Final scientific report

Project: FUPSOL
Time: 01.09.2010 – 31.12.2013

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 work on the project was being conducted in the framework of five subprojects carried out in five institutions working in close collaboration by the means of data exchange, intensive discussions and science meetings.

In the framework of **subproject A** ("*Reconstruction of past solar activity and TSI from analyzing radionuclide data, extrapolating the future solar activity and TSI from statistical modeling of the past 9300 years*") we prepared solar magnetic activity and energetic particle precipitation time series covering the period 1600-2200. We improved previously published reconstruction of past solar activity which was derived from ^{10}Be data from a Greenlandic ice core by applying principal component analysis to a combination of two ^{10}Be ice core records from both hemispheres and the ^{14}C tree ring record. We also applied two independent approaches based on fast Fourier transform and wavelet analysis to extract the spectral properties of the past 6000 years of this new solar activity record and to predict solar activity evolution for the next 500 years.

In the **subproject B** ("Calculating the time variable UV-visual-IR solar irradiance for the years 1600-2200 based on past and future solar activity proxies") we introduced the molecular opacity and additional (ad hoc) UV opacity to the Code for the Solar Irradiance (COSI). We applied the updated COSI code for the reconstruction of the solar spectral irradiance back to the Maunder minimum on the basis of solar activity record provided by the **subproject A** team. To estimate possible uncertainties of this reconstruction the treatment of the UV opacity was additionally validated using the measurements from the Large Yield RAdiometer (LYRA) onboard ESA PROBA-2 satellite. We participated in a synoptic program aimed to a search for cyclic variations of the turbulent magnetic fields of the quiet Sun. The **subproject B** team also participated in the alternative solar spectral irradiance reconstruction based on the assumption that Mg II index can be a good proxy for the solar irradiance in 120-400 nm spectral regions. We modified the statistical equilibrium calculation procedure which was necessary for the introduction of the new UV lines into the NLTE part of the COSI code. We worked on the COSI validation against observational data collected during the recent European missions PROBA-2, PICARD and SSI during the last 15 years calculated with other models. In order to better understand the 11-year solar irradiance variability we analyzed the SPM/VIRGO data for 2000-2012 and compared them against SIM/SORCE data. To estimate the uncertainties in our SSI reconstructions we took part in the analysis of sub-mm data from the James Clerk Maxwell telescope and compared them to our calculations with COSI. To further constrain the secular trend of the solar irradiance we compared the available photometric records of Sun-like stars with different reconstructions of the solar irradiance over the last 9000 years. We have provided three SSI reconstructions (1600-2100) with different estimations of the magnitude of the long-term variability to the **subproject D** team. We also worked on a simplified and more sophisticated NLTE model to better reproduce the profile of the Mg II line. We participated in the intercomparison between different spectral solar irradiance reconstructions and their impact on solar heating rates. We have shown that the recent measurements of the solar spectrum (SCIAMACHY/ENVISAT, SOLSPEC/ISS) agree with COSI calculations within their reported uncertainties. We also showed that our calculations of the SSI variability over the 2011-2013 period are in very good agreement with PREMOS/PICARD measurements. We replaced the iterative scheme of the simultaneous solution of the statistical equilibrium and radiative transfer equations implemented in COSI to the more efficient one. This allowed us to better reproduce strong UV lines in the solar spectrum. We used the COSI code to estimate the contribution of different spectral features to the TSI variability on different time scales. To better constrain the solar irradiance variability we extended the solar-stellar comparison activity and extrapolated SATIRE model of the solar variability to magnetically more active stars. We successfully reproduced the observed stellar photometric trends which may be considered as an indication that the variability of more active stars has the same basic causes as the Sun's. Our approach allows constraining the model of solar irradiance variability over a wide parameter space of physical parameters and helps to better understand the mechanisms of solar variability.

The compilation and providing of all non-solar forcings for the period 1600-2100 in proper formats for the model simulations was the aim of the **subproject C** ("Non-solar forcing"). The list of forcing includes time dependant concentrations of the greenhouse gases and ozone depleting substances, the stratospheric and tropospheric aerosols, emissions of short-lived species, land-surface properties, and equatorial zonal wind resulting from Quasi-Biennial Oscillation.

In the framework of the **subproject D** ("Transient simulations of the atmosphere and ocean response to the solar variability in the past, present and future"), we developed the atmosphere-ocean-chemistry-climate model (AOCCM)

