject C** in FUPSOL II concerns role of chemistry-climate interactions in the response of SOCOL-MPIOM to reduced solar forcing. Therefore, a number of experiments were conducted for different solar radiation reductions and with and without the interactive chemistry module (**Milestone C-C**). The solar forcing for these experiments was provided by **subproject A**. In particular, the response of the Atlantic Meridional Overturning Circulation (AMOC) was analyzed and two counteracting mechanisms were identified (Muthers et al., 2016b). The direct thermal effect of the reduced solar radiation causes a reduction of the sea surface temperatures and enhanced sea ice formation in the North Atlantic and Nordic Sea. This leads to an increase in the density of the upper ocean, which enhances deep convection and the AMOC. A second effect is initiated in the stratosphere, where the reduced solar radiation causes a weakening of the Northern polar vortex. By stratosphere-troposphere interactions these stratosphere anomalies propagate down to the surface and shift the Arctic Oscillation towards a negative phase. The resulting wind stress and heat flux anomalies weaken the overturning circulation and therefore counteract the thermal effect. With interactive chemistry, the second mechanism is more pronounced, due to the stronger stratospheric changes induced by ozone and water vapor changes. We are also part of a collaboration with **subproject D** on multi-decadal variability of the Quasi-Biennial Oscillation and the effect on the climate system (Broennimann et al. 2016) and on the Indian Monsoon variability as simulated in the SOCOL-MPIOM (Malik et al. 2016). Finally, we participated in a review publication on the climatic impacts of the 1815 Tambora eruptions where results from simulations performed during the FUPSOL project are included (Raible et al., 2016).

Subproject D ("Solar effects on the tropospheric weather") focuses on the influence of solar activity on European weather. In this subproject, a new method for reconstructing weather type classifications (WTCs) was developed. With this method, several reconstructions of daily WTCs were produced, going back to 1763 (Schwander et al. 2017, **Milestone D-A**). With one of them, a classification with 7 weather types that builds on the CAP9 classification of MeteoSwiss (reduced to 7 types), the effect of the 11-yr sunspot cycle was studied.

This new classification was then used to analyze the influence of solar activity on European weather. Changes in the frequency of occurrence of weather types linked to the 11-year cycle were analyzed. The sunspot number time series was used as a measure of solar activity. The data were divided in three categories, low, moderate and high solar activity using arbitrary thresholds (e.g. 33rd and 66th percentiles). The results show a tendency to have more days with an easterly (westerly) flow under low (high) solar activity (**Milestone D-B**). Parallel to a change in the occurrence of the weather types, there are also changes in the mean sea level pressure field within the weather types that are consistent across weather types. There is on average a lower pressure over the North Atlantic under high solar activity. This means a reduced zonal flow under low solar activity over Europe. Similar analyses of the SOCOL-simulations did not reveal a consistent picture in that respect ((**Milestone D-C**). A different classification was used for studying decadal variability in wind storm frequency in Switzerland (Schwander et al. in preparation).

The SOCOL-MPIOM simulations were analyzed together with observational data and climate reconstructions with respect to the imprint of multidecadal changes in solar activity on oceanic modes and on the Indian monsoon system. In a first step, the Indian monsoon characteristics as well as its relation to oceanic modes was evaluated in the model simulations, and an acceptable performance of the model was found (Malik et al. 2017a). Further studies then addressed the statistical relations between the Indian summer monsoon rainfall and oceanic modes as well as total solar irradiance across different time scales by using partial cross-correlation techniques. Results (Malik et al. 2017b, Malik and Brönnimann 2017) show that the effect of total solar irradiance on the Indian monsoon system proceeds via a change in the Atlantic Multidecadal Oscillation. This link was found consistently in the four model simulations, statistical reconstructions, and observations. Dynamically, the link to the monsoon rainfall operates via a change in the meridional temperature gradient across the Indian Ocean.

The FUPSOL model simulations and observations allowed a more detailed study of the 1815 Tambora eruption and the subsequent “Year Without a Summer”. A compilation of pressure data (Brugnara et al. 2015) allowed detailed diagnostic studies of the storm track over the Atlantic. FUPSOL simulations of the Tambora event were then used in a review paper of the physical science aspect (Raible et al. 2016) to further study the event. A more comprehensive review (including further analyses of FUPSOL model simulations) was published as a 48 p. booklet (Brönnimann and Krämer, 2016). Results showed that the Tambora eruption, together with the “unknown” eruption of 1808 and two eruptions in the 1830s, had a profound effect on global temperature and the monsoon systems.

