SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Ocean-Atmosphere Chemistry Climate Model Simulations for new WMO-SPARC-Chemistry Climate Model Initiative (CCMI)
Computer Project Account:	Spdewmo3
Start Year - End Year :	2015 - 2018
Principal Investigator(s)	Prof. Dr. Ulrike Langematz
Affiliation/Address:	Institut für Meteorologie Freie Universität Berlin Carl-Heinrich-Becker-Weg 6-10 12165 Berlin Germany
Other Researchers (Name/Affiliation):	Dr. Anne Kubin Dr. Janna Abalichin Dr. Markus Kunze During the project all at: Institut für Meteorologie, Freie Universität Berlin

The following should cover the entire project duration.

Summary of project objectives

Within this project, simulations with the Atmosphere-Ocean-Chemistry-Climate Model (AOCCM) ECHAM/MESSy/MPIOM (EMAC-O) were conducted as a contribution to the German research program “Mittelfristige Klimaprognosen” (MiKlip). The main focus within this project lies on the assessment of the importance of stratospheric solar forcing, decadal stratospheric internal variability and the role of atmosphere-ocean interactions for decadal climate prediction. Furthermore, the simulation was analysed in the projects SHARP and ISOLAA, both interested in atmosphere-ocean interactions.

Summary of problems encountered

We did not encounter any technical problems. The planned model simulations could not be carried out completely, as the responsible scientist, Dr. Janna Abalichin,left the group.

Experience with the Special Project framework

The administrative and technical support throughout the whole project was excellent.

Summary of results

The following simulations with the ocean-coupled Chemistry-Climate Model EMAC-MPIOM (hereafter EMAC-O) were performed and analysed on the ECMWF HPC Facility in the project period:

- e5ao_1960ctl: A control simulation with perpetual boundary conditions representative for the year 1960 but including the natural forcing by time-varying spectral solar irradiance. This simulation was run for 109 years.
- e5ao_1960ctlII: Continuation of e5ao_1960ctl simulation to enhance statistical robustness. This simulation was run for 141 years.
- e5ao_rcp6.0: A transient simulation from 1960 to 2095 including all anthropogenic and natural forcings such as greenhouse gases (GHG), ozone depleting substances (ODS), volcanic eruptions and spectral solar variability. The prescribed GHG concentrations followed the RCP6.0 scenario. The simulation was recommended as reference simulation within the Chemistry-Climate Model Initiative (CCMI) framework (Eyring et al., 2013). In the following, results of the control simulation are presented.
- rcp6.0: A transient simulation from 1960-2095 using the RCP6.0 scenario, but with prescribed sea-surface temperatures
- rcp8.5: same as before, but with extreme RCP8.5 GHG scenario

These simulations were the basis for two PhD theses, two Master theses, and three publications in peer reviewed journals. Three further publications will be submitted in the near future (Spiegl and Langematz, 2018; Kubin et al., 2018; Thiéblemont et al., 2018). In the following an overview of the scientific results obtained from these simulations is given:

Stratospheric dynamical variability in northern winter

Major stratospheric warmings (MSWs) are the most abrupt events of boreal wintertime polar stratospheric variability, and their influence may extend down to the troposphere. They are identified by applying the standard criterion for MSWs, i.e., the simultaneous reversal of the zonal mean zonal wind at 60°N and 10 hPa and the meridional temperature gradient between 60ºN and the pole at the same level. The comparison of the MSW statistics in the EMAC-O chemistry-climate model between the control simulation and the first 40 winters of the transient RCP6.0 scenario simulation yields an overall number of 7.8 events per decade in the control run and 9.3 events per decade in RCP6.0. Thus, the EMAC-O model shows a higher variability in the northern winter stratosphere than the NCEP/NCAR reanalysis data with 5.5 events per decade. The monthly distribution of the MSWs is given in **Figure 1** for the two EMAC-O simulations. It is seen that the MSW frequency is rather similar in both simulations from January to March, i.e. in mid and late winter. Larger differences are seen in early winter where the control simulation shows nearly equal frequencies in November and December while there is a clear preference for warmings in December in the transient simulation. This unrealistically high number of major warming events in early winter is a known problem of models from the ECHAM family (Charlton et al., 2007) and it seems to persist also in the ocean-coupled version used here.