SOCOL-MPIOM, which was the main modeling tool of the project. The first steps consisted in implementing and testing the energetic particle precipitation parameterizations (EPP). The previously developed modules were parallelized and extended to enable the application of EPP datasets provided by the **subproject A** team. The radiation code of the model was improved to better describe the heating rate response to the variability of the solar irradiance. Furthermore, an additional module was also installed to simulate the deposition rates of ^{10}Be and ^{7}Be in order to validate the model results against measurements. All external forcings for the model runs were implemented in close collaboration with the **subprojects A-C** teams. The implementation of the ocean module MPI-OM using the COSMOS framework acquired from the Max Plank Institute for Meteorology (MPIM), Hamburg, Germany was completed in an intense collaboration with the **subproject E** team, though with some delay due to longer than expected testing with respects to potential drifts in the coupled model version. After several spin-up model runs we carried out the transient simulations with changing boundary conditions together with the **subproject E** team. We performed and analyzed the results of all planned sensitivity runs for the Dalton minimum (DM) starting from 1780 paying special attention to the causes of cold period in Europe around 1816. We calculated the contribution of different anthropogenic and solar forcings to the evolution of the global ozone and climate during 21st century our using chemistry-climate model in time-slice mode without dynamical ocean to estimate potential magnitude of the effect of the solar activity decline and elucidate the role of different anthropogenic perturbations. We simulated the climate change until year 2100 using the AOCCM and two scenarios allowing a new grand solar minimum reaching lowest TSI values around 2080 and one scenario with constant solar forcing. For all scenarios, an 11-year-solar-cycle was underlain and two rather powerful (Pinatubo-like) and two small volcanic eruptions were introduced. We showed that with a strong solar irradiance decline of 6 W/m^2, the global average temperatures would – following the RCP4.5 scenario – be still raised by 1.6-1.7 K instead of 2 K without solar activity decline. Moreover the ozone layer recovery would be delayed by several tenths of years. We further analyzed and published the results of all DM sensitivity runs. The main results were a comparison of the model simulated surface temperature changes with different proxies, responses of the ocean heat content to the external shortwave and volcanic forcing and effects on precipitation patterns stemming from changes of the solar irradiance and volcanic eruptions.

During the **subproject E** ("Ocean-Atmosphere Interaction and its Response to Changes of the Solar Forcing") implementation we aimed on the development of the coupled AOCCM SOCOL-MPIOM. This work was carried out in close collaboration with **subproject D** team and the MPIM, Hamburg, Germany. The initialization fields for the ocean module were acquired from the Millennium run of similar model performed by MPIM. In order to test the stability of the simulated climate several sensitivity simulations in time slice mode were performed with and without the atmosphere chemistry module and with different values of the prescribed total solar irradiance. The output of these model runs was carefully analyzed and it was found that the spin-up run should be slightly extended to reach quasi-equilibrium state of the climate system. Besides the technical aspects, the **subproject E** team participated in the work on two review papers describing the role of the solar forcing and its interaction with internal variability. We carried out long term (1600-2000) simulations in collaboration with the **subproject D** team. A set of four simulations with different solar forcing was completed. Additionally, we assessed the impact of atmospheric chemistry on the ocean circulation as well as its interplay with volcanic eruptions. We prepared the technical paper describing the climate variability and, in particular, the impact of the solar forcing on the ocean in the long-term simulations. One aim of the publication is to address the role of interactive chemistry. Moreover, we carried out the sensitivity experiments for Tambora-type eruptions with and without atmospheric chemistry to assess whether the atmospheric response and the impact on the ocean could be affected by it. We analyzed in details the transient simulations for the period 1600-2000 and the control simulations for perpetual 1600 AD conditions. The specific response of the SOCOL-MPIOM model to volcanic forcing and the fact that in the period 1600-2000 solar minima occur in combination with several volcanic eruptions motivated a sensitivity study, where we investigated the role of different stratospheric ozone concentrations on the dynamical response of the atmosphere after large volcanic eruptions. Therefore we additionally performed an ensemble of sensitivity simulations where the interactive chemistry module of the model was deactivated. An important finding is that the dynamical response of the atmosphere to volcanic eruptions is dependent on the background stratospheric ozone concentration. In particular the stratosphere-troposphere coupling in the Northern Hemisphere is favored when the stratospheric ozone concentration has a larger meridional gradient during a volcanic eruption. Additionally, we investigated the role of the ocean for this set of sensitivity simulations, showing no significant contribution to the response behavior on the time scales considered. Thus, we conclude that the changes in response behavior are dominated by the signals originating from the stratosphere. Currently, we are assessing the question how the response is modulated, when an interactive chemistry model is coupled to the atmosphere model and how the response changes between preindustrial and modern climates and between different eruptions sized. For this publication SOCOL-MPIOM is modified in the way that the interactive chemistry can be disabled and the ozone concentrations simulated by the chemistry module can be applied as forcing in the simulations with interactive chemistry disabled. The forcing is implemented by a daily 3-dimensional data set directly on the model levels to avoid common problems related to the vertical interpolation of the ozone values. Using this setup, an additional control simulation for perpetual 1600 AD conditions is performed with ozone as external forcing. The comparison of the control simulations with and without interactive chemistry shows that the influence of the chemistry on the climate state and the variability is small given the absence of external forcing. Some differences are found for the stratosphere and the variability of the polar vortices, but they were too small to significantly affect the troposphere or the surface. Consequently, the interactive chemistry has no impact on the ocean circulation either. The corresponding publication summarizing these results will be submitted early spring 2014.