The FUPSOL simulations were also analyzed with respect to the effects of the Quasi-Biennial Oscillation (QBO) on the atmosphere (Brönnimann et al. 2017). Since the QBO was nudged, these simulations provided the unique opportunity of analyzing 1200 years of simulations, which could then be compared with observations. Results confirmed many of the hypotheses that have been raised as to the imprint of the QBO, namely the so-called “Holton-Tan”-effect (i.e., the imprint of the QBO in the stratospheric polar vortex) as well as an effect on high reaching tropical convection over the Pacific warm pool region. However, both effects were found to be small on average and subject to decadal variability due to random processes as well as due to climate changes (such as shifts in the circulation). Studying the mechanisms of stratosphere-troposphere coupling in the context of the QBO is also important for solar-climate links, which might proceed to thought similar mechanisms.

Several important climate events of the past 400 years were studied in SOCOL Version 2 simulations as part of the FUPSOL project. This work fed into the book “Climatic Changes Since 1700” (Brönnimann, 2015). Among these events is a previously unknown southward shift of the northern tropical belt from ca. 1945-1980, which preceded the subsequent (and ongoing) poleward shift (Brönnimann et al. 2015). A further study of SOCOL Version 2 simulations revealed a link between ozone depletion and tropical precipitation patterns, namely the South Pacific Convergence Zone (Brönnimann et al. 2017). Ozone depletion between the 1960s and the 1990s was found to have contributed to a wetting in spring in the tip of the SPCZ and a drying south of it. The mechanism might also be relevant for solar-climate links.

Collaboration

The collaboration between the teams during three years of the project was very intensive. During the reporting period, there have been four full day plenary meetings and several subgroup meetings in Zurich and Davos with participation by at least three of the five partners. The data exchange, active discussions, joint analyses the results and collective decisions allowed reaching the progress, which would not be reached without such collaboration.

To support the FUPSOL team involvement in international collaborations we actively participated in the organization of PAGES Solar Forcing Workshop: Constraining Solar Forcing by "Detection and Attribution" for the Holocene which was held in Davos in May 2014 (http://www.pages-igbp.org/calendar/2014/127-pages/1158-solar-forcing-2013) and first Swiss SCOSTEP workshop which was held in Bern in October 2016. The participants of FUPSOL actively participated in the organization of the first Swiss SCOSTEP work shop (http://www.naturwissenschaften.ch/service/events/5902) aimed at the enhanced collaboration between solar and climate scientists working in Switzerland.

1.2 Main research results and their relevance to the published, submitted or planned research output.

The main research results and their relevance to the published, submitted or planned research output to the present date can be summarized as follows:

We have

- Prepared and forwarded to the project partners solar forcing for the extension of the future climate simulation from 2100 to 2200 and for sensitivity studies (Arsenovic et al., 2017a, submitted to ACP; Muthers et al, 2016b);
- Prepared solar forcing for the paleoclimate simulations 850-1850 (Jungclaus et al., 2016, submitted to GMDD);
- Complied and described new model for the spectral solar irradiance reconstruction CHRONOS (Egorova et al.,2017, submitted to A&A);
- Demonstrated that the magnitude of SSI long-term variability obtained during NASA SORCE satellite mission is not supported by the observed ozone evolution (Ball et al., 2016).
- Demonstrated that colder climate during the Dalton minimum is caused by both volcanic eruptions and solar activity decrease (Anet et al., 2014).
- Simulated the climate and ozone response to the potential decline/recovery of solar activity in the future (Arsenovic et al., 2017a, submitted to ACP).
- Identified the role of middle range energy electrons in the NO_x production, ozone depletion, thermal and dynamical state of the atmosphere (Arsenovic et al., 2016).
- Demonstrated that new parameterization of the NO_x influx from the thermosphere allows to reach a good agreement between model and observations in the Southern Hemisphere (Arsenovic et al., 2017b, submitted to GRL).
- Demonstrated that about 35% of the early 20th century warming is driven by solar irradiance increase (Arsenovic et al., 2017c, submitted to GRL).
- Updated the parameterization of the gravity wave drag using the set-up from the ECHAM-6 version and performed a set of test model runs.
- Developed the parameterization of the heating rate response to solar irradiance variability for ECHAM-6 (Sukhodolov et al., 2014).
- Evaluated available codes for the photolysis rate calculations and define the most suitable code for our new model based on ECHAM-6 (Sukhodolov et al., 2016).
- Quantified temperature response to the 27-day solar irradiance variability and explained its weak statistical significance in the observation data ((Sukhodolov et al., 2017).

