**Scientific final report on CISA (Climate Implications of the Sun transition to high Activity mode) project**

## 1. Summary of the research work and its results

In the CISA project, we analyze the ozone and climate response to the solar irradiance changes caused by the switch of the Sun to higher activity mode which is characterized by the simultaneous decrease of the total and increase of the UV solar irradiance. The results obtained using a chemistry-climate model with an interactive ocean reveal the increase in the stratospheric ozone and temperature caused by higher levels of shortwave (100-380 nm) UV radiation. The introduced UV increase is also responsible for the pronounced increase in total ozone content. For the surface climate, the results are not so trivial because we obtained annual mean cooling for most of the globe, but at the same time, we do not observe expected statistically significant cooling over the northern high latitudes. This can be partly explained by the influence of the stratospheric ozone and temperature changes which can enhance the positive phase of the North Atlantic Oscillation bringing more energy to high latitudes. The model results show that this process partially compensates for extensive cooling due to the introduced solar energy deficit. In general, a possible switch of the Sun to a more active state can lead to a slightly cooler climate and some decrease in the surface UV. However, these changes cannot be considered as catastrophic.

The main objectives of the project have been fulfilled. We have prepared four scenarios for the SSI changes during the transition of the Sun to more active or passive states and simulated with the SOCOL model global climate and ozone layer changes caused by the suggested Sun transition. It allowed the evaluation of the climate response to the SSI perturbations in different spectral areas. In addition, we studied the climate implications of the decline of the solar activity suggested in CMIP6 project and demonstrated that the use of the recommended solar irradiance changes has only marginal climate and chemistry effects. The results of the project are presented in five publications and discussed at four international meetings. The main results of the project are briefly described below.

## 2. Objective one: Prepare several scenarios for the SSI changes during the transition of the Sun to more active or passive states.

With our collaborators from MPS (Shapiro et al., 2020) we have prepared spectral solar irradiance (SSI) data for three cases: (1) reference present-day Sun; (2) Sun in medium activity mode, and (3) Sun in highly active mode. Figure 1 illustrates relative changes related to Sun transition to the most active mode.