The aim of **subproject F** ("Evaluation and analysis of the model simulations") is to extract and understand the signature of solar variability on Earth's climate using a number of observation-based products (e.g., reanalysis, statistical reconstruction) and model simulations. For the latter, thorough validation is required, which is one of the milestones of this subproject, as well. We prepared several large data sets, in particular reanalysis, model outputs and 3-D statistical reconstruction. All data sets were downloaded and stored, at least at monthly resolution (higher temporal resolution data sets are planned to be downloaded soon as new storage devices will be available), they are therefore easily and quickly accessible and can be used both for the validation of the FUPSOL model and for the analysis of the solar signal in observations. We also prepared validation scripts for the comparisons of climatologies and transient values, and they were applied for the preliminary validation of the FUPSOL runs. We also analyzed the atmospheric signatures of the 11-year solar cycle in the available data sets using multiple linear regression analysis to separate the solar signal from other interannual to inter-decadal variability and the response of the mesospheric OH and H_2O data as observed by the Aura Microwave Limb Sounder (MLS) to 27-day solar variability. Analyses of the solar signature in observations revealed a significant and physically consistent imprint of the 11-yr solar cycle throughout the troposphere of the northern mid-latitudes in long upper-air data sets. We also compiled two-dimensional (latitude-height) historical ozone data from combining historical total ozone observation with chemistry climate model data. This data set was also analyzed with respect to the imprint of the 11-yr solar cycle. In addition to the solar effects, the volcanic imprint during the past 400 years was analyzed in reconstructions and model simulations. Large-ensemble simulations of the past 400 years with a GCM well reproduced the volcanic imprint found in reconstructions. Apart from the well-known winter signal, the simulations also reproduced the boreal summer signature which included a weakening of the Asian and African monsoons and an increase in precipitation over south-central Europe. In the simulations these features are related to each other. The increased summer precipitation over south-central Europe – expressed most prominently as "Years Without a Summer" – is arguably a consequence of the weakened African monsoon and a weakened northern Hadley cell, allowing a southward displacement of the storm track and more convective activity over the northern Mediterranean. Finally, for going further back in time, the suitability of climate proxies with respect to capturing variability at different time scales was analyzed. It was found that most proxies are spectrally biased, which makes them unsuitable to capture the strength of decadal variability when calibrated with interannual variability. Moreover, it was analyzed to what extent $\Delta^{18}O$ in Alpine ice cores represent seasonally or annually averaged air temperature.

In summary, the collaboration between teams during the project implementation was very intensive. During the reporting period we had five full day plenary meetings and several subgroup meetings in Bern, Zurich and Davos with participation by at least two 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.

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 produced the first "low noise" solar activity record covering the past 9400 years by combining two ^{10}Be ice core records, one from the northern hemisphere (GRIP) and one from the southern hemisphere (EDML), with the global ^{14}C tree ring record. The new "low noise" solar activity record covering the past 9400 years with a temporal resolution of 20 years has been published (Steinhilber et al., 2012)
- An estimate of solar activity evolution during the future 500 years has been carried out based on the spectral properties of the past. A steady decrease of future solar activity reaching approximately the level of the Dalton minimum in the year 2100 has been predicted (Steinhilber and Beer, 2013)
- We derived time series of energetic electron precipitation (EEP) and solar proton events (SPE) by making use of their relationship with the geomagnetic indices, the interplanetary magnetic field and nitrates concentration in ice cores. This record covers the period 1600 to the year 2100.
- We organized the joined workshop of the PAGES Solar Working Group and FUPSOL participants to discuss the role of the Sun in Climate change. The main results were published by Beer (2013).
- Time series of total and spectral irradiance for the period 1610-2100 were derived. These results were published by Shapiro et al., (2011).
- We analyzed ground based observations of the quiet Sun activity over the solar cycle. The paper was published by Kleint et al., (2011).
- Using the measurements from the Large Yield RAdiometer (LYRA) onboard ESA PROBA-2 satellite we estimated the uncertainties of the UV spectrum calculations with solar radiation code COSI, which is used for the calculations of the solar forcing in the past and future. The paper was published by Shapiro et al., (2013).