- Proved that the largest solar proton events can be identified from ^{10}Be record, but not observable in the nitrate deposition (Sukhodolov et al., 2017).
- Characterized the atmosphere and climate response to the solar irradiance variability on decadal time scale in the framework of IPCC SOLMIP project. The evaluation of IPCC models has been presented in 3 papers (Mitchel et al., 2015; Hood et al., 2015 and Misios et al., 2016).
- Prepared two review publications on the processes related to the solar influence on climate (Mironova et al, 2015; Rozanov et al., 2016)
- Evaluated our model performance in the framework of international projects SPARC CCMI (Morgenstern et al., 2017; Revell et al., 2016; Kuchar et al., 2017, submitted to JGR); VolMIP (Zanchettin et al., 2016) and SPARC SOLARIS/HEPP (Funke et al., 2017)
- Shown that the model SOCOL-MPIOM, which was developed in the first phase of the FUPSOL project, is characterized by a reasonable climate sensitivity, which agrees well with other CMIP5 models and the estimates from IPCC 2014 (Muthers et al. 2014).
- Addressed the importance of the interactive stratospheric ozone chemistry for simulations of large volcanic eruptions for different climatic background states (Muthers et al., 2015)
- Identified two counteracting mechanisms that govern the response of the AMOC to reduced solar forcing, with one mechanism being significantly strong only, if chemistry-climate interactions are considered in the AOGCM (Muthers et al., 2016b)
- Shown that the influence of different natural forcing factors on the BDC is either small (solar) or short-term (volcanos) and that anthropogenic forcing factors are major driver of multi-decadal scale BDC variations (Muthers et al, 2016a)
- Contributed to a review publication on the climatic impacts of the 1815 Tambora eruptions (Raible et al., 2016)
- Define the dependence of the atmospheric response to solar variability on the other forcing agents and requirements to the time series used for the analysis of solar signal (Kuchar et al., 2017).
- Found out that chemistry-climate interactions amplify the response of the climate system to a solar forcing (Muthers et al., 2016).
- Collected sub-daily pressure data from around 50 stations for the years 1815-1817 to study atmospheric circulation variability during the “Year Without a Summer”. The data support a southward shift of cyclone tracks over the North Atlantic in the summer of 1816 resulting from the dynamical effect of volcanic eruptions (Brugnara et al., 2015).
- Prepared two review publications on the climatic impacts of the 1815 Tambora eruptions (Raible et al., 2015, Brönnimann and Krämer 2016)
- Reconstructed a time series of daily weather types back to 1763 (Schwander et al., 2017).
- Analyzed the influence of the 11-year solar cycle on the frequency of occurrence of weather types and showed an increase in the number of days with an easterly flow over Europe (Schwander et al., 2017, in preparation).
- Demonstrated that the mean sea level pressure field over the North Atlantic has different patterns relative to the 11-year cycle characterizing by lower values for high solar activity (Schwander et al., 2017, in preparation).
- Demonstrated the skill of the AOCCM SOCOL-MPIOM in reproducing Indian monsoon characteristics and oceanic modes (Malik et al. 2017a)
- Established links between multidecadal changes in solar irradiance and the Indian monsoon system, which operate via the Atlantic Multidacadal Oscillation (Malik et al. 2017b, Malik and Brönnimann 2017)
- Discovered southward shift of the northern tropical belt from 1945-1980 in observation and the CCM SOCOL simulations (Brönnimann et al., 2015).
- Found new mechanisms of stratosphere-troposphere interaction by analyzing effects of ozone depletion (Brönnimann et al. 2017) and of the Quasi-Biennial Oscillation (Brönnimann et al. 2016) on the troposphere.
- Provided analysis of the specific key periods and key processes (including the 11-yr sunspot cycle) in CCM SOCOL simulations for the book “Climatic Changes since 1700” (Brönnimann,2015).

1.3 Major deviations from the research plan.

The main objectives declared in the proposal have been reached. A delay with solar irradiance reconstruction in **subproject A** was caused by a not very efficient work of the PhD student W. Adams, who in the second part of the project was not working due to sick leave. We compensated her contribution by hiring Dr. T. Egorova. There was a small 3-month delay in **subproject B** because of late start of Pavle Arsenovic as PhD student of IAC ETHZ and we have to ask for cost neutral extension of the project. By end of March **subproject B** was completed and P. Arsenovic will have his final examination on 17 May 2017. A substantial delay with ECHAM6 implementation was due to delayed appearance of the working ECHAM 6.3 model version which forced us to postpone the development of ECHAM-6 based model version. There was some delay in the **subproject D** due to problems with the computation of the weather types from the simulations with the AOCCM SOCOL-MPIOM and the preparation of the papers describing **subproject D** results. At the moment **subproject D** is completed and M. Schwander passed his final PhD examination on 13 April 2017. There were no deviations from the research plan in **subproject C**.