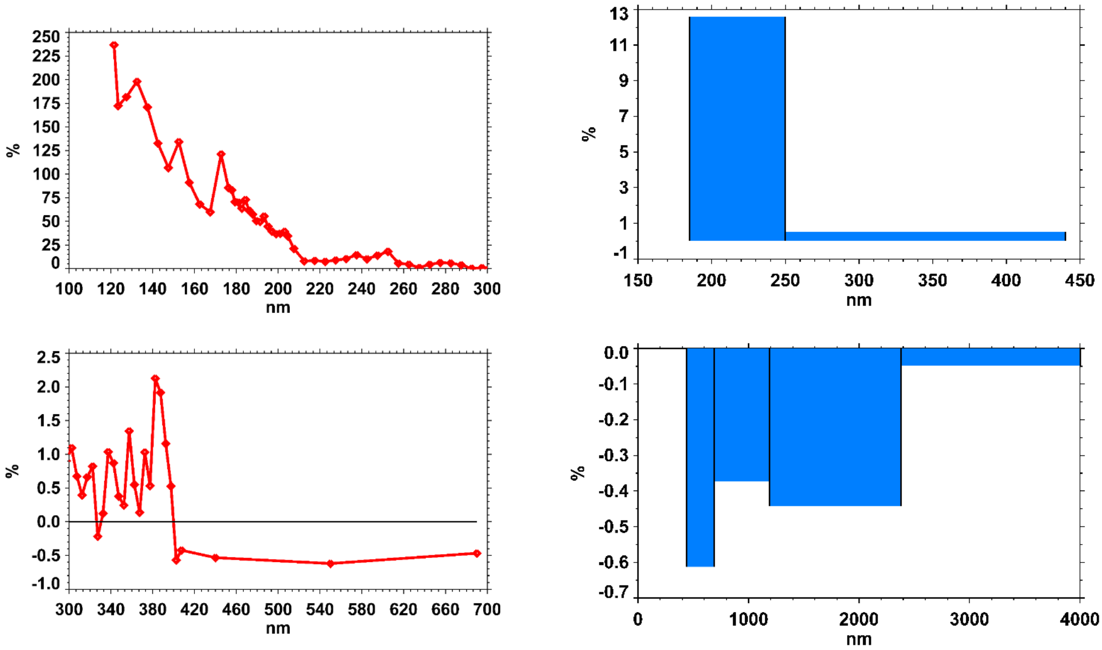


*Fig. 1. Left panel: Changes (%) of the SSI relative to the present-day SSI used for the photolysis rate calculations after the transition of the Sun to the high activity mode. Symbols illustrate spectral intervals used for photolysis calculations. Right panel: Changes (%) of the SSI used for the radiation fluxes and heating rates calculations after the transition of the Sun to the high activity mode. Columns illustrate spectral intervals used for the solar radiation flux and heating rate calculations.*

The obtained results demonstrate a large SSI increase in the chemically active spectral region from 120 to 380 nm. The magnitude of the increase reaches up to 240% in Ly-alpha, 120% in the Schumann-Runge continuum, and up to 20% in the Herzberg continuum. The response is somewhat smaller (within 2%) for Hartley and Higgins bands of ozone. For the longwave (above 400 nm) part of the solar spectrum, we obtained negative values which means that the irradiance response to the solar activity is not symmetrical relative to the wavelength. The TSI decrease for the experiment case is 4.4 W/m$^2$. The data were used for the preparation of the solar radiation forcing for the calculation of the radiation fluxes, heating, and photolysis rates in the SOCOL model.

The data were provided by the MPS team in a suitable proper format and used for preparing the solar radiation data used in the SOCOL model for calculating radiation balance and photolysis rates. The output files (irradiance and look-up-tables with photolysis rates) were stored in the self-explanatory netCDF format and can be used by modeling groups.

## 3. Objective two: Simulate the Earth's global climate and ozone layer changes caused by the suggested Sun transition.

We used the SOCOL model (Muthers et al., 2014; Sukhodolov et al., 2021) with the interactive ocean (MPIOM), which allows the evaluation of possible implications of the Sun activity switch for the terrestrial climate and ozone layer. With the model, we performed four 90-year-long experiments driven by different prescriptions of solar spectral irradiance (SSI). We run a reference case using SSI from the present-day solar maximum state, approximately the year 2000. Then we ran three experiments with monthly mean SSI calculated for the high activity mode (basic experiment), with the changed SSI for chemical-only calculations (chemistry run) and SSI for radiative balance (energy run) calculations. These experiments allow for separating the influence of different physical/chemical processes in the atmosphere. All experiments were initialized from a very long time slice spin-up run performed in the framework of the other project using preindustrial set-ups for all forcings.

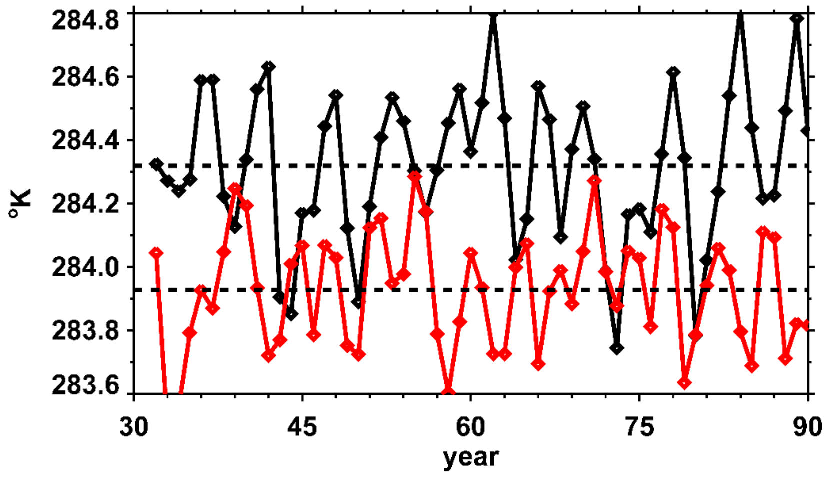


*Fig. 2. Evolution of the global and annual mean temperature at 950 hPa level during the last 60 years of the 90-year long runs for the reference (black) and experiment (red). Dashed lines show mean values for reference (284.320K) and experiment runs (283.928K).*

First, it is necessary to check whether a 90-year run is enough to reach a quasi-steady-state condition. Fig. 2 shows the evolution of the near global mean surface temperature for the last 60 years of the reference and basic experiment runs. This quantity is supposed to have maximum relaxation time due to the thermal and dynamical inertia of the ocean and should illustrate the presence of any substantial drifts. As we can see from Fig.2 both runs reach a rather stable temperature with some variations related to natural variability modes.