- We calculated the solar irradiance in the past using MgII index as a proxy and estimated the uncertainty of our solar irradiance reconstruction approach. The paper was published by Thuillier et al., (2011).
- The results of the SSI inter-comparison campaign confirmed that our SSI dataset agrees well with the state-of-the-art SATIRE-S and NRLSSI models in the Herzberg continuum spectral range and in the visible. The results were published by Ermoli et al., (2013) and by Thuillier et al. (2013, 2014).
- On the basis of Sun-like stars analysis we found out that 0.17 % change of the solar visible irradiance (which corresponds to 1.9-2.7 W/m^2 TSI change) between the Maunder minimum period and present is within 95% confidence range. The paper describing our findings was published by Shapiro et al., (2013).
- The reanalysis of James Clerk Maxwell telescope data showed that the applied in COSI model "A" could be too cool. We have shown that, by adopting it, the quiet-Sun irradiance variations can be overestimated by up to two times. The results were published by Judge et al., (2012). COSI calculations of the quiet Sun's solar spectrum are compared with the most recent measurements and reference spectra (Thuillier et al., 2014).
- The solar irradiance data obtained by VIRGO/SOHO were used to constrain the spectral profile of the solar variability on the activity time scale (Wehrli et al. 2013).
- The new scheme for simultaneous solution of the radiative transfer and statistical equilibrium are implemented into COSI. A paper is in preparation.
- We have proposed a method to use stellar photometric data for constraining solar variability on the activity time scale (Shapiro et. 2014)
- We have shown that our SSI reconstructions for 2011-2013 periods agree well with PREMOS/PICARD measurements. A paper is in preparation.
- We compiled non-solar forcing which for the model simulations. A paper about stratospheric aerosol time series covering last 400 years was published by Arfeuille et al. (2014).
- We produced model boundary conditions (forcing data sets) for the 21st century, including a novel, detailed stratospheric aerosol data set.
- We completed all planned sensitivity runs for Dalton minimum conditions and established the contribution of different factors. Two papers were published by Anet et al., (2013a, 2013c).
- We simulated the effects of GCR, SPE and EEP on chemical composition and climate to validate our parameterizations of these processes. Five papers were published (Calisto et al., 2011, 2012, 2013; Funke et al., 2011, Rozanov et al., 2012a).
- We have improved solar radiation code of the model to better represent the heating rate response to solar irradiance variability. The paper was published by Sukhodolov et al., (2014).
- We found that the observed response of the mesospheric OH and H_2O to the solar irradiance variability is strong for the solar maximum and negligible for the solar minimum which confirms their theoretically expected coupling. These results were published by Shapiro A.V. et al., (2013).
- We identified the contribution of different forcing to the global ozone and climate evolution during 21st century using chemistry-climate model without dynamical ocean. The results were presented in two papers (Rozanov et al., 2012b; Zubov et al., 2013).
- We simulated the climate change until year 2100 using AOCCM and two scenarios allowing a new grand solar minimum reaching lowest TSI values around 2080 and one scenario with constant solar forcing.
- We showed that with a strong solar irradiance decline the global average temperatures would be still raised by 1.6-1.7 K instead of 2 K without solar activity decline. Moreover, in this run the global mean ozone layer recovery would not be reached without further limitation of the ozone destroying substances limitations. These results were published by Anet et al., (2013b).
- We analyzed the role of the solar forcing and its interaction with internal variability in the climate system. This information was used for the analysis of our long-term model simulation results. Three papers were published (Trouet et el., 2012; Pinto and Raible, 2012; Raible et al., 2014).
- We introduce a new method to identify the ITCZ, which will enable us to better assess solar and volcanic impacts on the tropics (Laederach and Raible (2013).
- Form our simulations of the Tambora effects we found out that the contribution of the interactive chemistry to global climate is small, however, on a regional scale some pronounced differences are found for the winter warming pattern in the Northern hemisphere (Muther et al. , 2014b).
- We found out that the dynamical response of the atmosphere to volcanic eruptions is dependent on the background stratospheric ozone concentration (Muther et al., 2014a).
- We analyzed the response of the atmosphere to 11-year solar cycle using collected data sets, composite and multiple regression analysis. We found a consistent response of the northern middle latitude troposphere to the 11-yr solar cycle in long, observation-based 3-dimensional atmospheric data sets covering 8 solar cycles. A paper about the results was published by Brugnara et al., (2013).
- We analyzed the effect of volcanic eruptions in sub-daily temperature from early instrumental data and model simulations and found a small but consistent imprint in the diurnal temperature range (Auchmann et al. 2013).
- Based on the analysis of model simulations and reconstructions with respect to effect of volcanic eruptions on the water cycle, we postulate a new mechanism: Volcanic eruptions lead to rainy summers in south-central Europe as a consequence of a weakening of the African monsoon. This new mechanism eventually may explain the "Years without a summer" (Wegmann et al. 2014).

- We analyzed the spectral signature of tree rings and compared it to the spectral signatures of precipitation and temperature variability in observations, models, and reanalyses. Results show that tree ring proxies are spectrally biased – they were published in Nature Climate Change (Franke et al. 2013).
- We analyzed signal preservation in an Alpine ice core and found that $d^{18}O$ in ice cores well represents precipitation-weighted temperature although it may not correlate at all with annual mean temperature (Brönnimann et al. 2013a)
- We produced a two-dimensional historical ozone data set back to 1900 from combining historical total column ozone observations with an ensemble of chemistry climate model simulations. For this purpose we developed an "off-line" data assimilation scheme based on the Ensemble Kalman filter. The resulting data set was analyzed with respect to 11-yr solar variability and other characteristic features (Brönnimann et al. 2013b).

1.3 Major deviations from the research plan.

A noticeable deviation from the research plan was related to the error in the land-surface boundary conditions described above. This led to the restart of the simulations, which slowed down the project implementation. As the result the simulations of the future were delayed by approximately 3 months. This gap was covered during a 3-month no-cost extension of the project. Finally, the proposed plan and milestones were completely fulfilled and all deliverables were provided.