1.4 The contributions made by the project staff.

T. Egorova (PMOD/WRC and IAC ETHZ) and W. Schmutz (PMOD/WRC), in collaboration with A. Shapiro (since summer 2014 MPS, Göttingen, Germany) worked on the development of CHRONOS code and preparation of the spectral solar irradiance data set for different climate simulations. P. Arsenovic (IAC ETHZ), T. Peter (IAC ETHZ), B.-P. Luo (IAC ETHZ) and E. Rozanov (IAC ETH and PMOD/WRC) worked on implementation of the middle range energy and auroral electrons, gravity wave drag parameterization and simulations of the 20th century and future climate and ozone layer. E. Rozanov (IAC ETH and PMOD/WRC), T. Peter (IAC ETHZ) and W. Schmutz (PMOD/WRC) worked on the evaluation and improvement of the heating and photolysis rates calculation modules, simulation of the atmospheric response to short term solar related variability. E. Rozanov (IAC ETH and PMOD/WRC) participated in SPARC CCMI, SPARC HEPPA-2, IPCC VolMIP, SOLMIP and PMIP activities. S. Muthers (Univ. Bern) and C. Raible (Univ. Bern) performed sensitivity simulations for CO_2, volcanic eruptions, and solar forcing and analyzed the results. M. Schwander (Univ. Bern) developed a new method and generated a new weather types time series that was used to analyze the influence of solar activity on tropospheric weather in Europe. S. Brönnimann (Univ. Bern) analyzed FUPSOL simulations as well as older SOCOL simulations with respect to links between stratosphere and troposphere and links between solar variability and the Indian monsoon.

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

Subproject B had a delay of 2 months due to late hiring of the PhD student. The delay was compensated by the granted cost neutral extension of the project. **Subproject A** has reached Milestone B, that we delivered SSI data (1600-2200) as input to the other subprojects thanks to a strong support by the advisors. However, otherwise the PhD student (W. Adams) has not made substantial progress, was on sick leave since December 15, 2015 and finally left the project. We hired Dr. T. Egorova and she completed intended goals of **subproject A**. The project manager Dr. Eugene Rozanov has temporary (from 1.10.2015 until 30.11.2016) stopped to manage the FUPSOL-II project due to internal project re-assignments, but he was still involved in FUPSOL-II as an expert advisor and co-author of publications. We have assigned a new project manager to the project in the person of Dr. Beiping Luo. He was employed 80 % at the PMOD/WRC and he has newly assigned 50 % of his time to manage and lead the project. He way similarly qualified as E. Rozanov in that he has excellent knowledge and many years of experience in climate simulation. On December 2016 we changed back the project management to Dr. Rozanov for the last 4 months of the project.

2. Research output

Here we mention 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.

Participants of the FUPSOL project are marked in bold.

Submitted papers:

Arsenovic, P., **E. Rozanov**, J. Anet, A. Stenke, and **T. Peter**, Implications of potential future grand solar minimum for ozone layer and climate, submitted to ACP, 2017a.

Relevance to the project: *We describe the simulated climate and ozone layer in the future and the influence of potential solar activity decrease.*

Arsenovic, P., A. Damiani, E. **Rozanov**, B. Funke, and T. **Peter**, Evaluation of modelled NO_x and ozone responses to energetic particle precipitation in the South Hemispheric winter, submitted to GRL, 2017b

Relevance to the project: *We applied new parameterization of the NO_x influx and compared the model results with satellite data.*

Arsenovic, P., E. Rozanov, and T. Peter, Contributions of natural and anthropogenic forcings to the early 20th century warming, submitted to GRL, 2017c

Relevance to the project: *In this paper we analyze the contribution of the solar forcing to early 20th century warming in comparison with anthropogenic and volcanic forcing.*

Brönnimann, S., M. Jacques-Coper, **E. Rozanov,** A. M. Fischer, O. Morgenstern, G. Zeng, H. Akiyoshi, and Y. Yamashita, South Pacific Convergence Zone Affected by Ozone Depletion and Recovery. Env. Res. Lett. (revised), 2017.

Relevance to the project: *We report a link between stratospheric ozone depletion and tropical precipitation based on SOCOL V2 simulations. The relation might also be relevant for solar-climate links.*

Egorova, T., **E. Rozanov**, A.I. Shapiro, I. Usoskin, J. **Beer**, R. Tagirov, **T. Peter** , and **W. Schmutz**, Revised historical solar forcing using updated model and proxy data , submitted to Astronomy & Astrophysics, 2017.

Relevance to the project: *We describe CHRONOS model and reconstructions of the spectral solar Irradiance since 6000 BCE.*

Kuchar, A., **E. Rozanov**, W. Ball, A. Stenke, L. Revell, P. Pisoft, and **T. Peter**, Attribution of lower-stratospheric tropical temperature variations to the 11-year solar cycle, submitted to JGR, 2017.

Relevance to the project: *We analyze the dependence of the atmospheric response to solar irradiance variability on the other forcing agents and requirements to the time series used for the analysis of solar signal.*

Malik, A., **S. Brönnimann,** P. Perona, Statistical Link between External Climate Forcings and Modes of Ocean Variability. Climate Dynamics (revised), 2017b.