The near-surface (950 hPa) global and annual mean temperature derived from the model's experiments shows that in case of high solar activity (red line), we have systematically cooler Earth by about 0.4 K as expected from TSI drop by 4.4 W/m$^2$.

**Objective three:** Evaluate the climate response of the SSI perturbations in different spectral areas.

Fig. 3 illustrates the response of the annual zonal mean ozone mixing ratio and temperature to the implied changes in spectral solar radiation. For the basic case, the ozone mixing ratio robustly increases in the entire domain, but the maximal effect exceeding 12% is observed in the middle stratosphere from 30 to 40 km poleward from 30$^o$ latitudes. Another maximum of about 9% magnitude is observed in the lower tropical stratosphere. A smaller increase of around 4% is visible in the rest of the stratosphere, lower mesosphere, and lower troposphere. The obtained ozone increase is driven by a combination of photochemical and dynamical processes. The enhanced oxygen photolysis caused by the introduced up to 20% (see Fig. 1) UV irradiance enhancement in the Herzberg continuum is mostly responsible for the stratospheric ozone increase (e.g., Sukhodolov et al., 2016). Comparison of the results presented in Fig.3(a, c) shows that chemical processes dominate the ozone response in the entire model domain except for the lower tropical stratosphere. In the location, the ozone increase is explained by a colder surface climate caused by a decrease in the solar energy absorbed at the surface (see right panel of Fig.3). This process leads to a deceleration of the Brewer-Dobson circulation (BDC) and a weaker updrift of the tropospheric air with a low ozone mixing ratio (e.g., Zubov et al., 2013). This ozone increase is very well visible in Fig.3(e) for the “energy” run when the chemical processes were not directly impacted by SSI changes. The temperature changes in the stratosphere are also mostly driven by increased UV absorption by the enhanced ozone, however, the “energy” related radiation (see Fig.1, right panel) also contributes about 20-30% to the warming above 30 km due to ozone absorption of the UV radiation for the wavelength shorter than 250 nm. In the troposphere the longwave part of the

SSI dominates, and its decrease drives substantial cooling there. It is interesting to note small but significant cooling over the northern high latitudes related to pure chemical processes (see Fig.3(d)).