1.4 The contributions made by the project staff.

F. Steinhilber and J. Beer (EAWAG) developed and provided the time series (1600-2100) of solar modulation potential, geomagnetic Ap index, intensity of the solar proton events for the solar irradiance reconstruction and model simulations. A. Shapiro, W. Schmutz and E. Rozanov (PMOD/WRC) developed and provided the reconstruction of the solar irradiance in the past (1600-2000) and projection to the future (2000-2100). Y. Brugnara (Univ. Bern), S. Brönnimann (Univ. Bern) and E. Rozanov (PMOD/WRC, Davos) contributed to the development of the non-solar forcing in the framework of the subproject C. Project C does not receive SNF funding. The contributions by F. Arfeuille (ETH Zurich) and J. Bhend (ETH Zurich) to the development of the non-solar forcing are much appreciated. J. Anet (IAC ETHZ), S. Muthers (Univ. Bern), E. Rozanov (PMOD/WRC) worked on the development of the coupled atmosphere-ocean-chemistry model and experimental set-up. J. Anet (IAC ETHZ) and E. Rozanov (PMOD/WRC) introduced proper parameterizations for energetic particle precipitation effects and validation of the applied approaches. S. Muthers (Univ. Bern), J. Anet (IAC ETHZ) and C. Raible (Univ. Bern) acquired initialization fields for ocean model from MPIM (Hamburg, Germany) and adapted them for the model. They also cooperated in tuning the coupled AO-CCM to avoid any major drifts in the ocean. S. Muthers (Univ. Bern), J. Anet (IAC ETHZ), C. Raible (Univ. Bern), T. Peter (IAC ETHZ) and E. Rozanov (PMOD/WRC) analyzed the results of transient model runs and sensitivity studies.

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

Subproject F had a delay of 2 months due to problems filling the PhD position. In spring 2012, Yuri Brugnara (PhD student in UniBe) decided to quit the project (see correspondence with SNF) due to health issue and personal reasons. He was replaced by Florian Arfeuille, who previously worked as an (unfunded) postdoc in the project. The total salary costs for the project remain the same.

2. Research output:

Participants of the FUPSOL project are marked in bold.

<u>**Papers in preparation:**</u>

1. **Muthers, S.**, **F. Arfeuille,** and **C. Raible**, The response of stratospheric ozone to strong tropical volcanic eruptions and how ozone modulated the dynamical changes, in prep., to be submitted to ACPD, 2014b.
   Relevance to the project: We estimate the contribution of the interactive chemistry to dynamical changes after volcanic eruptions.
2. **Muthers, S.**, **J. Anet**, **C. Raible**, **S. Brönnimann**, **E. Rozanov**, A. Stenke, **T. Peter**, **F. Arfeuille**, **A. I. Shapiro**, **J. Beer**, **F. Steinhilber**, **Y. Brugnara**, and **W. Schmutz** , The coupled atmosphere–chemistry–ocean model SOCOL–MPIOM, in prep, to be submitted to GMD, 2014c.
   Relevance to the project: We describe the model and analyze its performance.

<u>**Papers submitted or in press:**</u>

1. **Shapiro**, **A.I.**, S. Solanki, N. Krivova, **W. Schmutz**, W. Ball, R. Knaack, **E. Rozanov**, and Y. Unruh, "The variability of Sun-like stars: reproducing observed photometric trends", submitted to Astronomy and Astrophysics, 2014.
   Relevance to the project: We show how the stellar measurements allow us to better constrain and understand the SSI variability on the activity time scale.

2. **Muthers, S.**, **J. G. Anet**, **C. C. Raible**, **S. Brönnimann**, **E. Rozanov**, **F. Arfeuille**, **T. Peter**, **A. I. Shapiro**, **J. Beer**, **F. Steinhilber**, **Y. Brugnara**, and **W. Schmutz.** , Northern hemispheric winter warming pattern after tropical volcanic eruptions: Sensitivity to the ozone climatology, J. Geophys. Res. Atmos., 119, doi:10.1002/2013JD020138, 2014.
   Relevance to the project: We analyze the sensitivity of the climate response to the state of the polar vortex.
3. **Raible, C. C.**, F. Lehner, J. F. Gonzalez-Rouco, and L. Fernandez-Donado, Changing correlation structures of the Northern Hemisphere atmospheric circulation from 1000 to 2100 AD, *Climate of the Past*, in press, 2014.
   Relevance to the project: We assess the internal variability of dominant modes of the large-scale atmospheric circulation in different model simulations for the last millennium.
4. Wegmann, M., **S. Brönnimann**, J. Bhend, J. Franke, D. Folini, M. Wild, J. Luterbacher, Volcanic influence on European summer precipitation through monsoons: Possible cause for "Years Without a Summer". *J. Climate* accepted, 2014.
   Relevance to the project: We present a new mechanism of how volcanic eruptions (including the Tambora eruption in 1815) affect summer precipitation in south-central Europe.