Relevance to the project: *We find a link between multi-decadal variability in solar irradiance and oceanic modes based on FUPSOL simulations.*

Malik, A., and **S. Brönnimann,** Factors Affecting the Inter-annual to Centennial Timescale Variability of Indian Summer Monsoon Rainfall Climate Dynamics (submitted), 2017.

Relevance to the project: *We evaluate the relation between the Indian monsoon system and oceanic modes as well as solar irradiance variability.*

Schwander, M., M. Rohrer, **S. Brönnimann,** Influence of solar activity on the occurrence of Central European weather types from 1763 to 2009. Clim. Past Discuss., doi:10.5194/cp-2017-8, in review, 2017.

Relevance to the project: *We analyze the effect of the 11-yr sunspot cycle on the frequency of weather types over Europe as well as the imprint of the 11-yr sunspot cycle on meteorological fields in observation-based data and in the FUPSOL simulations.*

Published papers (from "Output data" container)

Arsenovic, P., **Rozanov**, E., Stenke, A., Funke, B., Wissing, J.M., Mursula, K., Tummon, F., **Peter**, T. (2016), The influence of Middle Range Energy Electrons on atmospheric chemistry and regional climate, in *Journal of Atmospheric and Solar-Terrestrial Physics,* 149, 180-190 Link / External URL of publication: http://www.sciencedirect.com/science/article/pii/S13646 82616301080

Relevance to the project: *We describe the contribution of the middle range energy electrons to the chemical and climatological state of the atmosphere simulated with AOCCM SOCOL.*

Ball, W. T., Haigh, J. D., **Rozanov**, E. V., Kuchar, A., Sukhodolov, T., Tummon, F., Shapiro, A. V., **Schmutz**, W. (2016), High solar cycle spectral variations inconsistent with stratospheric ozone observations, in *Nature Geoscience,* 9(3), 206-209

Relevance to the project: *We demonstrate that the magnitude of SSI long-term variability obtained during NASA SORCE satellite mission is not supported by the observed ozone evolution.*

Ball, William T., Kuchař, Aleš, **Rozanov**, Eugene V., Staehelin, Johannes, Tummon, Fiona, Smith, Anne K., Sukhodolov, Timofei, Stenke, Andrea, Revell, Laura, Coulon, Ancelin, **Schmutz**, Werner, **Peter,** Thomas (2016), An upper-branch Brewer–Dobson circulation index for attribution of stratospheric variability and improved ozone and temperature trend analysis, in *Atmospheric Chemistry and Physics,* 16(24), 15485-15500 Link / External URL of publication: www.atmos-chem-phys.net/16/15485/2016/

Relevance to the project: *We present the new proxy for more accurate extraction of the ozone response to solar variability from satellite observations.*

Ball, William T., **Schmutz,** Werner, Fehlmann, André, Finsterle, Wolfgang, Walter, Benjamin (2016), Assessing the beginning to end-of-mission sensitivity change of the PREcision MOnitor Sensor total solar irradiance radiometer (PREMOS/PICARD), in *Journal of Space Weather and Space Climate,* 6, A32-A32 Link / External URL of publication: http://www.swsc-journal.org/articles/swsc/abs/2016/01/swsc160011/swsc 160011.html

Relevance to the project: *We analyze the performance of the space based solar irradiance monitor.*

Brönnimann, Stefan, Fischer, Andreas M., **Rozanov**, Eugene, Poli, Paul, Compo, Gilbert P., Sardeshmukh, Prashant D. (2015), Southward shift of the northern tropical belt from 1945 to 1980 (vol 8, pg 969, 2015), in *NATURE GEOSCIENCE,* 8(12), 969-974

Relevance to the project: *We present one of the possible effects of climate change.*

Brönnimann Stefan (2016), *Climatic Changes Since 1700,* Springer: Switzerland

Relevance to the project: *In this book some results of FUPSOL project have been used to illustrate the functioning of the climate system.*

Brönnimann, Stefan, Malik, Abdul, Stickler, Alexander, Wegmann, Martin, **Raible**, Christoph C., **Muthers**, Stefan, Anet, Julien, **Rozanov**, Eugene, **Schmutz**, Werner (2016), Multidecadal variations of the effects of the Quasi-Biennial Oscillation on the climate system, in *Atmospheric Chemistry and Physics,* 16(24), 15529-15543 Link / External URL of publication: www.atmos-chem-phys.net/16/15529/2016/

Relevance to the project: *We establish the relation between the QBO and tropospheric climate in FUPSOL simulations; the mechanisms found might also be relevant for the effect of solar-climate links.*

Brönnimann, S., D. Krämer, Tambora and the "Year Without a Summer" of 1816. A Perspective on Earth and Human Systems Science. Geographica Bernensia G90, 48 pp., ISBN 978-3-905835-46-5, doi:10.4480/GB2016.G90.01, 2016.