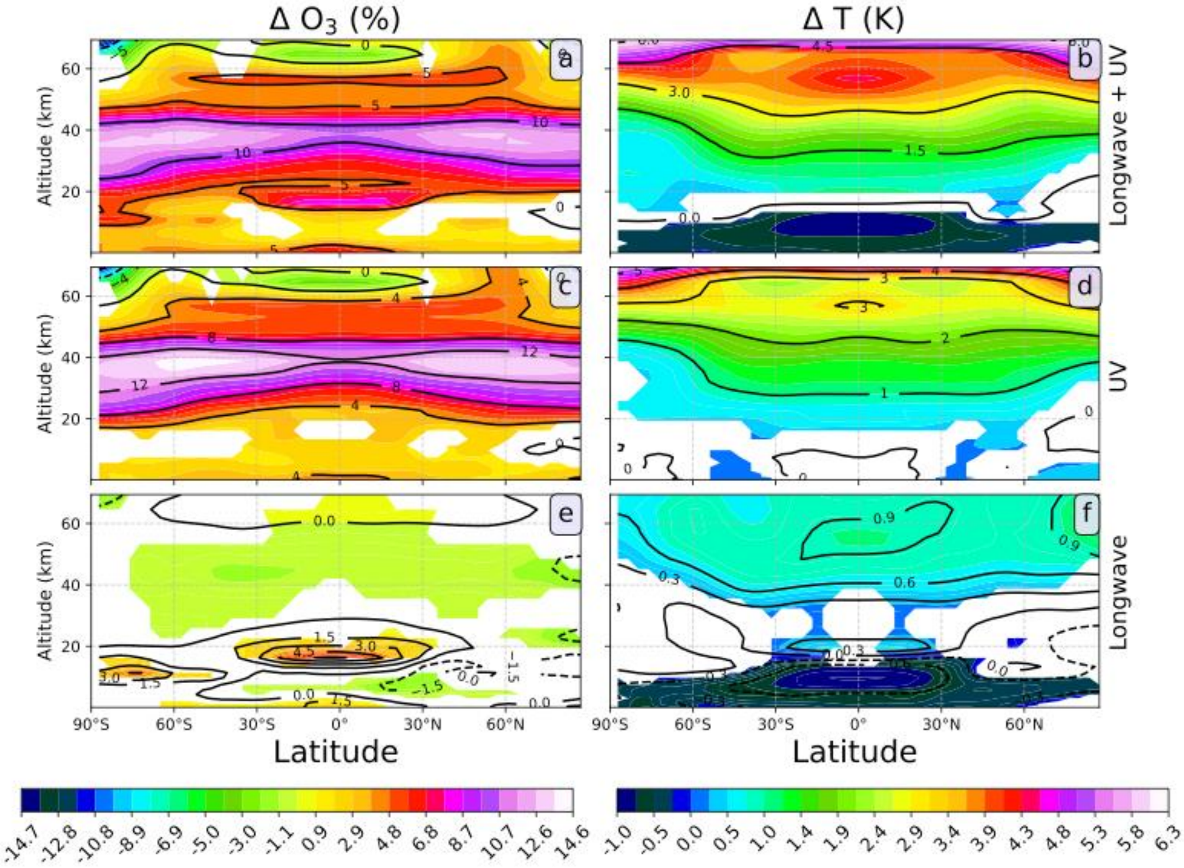


*Fig. 3. Zonal mean annual mean changes in $O_3$ mixing ratio (%, left panel) and temperature (K, right panel) obtained from "basic" (a, b), "chemistry" (c, d), and "energy" (e, f) runs relative to the "reference" simulation. The colored areas show the data with a statistical significance of more than 95%. The solid and dashed contour lines represent positive and negative responses, respectively.*

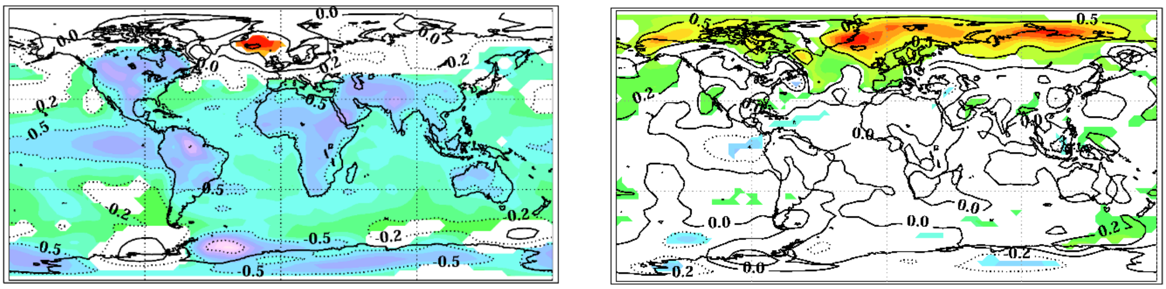

*Fig. 4. The change in annual mean near-surface temperature obtained with 'basic' (left), and 'chemistry' (right) relative to the 'reference' simulation. The coloured areas show the response with a statistical significance of more than 95%.*

The response of the near-surface temperature is demonstrated in Fig. 4 for "basic" and "chemistry" experiments. Weaker energy income caused by suppressed deep penetrating (wavelength exceeding 400 nm) radiation leads to global cooling exceeding 0.5 K over land masses except in Northern Europe, Russia, and Alaska. The ocean surface cooling is present everywhere, but most pronounced over the tropical eastern Pacific. Over the northern high latitudes, the response is slightly positive but only marginally significant. The obtained pattern resembles the surface temperature response to a strong decrease in solar irradiance obtained by Arsenovic et al. (2018). However, the difference over the northern high latitudes is substantial. The same feature was also simulated by Ammann et al. (2007) for the case with an increase of the TSI by 1 W/m$^2$. In comparison to our results, their model demonstrates polar amplification producing more pronounced cooling over the high northern latitudes. In our case enhanced ozone mixing ratio and temperature gradient in the stratosphere led to a slightly warmer climate over the northern middle to high latitudes due to the intensification of the polar night jet and enhancement of the positive North Atlantic Oscillation phase. It is demonstrated in Fig.4 (right) which shows that for the "chemistry", the stratospheric ozone and temperature changes lead to the pronounced high latitude warming.