Output data:

1. Abreu, J. A.; **Beer, J.**; Ferriz-Mas, A.; McCracken, K. G.; **Steinhilber, F.**, Is there a planetary influence on solar activity?, Astronomy and Astrophysics, 548,A88, doi: 10.1051/0004-6361/201219997, 2012.
   Relevance to the project: We attempt to explanation the observed periods in the solar activity variation.
2. **Anet, J.**, **S. Muthers**, **E. Rozanov**, **C. Raible**, **T. Peter**, **A. Stenke**, **A. I. Shapiro**, **J. Beer**, **F. Steinhilber**, **S. Brönnimann**, **F. Arfeuille**, Y. Brugnara, and **W. Schmutz**, Forcing of stratospheric chemistry and dynamics during the Dalton Minimum, Atmos. Chem. Phys., 13, 10951–10967, doi:10.5194/acp-13-10951-2013, 2013.
   Relevance to the project: We analyze the influence of different forcing on the stratosphere during the Dalton Minimum.
3. **Anet, J.**, **E. Rozanov**, **S. Muthers**, **T. Peter**, **S. Bronnimann**, **F. Arfeuille**, **J. Beer**, **A. I. Shapiro**, **C. Raible**, **F. Steinhilber**, and **W. Schmutz**, Impact of a potential 21st century "grand solar minimum" on surface temperatures and stratospheric ozone, *Geophys. Res. Lett.*, *40*, 4420–4425, doi:10.1002/grl.50806, 2013.
   Relevance to the project: We discuss implications of possible solar activity decline for global climate and ozone layer.
4. **Anet, J.**, **S. Muthers**, **E. Rozanov**, **C. Raible**, A. Stenke, **A. I. Shapiro**, **S. Brönnimann**, **F. Arfeuille**, **Y. Brugnara**, **J. Beer**, **F. Steinhilber**, **W. Schmutz and T. Peter**, Impact of solar vs. volcanic activity variations on tropospheric temperatures and precipitation during the Dalton Minimum, Clim. Past Discuss., 9, 6179–6220, doi:10.5194/cpd-9-6179-2013, 2013.
   Relevance to the project: We discuss the influence of different forcing on the tropospheric climate during the Dalton Minimum.
5. **Arfeuille, F.**, D. Weisenstein, H. Mack, **E. Rozanov**, **T. Peter**, and **S. Brönnimann**, Volcanic forcing for climate modeling: a new microphysics-based dataset covering years 1600–present, Clim. Past, 10, 359–375, doi: 10.5194/cp-10-359-2014, 2014.
   Relevance to the project: We present a new volcanic forcing data set that is used in the FUPSOL simulations.
6. Auchmann, R., **F. Arfeuille** , M. Wegmann , J. Franke , M. Barriendos , M. Prohom , A. Sanchez-Lorenzo , J. Bhend, M. Wild , D. Folini , P. Štěpánek, and **S. Brönnimann,** Impact of volcanic stratospheric aerosols on diurnal temperature range (DTR) in Europe over the past 200 years: observations vs. model simulations. *J. Geophys. Res.*, 118, 9064–9077, doi:10.1002/jgrd.50759, 2013.Relevance to the project: We analyze changes in the diurnal temperature range following volcanic eruptions; the changes occure due to the decrease in surface short wave radiation.
7. **Beer, J**.; McCracken, K. G.; Abreu, J.; Heikkilae, U.; **Steinhilber, F.** Cosmogenic Radionuclides as an Extension of the Neutron Monitor Era into the Past: Potential and Limitations, Space Science Reviews, 176, 1-4, 89-100, doi: 10.1007/s11214-011-9843-3, 2013.
   Relevance to the project: We discuss how to use radionuclides for the analysis of the past.
8. **Beer, J.**, The Sun and its role in climate change, Pages News, 21,2,86, 2013.
   Relevance to the project: Main results from the workshop of the PAGES Solar Working Group are described.
9. **Brönnimann, S.**, I. Mariani, M. Schwikowski, R. Auchmann, A. Eichler, Simulating the temperature and precipitation signal in an Alpine Ice core. *Clim. Past.,* **9,** 2013-2022, 2013a.
   Relevance to the project: We analyze ice core proxies in the Alps and explains why they do not well represent annual temperature.
10. **Brönnimann, S.**, J. Bhend, J. Franke, S. Flückiger, A. M. Fischer, R. Bleisch, G. Bodeker, B. Hassler, **E. Rozanov**, and M. Schraner, A global historical ozone data set and prominent features of stratospheric variability prior to 1979. *Atmos. Chem. Phys.,* **13,** 18, 9623-9639, doi: 10.5194/acp-13-9623-2013, 2013b.
    Relevance to the project: We present a new, 2-Dozone data set for the period 1900 to present based on observation and chemistry climate model simulations. The imprint of the sunspot cycle in ozone is analyzed.
11. **Brugnara, Y.**, **S. Brönnimann**, J. Luterbacher, **E. Rozanov.** Influence of the sunspot cycle on the Northern Hemisphere wintertime circulation from long upper-air data sets. *Atmos. Chem. Phys.* **13,** 12, 6275-6288. Doi: 0.5194/acp-13-6275-2013, 2013.

Relevance to the project: The paper analyses the imprint of the sunspot cycle on sea-level pressure over the past 250 years and on upper-level circulation during the past 80 years.