Relevance to the project: *In this book a review of the effects of the Tambora eruption is given, including an analysis of FUPSOL simulations.*

Brugnara, Y., Auchmann, R., **Brönnimann**, S., Allan, R. J., Auer, I., Barriendos, M., Bergstrom, H., Bhend, J., Brazdil, R., Compo, G. P., Cornes, R. C., Dominguez-Castro, F., van Engelen, A. F. V., Filipiak, J., Holopainen, J., Jourdain, S., Kunz, M., Luterbacher, J., Maugeri, M., Mercalli, L., Moberg, A., Mock, C. J., Pichard, G., Reznckova, L., van der Schrier, G. (2015), A collection of sub-daily pressure and temperature observations for the early instrumental period with a focus on the "year without a summer" 1816, in *CLIMATE OF THE PAST,* 11(8), 1027-1047 Link / External URL of publication: http://www.clim-past.net/11/1027/2015/

Relevance to the project: *We describe the peculiarities of the weather in 1816, which might be related to volcanic eruptions or pronounced solar minimum.*

Funke, Bernd, Ball, William, Bender, Stefan, Gardini, Angela, Harvey, V. Lynn, Lambert, Alyn, López- Puertas, Manuel, Marsh, Daniel R., Meraner, Katharina, Nieder, Holger, Päivärinta, Sanna-Mari, Pérot, Kristell, Randall, Cora E., Reddmann, Thomas, **Rozanov**, Eugene, Schmidt, Hauke, Seppälä, Annika, Sinnhuber, Miriam, Sukhodolov, Timofei, Stiller, Gabriele P., Tsvetkova, Natalia D., Verronen, Pekka T., Versick, Stefan, von Clarmann, Thomas, et al. (2017), HEPPA-II model–measurement intercomparison project: EPP indirect effects during the dynamically perturbed NH winter 2008–2009, in *Atmospheric Chemistry and Physics,* 17(5), 3573-3604 Link / External URL of publication: www.atmos-chem-phys.net/17/3573/2017/

Relevance to the project: *We evaluate our model performance in simulating downward NO_x propagation against satellite observations.*

Hood, L. L., Misios, S., Mitchell, D. M., **Rozanov**, E., Gray, L. J., Tourpali, K., Matthes, K., Schmidt, H., Chiodo, G., Thieblemont, R., Shindell, D., Krivolutsky, A. (2015), Solar signals in CMIP-5 simulations: the ozone response, in *QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY,* 141(692), 2670-2689

Relevance to the project: *We discuss the performance of the model participated in IPCC in the simulation of the ozone layer response to the solar irradiance variability. It can be used for the evaluation of our model results.*

Jungclaus, Johann H., Bard, Edouard, Baroni, Mélanie, Braconnot, Pascale, Cao, Jian, Chini, Louise P., **Egorova**, Tania, Evans, Michael, González-Rouco, J. Fidel, Goosse, Hugues, Hurtt, Georges C., Joos, Fortunat, Kaplan, Jed O., Khodri, Myriam, Klein Goldewijk, Kees, Krivova, Natalie, LeGrande, Allegra N., Lorenz, Stephan J., Luterbacher, Jürg, Man, Wenmin, Meinshausen, Malte, Moberg, Anders, Nehrbass- Ahles, Christian, Otto-Bliesner, Bette I., et al. (2016), The PMIP4 contribution to CMIP6 - Part 3: the Last Millennium, Scientific Objective and Experimental Design for the PMIP4 “past1000” simulations, in *Geoscientific Model Development Discussions*, 1-34 Link / External URL of publication: http://www.geosci-model-dev-discuss.net/gmd-2016- 278/

Relevance to the project: *The paper describes solar forcing calculated by* ***subproject A*** *team.*

Malik, Abdul, **Brönnimann**, Stefan, Stickler, Alexander, **Raible**, Christoph C., **Muthers**, Stefan, Anet, Julien, **Rozanov**, Eugene, **Schmutz**, Werner (Accepted / In Press), Decadal to multi-decadal scale variability of Indian summer monsoon rainfall in the coupled ocean-atmosphere-chemistry climate model SOCOL-MPIOM, in *Climate Dynamics*, 1-22

Relevance to the project: *We evaluate the FUPSOL simulations with respect to their ability to reproduce important characteristics of the Indian monsoon system and oceanic modes.*

Mironova, Irina A., Aplin, Karen L., Arnold, Frank, Bazilevskaya, Galina A., Harrison, R. Giles, Krivolutsky, Alexei A., Nicoll, Keri A., **Rozanov**, Eugene V., Turunen, Esa, Usoskin, Ilya G. (2015), Energetic Particle Influence on the Earth's Atmosphere, in *SPACE SCIENCE REVIEWS,* 194(1-4), 1-96