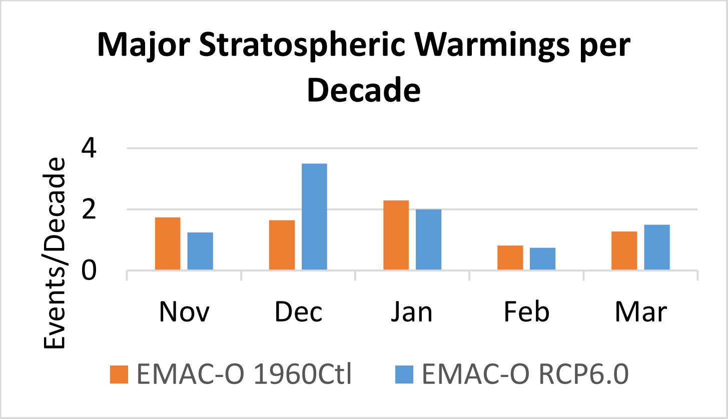

Figure 1: Monthly distribution of Major Stratospheric Warmings in two ocean-coupled simulations given as events per decade. The orange bars depict the control simulation results while the distribution for the first 40 years (i.e. 1960/61 to 1999/2000) of the transient simulation are given in blue.

El Niño-Southern Oscillation signal in the control simulation

The variability of the tropical sea surface temperatures (SSTs) has a direct impact on the general atmospheric circulation through enhanced convection in the areas with higher SSTs as well as via teleconnections by the El Niño-Southern Oscillation (ENSO) phenomenon. Enhanced convection in the tropical region leads to an enhanced poleward transport of trace gases such as water vapour or ozone, which contributes to the radiative forcing of the atmosphere.

The variability of the SSTs is represented by the time series of the NINO3.4 index, an areal average of the monthly SSTs in the eastern equatorial Pacific (Rasmusson and Carpenter, 1982). The power spectrum of the SSTs in the NINO3.4 region in the EMAC-O 1960CTL simulation (**Figure 2**) shows that the Pacific SSTs vary with a mean period of 40 months (3.3 years), well capturing the main period of the observed NINO3.4 index (Bellenger et al., 2014). The ocean components of some CMIP5 models suffer from a too short period of the ENSO events by around 2 years, with a strongly periodic occurrence of the ENSO events. With the occurrence of the distinct secondary maxima in the power spectrum with time periods of 34, 43 and 95 months in **Figure 2**, the ability of EMAC-O to simulate irregular (non-periodic) SST variability is given.

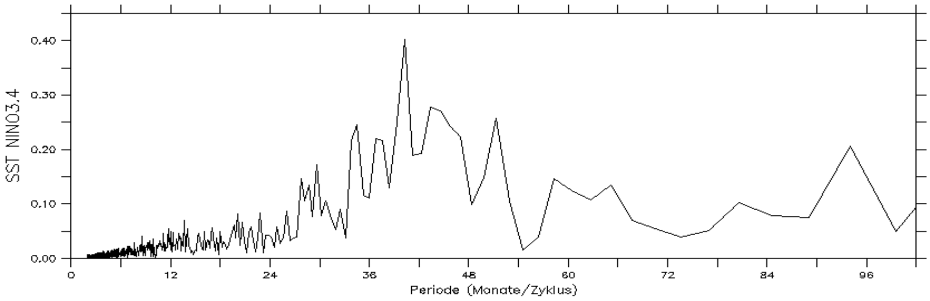

Figure 2: Power spectrum of the monthly NINO3.4 index in the EMAC-O 1960CTL simulation (141 years).