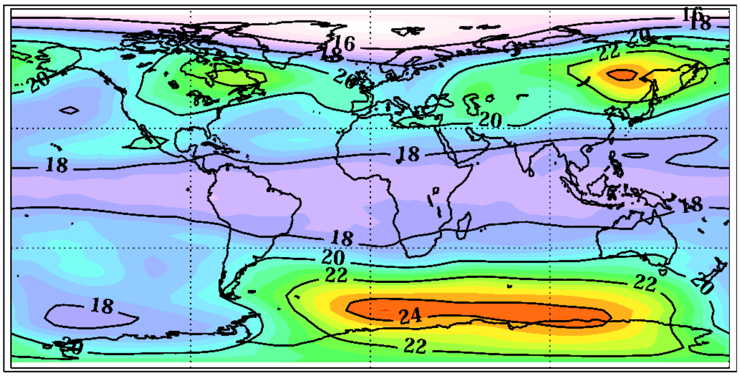

*Fig. 5. Changes (Dobson Units) of the annual mean total column ozone caused by the transition of the Sun to the high activity mode. The color pattern shows statistically significant at 95% level response.*

The response of the total column ozone (TCO) is presented in Fig. 5. The TCO response is positive everywhere and almost totally controlled by chemical forcing. The magnitude varies from 16 Dobson units (DU) over the northern high latitudes to more than 24 DU over the southern polar cap. There are also several areas over the northern middle latitudes where the total column ozone increase exceeds 20 DU. The obtained pattern resembles the TCO response simulated by Steinbrecht et al. (2006) for the boreal winter season with two maxima over eastern Russia and southern middle latitudes. The magnitude of the response is slightly smaller in our case because we show annual mean values. For the winter season (not shown) we obtained a better agreement. The relative TCO increase is within 5-10% which should decrease the surface UV radiation dose.

**Objective four:** Propose an international model intercomparison project for the SCOSTEP PRESTO Pillar 3 activity.

We published an announcement in the SCOSTEP PRESTO Newsletters (Vol. 26, January 2021, p. 8) describing our project and inviting modeling groups to perform similar runs. The project was approved by the PRESTO Pillar 3 leaders and will be implemented in 2023.

**Additional study:** Climate impact of the CMIP6 solar irradiance forcing.

Predictions of solar activity in the future are difficult to make due to the chaotic state of solar dynamo and the high nonlinearity of physical processes on the Sun. Therefore, the Climate Intercomparison Project Phase 6 (CMIP6) used a statistical approach and recommended two different solar forcings for the simulations. The reference scenario was developed as the standard forcing, whereas the alternative forcing has lower solar activity. In this study, we use both forcings in a set of experiments with the SOCOL (Sukhodolov et al/. 2021) to explore the importance of the alternative CMIP6 solar forcing for future climate and ozone layer variability. In general, the difference in solar forcing is small and thus most changes at the surface and at high altitudes are not significant. In addition, only the active phases of the Sun, which have the largest difference in amplitude of the forcing, are investigated. In this case, some statistically significant patterns emerge, mostly in the stratosphere, but still, the magnitude of the changes is not very large and a noticeable climate response to these changes is not expected and also not found. Our results (Sedlacek et al., 2022) indicate that low amplitude solar forcings such as the EXT CMIP6 or similar are not worthwhile considering during the next CMIP type of activities. The proposed solar irradiance decline does not represent any danger to the ozone layer.

**2. Research output:**

The obtained data were stored on external hard drives and are available for external users on request. Also, the data used for papers have been uploaded to Mendeley data archive (Rozanov, 2022).