Relevance to the project: *We summarized the recent progress in the study of precipitating energetic particles impact on the atmosphere and discussed the most promising directions to further studies.*

Misios, S., Mitchell, D. M., Gray, L. J., Tourpali, K., Matthes, K., Hood, L., Schmidt, H., Chiodo, G., Thiéblemont, R., **Rozanov**, E., Krivolutsky, A. (2016), Solar signals in CMIP-5 simulations: effects of atmosphere-ocean couplingSurface Solar Signals in CMIP-5, in *Quarterly Journal of the Royal Meteorological Society,* 142(695), 928-941

Relevance to the project: *We discuss the performance of the model participated in IPCC in the simulation of the tropospheric climate response to the solar irradiance variability. It can be used for the evaluation of our model results.*

Mitchell, D. M., Misios, S., Gray, L. J., Tourpali, K., Matthes, K., Hood, L., Schmidt, H., Chiodo, G., Thieblemont, R., **Rozanov**, E., Shindell, D., Krivolutsky, A. (2015), Solar signals in CMIP-5 simulations: the stratospheric pathway, in *QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY,* 141(691), 2390-2403 Link / External URL of publication: http://onlinelibrary.wiley.com/doi/10.1002/qj.2530/pdf

Relevance to the project: *We discuss the performance of the model participated in IPCC in the simulation of the stratospheric response to the solar irradiance variability. It will be used for the evaluation of our model results.*

Morgenstern, Olaf, Hegglin, Michaela I., **Rozanov**, Eugene, O'Connor, Fiona M., Abraham, N. Luke, Akiyoshi, Hideharu, Archibald, Alexander T., Bekki, Slimane, Butchart, Neal, Chipperfield, Martyn P., Deushi, Makoto, Dhomse, Sandip S., Garcia, Rolando R., Hardiman, Steven C., Horowitz, Larry W., Jöckel, Patrick, Josse, Beatrice, Kinnison, Douglas, Lin, Meiyun, Mancini, Eva, Manyin, Michael E., Marchand, Marion, Marécal, Virginie, Michou, Martine, et al. (2017), Review of the global models used within phase 1 of the Chemistry–Climate Model Initiative (CCMI), in *Geoscientific Model Development,* 10(2), 639-671 Link / External URL of publication: www.geosci-model-dev.net/10/639/2017/

Relevance to the project: *The paper describes chemistry-climate models and external forcing data for SPARC CCMI activity.*

Muthers, S., Anet, J. G., Stenke, A., **Raible**, C. C., **Rozanov**, E., **Brönnimann**, S., Peter, T., Arfeuille, F. X., Shapiro, A. I., **Beer**, J., Steinhilber, F., Brugnara, Y., **Schmutz**, W. (2014), The coupled atmosphere- chemistry-ocean model SOCOL-MPIOM, in *GEOSCIENTIFIC MODEL DEVELOPMENT,* 7(5), 2157-2179 Link / External URL of publication: http://www.geosci-model-dev.net/7/2157/2014/

Relevance to the project: *We document the main model tool of the project.*

Muthers, S., Arfeuille, F., **Raible**, C. C., **Rozanov**, E. (2015), The impacts of volcanic aerosol on stratospheric ozone and the Northern Hemisphere polar vortex: separating radiative-dynamical changes from direct effects due to enhanced aerosol heterogeneous chemistry, in *ATMOSPHERIC CHEMISTRY AND PHYSICS,* 15(20), 11461-11476 Link / External URL of publication: http://www.atmos-chem-phys.net/15/11461/2015/

Relevance to the project: *We assessed the influence of atmospheric ozone chemistry on the dynamical response of the stratospheric circulation to strong volcanic eruptions.*

Muthers, S., Kuchar, A., Stenke, A., Schmitt, J., Anet, J. G., Raible, C. C., Stocker, T. F. (2016a), Stratospheric age of air variations between 1600 and 2100, in *Geophysical Research Letters,* 43(10), 5409-5418

Relevance to the project: *We analyze the stratospheric age of the air evolution and its connection to solar activity.*

Muthers, Stefan, **Raible**, Christoph C., **Rozanov**, Eugene, Stocker, Thomas F. (2016b), Response of the AMOC to reduced solar radiation; the modulating role of atmospheric chemistry, in *Earth System Dynamics,* 7(4), 877-892 Link / External URL of publication: http://www.earth-syst-dynam.net/7/877/2016/esd-7- 877-2016.html

Relevance to the project: *We describe the role of chemistry-climate interactions in the amplification of the climate system response to solar forcing.*