Is the Brewer-Dobson circulation increasing or moving upward? (Oberländer-Hayn et al., 2016)

The meridional circulation of the stratosphere, or Brewer-Dobson circulation (BDC), is projected to accelerate with increasing greenhouse gas (GHG) concentrations. The acceleration is typically quantified by changes in the tropical upward mass flux (Ftrop) across a given pressure surface. Simultaneously, models project a lifting of the entire atmospheric circulation in response to GHGs; notably, the tropopause rises about a kilometer over this century. In this study, it is shown that most of the BDC trend is associated with the rise in the circulation. Using a chemistry-climate model (CCM), Ftrop trends across 100 hPa are contrasted with those across the tropopause: while Ftrop at 100 hPa increases 1–2 %/decade, the mass flux entering the atmosphere above the tropopause actually decreases. Similar results are found for other CCMs, suggesting that changes in the BDC may better be described as an upward shift of the circulation, as opposed to an increase, with implications for the mechanism and stratosphere-troposphere exchange.

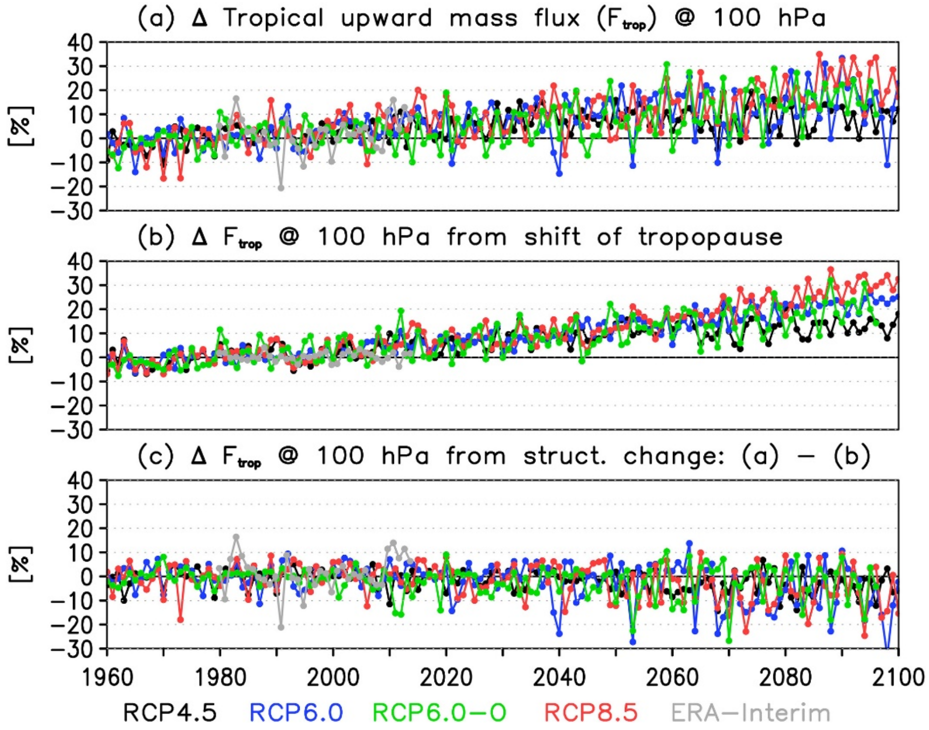

Figure 3: Annual mean change in tropical upward mass flux at 100 hPa of EMAC simulations RCP4.5 (black), RCP6.0 (blue), RCP6.0-O (green), and RCP8.5 (red) from 1960 to 2100 (1960–2096 for RCP6.0-O) and ERA-Interim data (grey) from 1979 to 2013 compared to the mean of the years 1960–2000 (ERA-Interim: 1979–2000) (%) for (a) total change (ΔFtrop), (b) change from shift of the tropopause (ΔFshift), and (c) structural change (ΔFstruct).

Impact of rising greenhouse gas concentrations on future tropical ozone and UV exposure (Meul et al., 2016)

Future projections of tropical total column ozone (TCO) are challenging, as its evolution is affected not only by the expected decline of ozone depleting substances but also by the uncertain increase of greenhouse gas (GHG) emissions. To assess the range of tropical TCO projections, we analyze simulations with a chemistry-climate model forced by three different GHG scenarios (Representative Concentration Pathway (RCP) 4.5, RCP6.0, and RCP8.5). We find that tropical TCO will be lower by the end of the 21st century compared to the 1960s in all scenarios with the largest decrease in the medium RCP6.0 scenario. Uncertainties of the projected TCO changes arise from the magnitude of stratospheric column decrease and tropospheric ozone increase which both strongly vary between the scenarios. In the three scenario simulations the stratospheric column decrease is not compensated by the increase in tropospheric ozone. The concomitant increase in harmful ultraviolet irradiance reaches up to 15% in specific regions in the RCP6.0 scenario.