12. Calisto, M., I. Usoskin, **E. Rozanov**, and **T. Peter**, Influence of Galactic Cosmic Rays on atmospheric composition and dynamics, Atmos. Chem. Phys., 11, 4547–4556, doi:10.5194/acp-11-4547-2011, 2011.
    Relevance to the project: We describe the representation of the galactic cosmic rays in our model.
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15. Egorova, T., **E. Rozanov**, A. V. Shapiro, and **W. Schmutz**, Principal Possibility of the Successful Nowcast and Short-Term Forecast in the Middle Atmosphere Based on the Observed UV Irradiance, International Journal of Geophysics, vol. 2012, Article ID 298431, 7p, doi:10.1155/2012/298431, 2012.
    Relevance to the project: We analyze the short term response of the middle atmosphere to solar irradiance variability.
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    Relevance to the project: We validate the results of the COSI code against other similar codes and observations.
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    Relevance to the project: We concluded that tree ring proxies are spectrally biased and cannot reproduce characteristic differences between temperature and precipitation variability.
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    Relevance to the project: We discuss possible uncertainties of our reconstruction of the solar irradiance. The support from FUPSOL was not acknowledged by mistake.
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    Relevance to the project: We discuss the probability of extreme space weather events.
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    Relevance to the project: This paper allows testing the main assumption of our solar irradiance reconstructions.
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    Relevance to the project: We introduce a method to identify the position of the ITCZ in gridded data.
23. McCracken, K. G.; Beer, J.; **Steinhilber, F.**; Abreu, J., A Phenomenological Study of the Cosmic Ray Variations over the Past 9400 Years, and Their Implications Regarding Solar Activity and the Solar Dynamo, Solar Physics, 286, 2, 609-627, doi: 10.1007/s11207-013-0265-0, 2013.
    Relevance to the project: We discuss the variability of the Cosmic rays.
24. Pinto, J., and **C. C. Raible**, Past and Recent Changes in the NAO, Interdisciplinary Reviews Climate Change, 3, 79-90, 2012.
    Relevance to the project: We analyze the role of the solar forcing and its interaction with internal variability in the climate system. This information is necessary to analyze our long-term model simulation results.
25. **Rozanov, E.**, Calisto M., Egorova T., **Peter T.**, **Schmutz W.,** The influence of the precipitating energetic particles on atmospheric chemistry and climate, Surveys in Geophysics, 33, 3, Page 483-501, doi:10.1007/s10712-012-9192-0, 2012a.
    Relevance to the project: We describe the representation of the energetic particle precipitations in our model and estimate their potential significance for the atmosphere and climate.
26. **Rozanov**, E., T. Egorova, **A.I. Shapiro**, and **W. Schmutz**, Modeling of the atmospheric response to a strong decrease of the solar activity, In: *Comparative Magnetic Minima: Characterizing quiet times in the Sun and stars Proceedings IAU Symposium No. 286, 2011, C. H. Mandrini & D. F. Webb. eds.*, International Astronomical Union, 215-224, doi:10.1017/S1743921312004863, 2012b.

Relevance to the project: We illustrate potential magnitude of the effect of the solar activity decline on ozone recovery and greenhouse warming.