Raible, Christoph C., **Brönnimann**, Stefan, Auchmann, Renate, Brohan, Philip, Frölicher, Thomas L., Graf, Hans-F., Jones, Phil, Luterbacher, Jürg, Muthers, Stefan, Neukom, Raphael, Robock, Alan, Self, Stephen, Sudrajat, Adjat, Timmreck, Claudia, Wegmann, Martin (2016), Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effectsTambora 1815 as a test case for high impact volcanic eruptions, in *Wiley Interdisciplinary Reviews: Climate Change,* 7(4), 569-589 Link / External URL of publication: http://onlinelibrary.wiley.com/doi/10.1002/wcc.407/epdf

Relevance to the project: *We summarize the climatic impacts of the 1815 Tambora eruptions and its possible overlap with solar activity minimum.*

Revell, Laura E., Stenke, Andrea, **Rozanov**, Eugene, Ball, William, Lossow, Stefan, **Peter**, Thomas (2016), The role of methane in projections of 21st century stratospheric water vapour, in *Atmospheric Chemistry and Physics,* 16(20), 13067-13080 Link / External URL of publication: www.atmos-chem-phys.net/16/13067/2016/

Relevance to the project: *We evaluate the performance of our model in calculation of the water vapor trends.*

Rozanov, E., Georgieva, K., Mironova, I., Tinsley, B., Aylward, A. (2016), Foreword: Special issue on "Effects of the solar wind and interplanetary disturbances on the Earth's atmosphere and climate", in *Journal of Atmospheric and Solar-Terrestrial Physics,* 149, 146-150

Relevance to the project: *We summarized the recent progress in the study of energetic particles and interplanetary magnetic field disturbances influence on climate.*

Sukhodolov, T., **Rozanov,** E., Shapiro, A. I., Anet, J., Cagnazzo, C., **Peter**, T., **Schmutz**, W. (2014), Evaluation of the ECHAM family radiation codes performance in the representation of the solar signal, in *GEOSCIENTIFIC MODEL DEVELOPMENT,* 7(6), 2859-2866 Link / External URL of publication: http://www.geosci-model-dev.net/7/2859/2014/

Relevance to the project: *We discuss the performance of several radiation codes and describe the parameterization to improve the response of ECHAM-6 radiation code to solar irradiance variability.*

Sukhodolov, Timofei, **Rozanov**, Eugene, Ball, William, Bais, Alkiviadis, Tourpali, Kleareti, Shapiro, Alexander, Telford, Paul, Smyshlyaev, Sergey, Fomin, Boris, Sander, Rolf, Bossay, Sébastien, Bekki, Slimane, Marchand, Marion, Chipperfield, Martyn P., Dhomse, Sandip, Haigh, Joanna D., **Peter**, Thomas, **Schmutz**, Werner (2016), Evaluation of the simulated photolysis rates and their response to solar irradiance variability, in *Journal of Geophysical Research: Atmospheres,* 121(10), 6066 -6084

Relevance to the project: *We compare the performance of several codes for the photolysis rate calculations. The results will be used to choose the most effective code for the new model based on ECHAM-6.*

Sukhodolov, Timofei, **Rozanov,** Eugene, Ball, William T., **Peter,** Thomas, **Schmutz**, Werner (2017), Modelling of the middle atmosphere response to 27-day solar irradiance variability, in *Journal of Atmospheric and Solar-Terrestrial Physics,* 152-153, 50-61

Relevance to the project: *We analyze the atmospheric response to solar irradiance variability caused by the Sun rotation*

Sukhodolov, Timofei, Usoskin, Ilya, **Rozanov**, Eugene, Asvestari, Eleanna, Ball, William T., Curran, Mark A. J., Fischer, Hubertus, Kovaltsov, Gennady, Miyake, Fusa, **Peter**, Thomas, Plummer, Christopher, **Schmut**z, Werner, Severi, Mirko, Traversi, Rita (2017), Atmospheric impacts of the strongest known solar particle storm of 775 AD, in *Scientific Reports,* 7, 45257-45257 Link / External URL of publication: https://www.nature.com/articles/srep45257

Relevance to the project: We discuss the effects of the strongest solar proton event in history.

Zanchettin, D., Khodri, M., Timmreck, C., Toohey, M., Schmidt, A., Gerber, E. P., Hegerl, G., Robock, A., Pausata, F. S. R., Ball, W. T., Bauer, S. E., Bekki, S., Dhomse, S. S., LeGrande, A. N., Mann, G. W., Marshall, L., Mills, M., Marchand, M., Niemeier, U., Poulain, V., **Rozanov**, E., Rubino, A., Stenke, A., Tsigaridis, K., Tummon, F. (2016), The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP): experimental design and forcing input data for CMIP6, in *Geoscientific Model Development,* 9(8), 2701-2719 Link / External URL of publication: www.geosci-model-dev.net/9/2701/2016/

Relevance to the project: This paper presents experimental design and external forcing for CMIP-6 VolMIP activity.