**Publication list**

- Egorova, T., A.V. Shapiro, A.I. Shapiro and E. Rozanov (2021): Climate Implications of the Sun Transition to High Activity Mode, SCOSTEP PRESTO Newletters, 26, p. 8.
- Egorova, T., A.V. Shapiro, A.I. Shapiro and E. Rozanov (2021): Climate Implications of the Sun Transition to High Activity Mode, abstract for XXXIII General Assembly and Scientific Symposium (GASS) of the International Union of Radio Science (Union Radio Scientifique Internationale-URSI), https://www.ursi2021.org/wordpress/wp-content/uploads/ursi-gass2021_finalprogramme3.pdf.
- Egorova, T., A.V. Shapiro, A.I. Shapiro, and E. Rozanov (2022): Implications of the Sun Transition to High Activity Mode for ozone layer and climate, Journal of the Atmospheric and Solar-Terrestrial Physics, 2023 (submitted to JASTP in August 2022, under review).
- Rozanov, E., (2022): "CISA" dataset, Mendeley Data, V1, https://doi.org/10.17632/ykrt7cpdxj.1
- Sedlacek, J., T. Sukhodolov, T. Egorova, A. Karagodin-Doyennel and E. Rozanov (2023): Future climate under CMIP6 solar activity scenarios, 2023 (submitted in 2022 to Earth and Space Science).

**Planned publications**

- Shapiro A.V., Egorova, T., Shapiro A.I., and Rozanov E.: Climate Implications of the Sun transition to higher activity mode: role of the atmospheric chemistry, 2023 (will be submitted in 2023).

**Conference attendance**

1. XXXIVth URSI General Assembly and Scientific Symposium, 28.08-4.09.2021, Rome, Italy
    - Egorova, T., A.V. Shapiro, A.I. Shapiro and E. Rozanov, Climate Implications of the Sun transition to high Activity mode. Oral talk.
2. SCOSTEP's 15th Quadrennial Solar Terrestrial Physics Symposium (STP-15) Feb. 21-25, 2022, India, Online:
    - Sedlacek, J., T. Egorova, T. Sukhodolov, A. Karagodin, E. Rozanov, Influence of solar irradiance on future climate. Oral talk.

- Egorova, T., A.V. Shapiro, A.I. Shapiro and E. Rozanov, Climate Implications of the Sun transition to high Activity mode. Oral talk.

3. SPARC HEPPA-SOLARIS meeting, 13-15.06.2022, Bergen, Norway
    - Sedlacek, J., Influence of solar irradiance on future climate, Oral
4. Problems of GEOCOSMOS-2022, 4.11-6.11.2022, Saint Petersburg, Russia
    - Rozanov, E., T. Egorova, The ozone layer state during Sun transition to higher activity mode, Oral talk

**Team meetings:**

1. August 2021, PMOD/WRC, Davos
2. October 2022, PMOD/WRC, Davos.

**References:**


Ammann, C.M., et al., 2007. Solar influence on climate during the past millennium: results from transient simulations with the NCAR Climate System Model. Proc. Natl. Acad. Sci. 104,3713–3718. https://doi.org/10.1073/pnas.0605064103.

Arsenovic, P., et al., 2018. Implications of potential future grand solar minimum for ozone layer and climate. Atmos. Chem. Phys. 18, 3469–3483. https://doi.org/10.5194/acp-18-3469-2018.

Muthers, S., et al., 2014. The coupled atmosphere–chemistry–ocean model SOCOL-MPIOM, Geosci. Model Dev., 7, 2157–2179. https://doi.org/10.5194/gmd-7-2157-2014.

Shapiro, A.I., et al., 2020. Solar-cycle irradiance variations over the last four billion years. A&A, 636, A83. https://doi.org/10.1051/0004-6361/201937128.

Steinbrecht, W., et al., 2006. Interannual variation patterns of total ozone and lower stratospheric temperature in observations and model simulations. Atmos. Chem. Phys., 6, 349–374, https://doi.org/10.5194/acp-6-349-2006.

Sukhodolov, T., et al., 2016. Evaluation of simulated photolysis rates and their response to solar irradiance variability. J. Geophys. Res. Atmos., 121. https://doi.org/10.1002/2015JD024277.

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

Zubov, V., et al., 2013. Role of external factors in the evolution of the ozone layer and stratospheric circulation in 21st century, Atmos. Chem. Phys., 13, 4697-4706. https://doi.org/10.5194/acp-13-4697-2013.