27. **Shapiro, A.I.**, **W. Schmutz**, **E. Rozanov**, M. Schoell, M. Haberreiter, A. V. Shapiro, and S. Nyeki, A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing, Astronomy&Astrophysics,529, A67, doi: 10.1051/0004-6361/201016173, 2011.
    Relevance to the project: We describe our reconstructions of the total and spectral solar irradiance, which are used as a solar forcing for the model simulations.
28. **Shapiro, A.I.**, **W. Schmutz**, M. Dominique, A.V. Shapiro, Eclipses observed by LYRA - a sensitive tool to test the models for the solar irradiance, Solar Physics, 286, 1, 271-287, doi: 10.1007/s11207-012-0063-0, 2013.
    Relevance to the project: We verify the calculations of the UV spectrum by solar radiation code COSI, which is used for the calculations of the solar forcing in the past and future.
29. **Shapiro, A.I.**, **W. Schmutz**, G. Cessateur, and **E. Rozanov**, The place of the Sun among the Sun-like stars, A&A, 552, A114, DOI: 10.1051/0004-6361/201220512, 2013.
    Relevance to the project: In this paper we show that the analysis of available photometric records of Sun-like stars can help to constrain the historical solar variability.
30. Shapiro, A.V., **E. Rozanov**, **A. I. Shapiro**, S. Wang, T. Egorova, **W. Schmutz**, and **T. Peter**, Signature of the 27-day solar rotation cycle in mesospheric OH and H_2O observed by the Aura Microwave Limb Sounder, Atmos. Chem. Phys., 12, 3181-3188, doi:10.5194/acp-12-3181-2012, 2012.
    Relevance to the project: We found that the mesospheric hydroxyl is a good proxy for the solar irradiance variability and it can be used for the model validation.
31. Shapiro, A.V., **Shapiro, A. I.**, Dominique, M., Dammasch, I., Wehrli, C., **Rozanov, E.**, and **Schmutz, W.**, Detection of Solar Rotational Variability in the *Large Yield RAdiometer* (LYRA) 190 – 222 nm Spectral Band, Solar Physics, 286, 289-301, DOI 10.1007/s11207-012-0029-2, 2013.
    Relevance to the project: We verify our calculations of the UV variability on the time scale of solar rotation.
32. Shapiro, A. V., **E. Rozanov**, **A. I. Shapiro**, T. A. Egorova, J. Harder, M. Weber, A. K. Smith, **W. Schmutz**, and **T. Peter**, The role of the solar irradiance variability in the evolution of the middle atmosphere during 2004–2009, J. Geophys. Res. Atmos., 118, 3781–3793, doi:10.1002/jgrd.50208, 2013.
    Relevance to the project: We discuss the contribution of SSI to the middle atmosphere beaviour.
33. **Steinhilber, F.**, Abreu, J.A., **Beer, J.**, Brunner, I., Christl, M., Fischer, H., Heikkila, U., Kubik, P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H., Wilhelms, F., 9400 years of cosmic radiation and solar activity from ice cores and tree rings. Proceedings of the National Academy of Sciences of the United States of America 109, 5967-5971., 2012.
    Relevance to the project: We describe long-term time series of the past solar activity.
34. **Steinhilber, F**., and **J. Beer**, Prediction of solar activity for the next 500 years, J. Geophys. Res. Space Physics, 118, 1861–1867, doi:10.1002/jgra.50210, 2013.
    Relevance to the project: We describe the prediction of the solar activity in the future which is used to produce future solar forcing for the model runs.
35. Stenke, A., M. Schraner, **E. Rozanov**, T. Egorova, B. Luo, and **T. Peter**, The SOCOL version 3.0 chemistry-climate model: description, evaluation, and implications from an advanced transport algorithm, Geosci. Model Dev., 6, 1407–1427, doi:10.5194/gmd-6-1407-2013, 2013.
    Relevance to the project: We describe the model SOCOL, which is exploited in the project and its validation.
36. Sukhodolov, T., **E. Rozanov**, **A. I. Shapiro**, **J. Anet**, C. Cagnazzo, **T. Peter** and **W. Schmutz**, Evaluation of the ECHAM family radiation codes performance in the representation of the solar signal, Geosci. Model Dev. Discuss., 7, 1337-1356, doi:10.5194/gmdd-7-1337-2014, 2014.
    Relevance to the project: We present our approach to calculate the heating rate response to solar iradiance variability.
37. Thuillier, G., M. DeLand, **A.I. Shapiro, W. Schmutz**, D. Bolsée, S. Melo, The solar spectral irradiance as a function of the Mg II index for atmosphere and climate modelling, Solar Physics, 277, 2, 245-266, doi: 10.1007/s11207-011-9912-5. 2012.
    Relevance to the project: In this paper an alternative approach to calculate solar irradiance in the past and future is considered and compared with our approach.
38. Thuillier, G. Bolsee, D. and Schmidtke, G. Foujols, T. Nikutowski, B. **Shapiro, A.I.,** Brunner, R. Weber, M., Erhardt, C. Herse, M. Gillotay, D. Peetermans, W. Decuyper, W., Pereira, N., Haberreiter, M., Mandel, H., **Schmutz, W**., "The Solar Irradiance Spectrum at Solar Activity Minimum Between Solar Cycles 23 and 24", Solar Physics, 307T, 2013
    Relevance to the project: We validate the spectrum of the quiet Sun calculated by COSI against the most recent measurements and reference spectra.
39. Thuillier, G.; Melo, S. M. L.; Lean, J.; Krivova, N. A.; Bolduc, C.; Fomichev, V. I.; Charbonneau, P.; **Shapiro, A. I.**; **Schmutz, W.**; Bolsee, D., Analysis of Different Solar Spectral Irradiance Reconstructions and Their Impact on Solar Heating Rates, Solar Physics, 289, 4, 1115-1142, 2014.
    Relevance to the project: We compare our SSI reconstruction with several other recently published reconstructions.
40. Trouet, V., J. D., Scourse and **C. C. Raible**, Storminess and Atlantic Meridional Overturning Circulation during the Last Millennium: reconciling contradictory proxy records of NAO variability, Global and Planetary Change, 84-85, 48-55, 2012.

Relevance to the project: We show that the role of the solar forcing and its interaction with internal variability in the climate system is not clearly defined in the literature.

41. Wehrli, C.; **Schmutz, W.**; **Shapiro, A.I.**, Correlation of spectral solar irradiance with solar activity as measured by VIRGO, Astronomy&Astrophysics, 556, L3, doi: 10.1051/0004-6361/201220864, 2013.
    Relevance to the project: We compare SSI variability from VIRGO against other data sets.
42. Zubov, V., **E. Rozanov**, T. Egorova, I. Karol, and **W. Schmutz**, Role of external factors in the evolution of the ozone layer and stratospheric circulation in 21st century, Atmos. Chem. Phys., 13, 4697-4706, doi:10.5194/acp-13-4697-2013, 2013.
    Relevance to the project: In this paper we estimate the contribution of several factors to the evolution of the global ozone and climate, which will be used to analyze the simulated behavior of model parameters in the future.