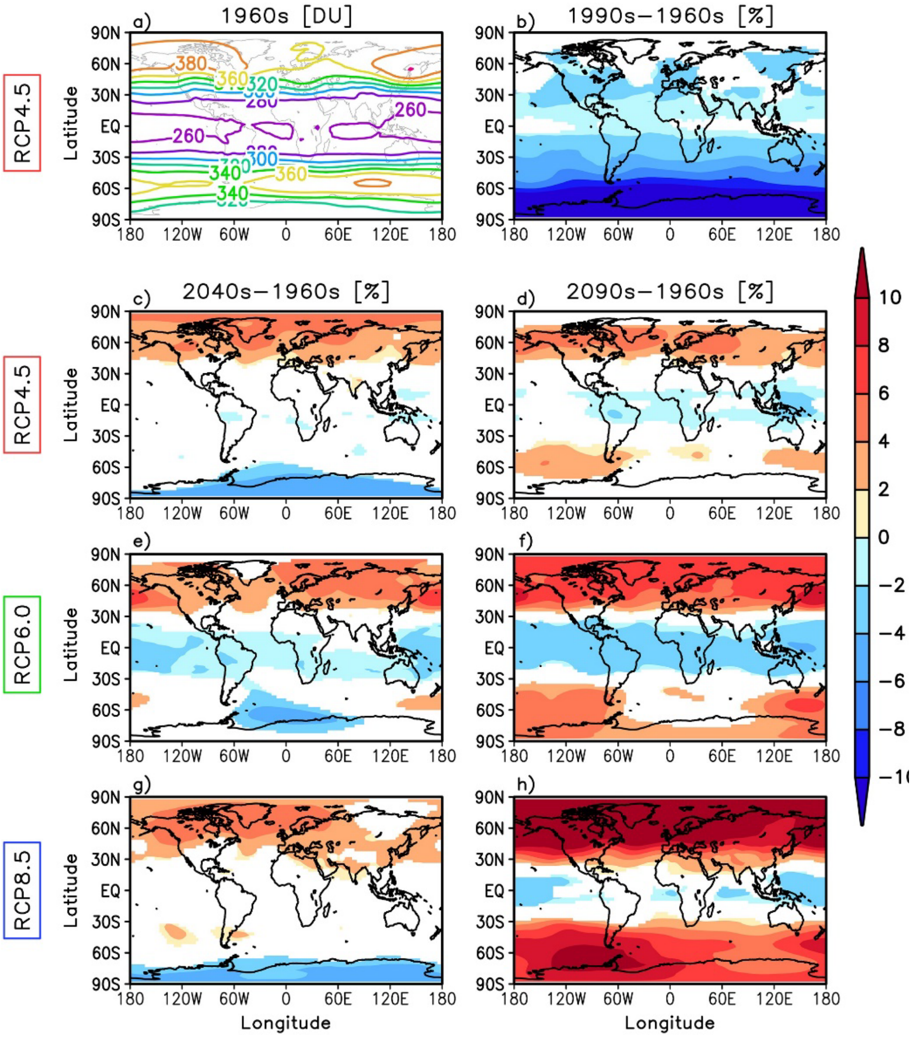

Figure 4: Geographical distribution of the annual mean TCO in DU in (a) the RCP4.5 simulation for the 1960s mean and the relative TCO difference between the (b) 1990s and 1960s, (c) 2040s and 1960s, and (d) 2090s and 1960s in % in the RCP4.5 simulation. (e and f) Same as Figures 1c and 1d but for the RCP6.0 simulation. (g and h) Same as Figures 1c and 1d but for the RCP8.5 simulation. Statistically significant changes on the 95% confidence level are coloured.

In the future, the total ozone column will rise in the future above 1960 levels at high latitudes, but be lower than 1960 in the tropics. Future tropical ozone decrease will be strongest in the medium RCP GHG scenario.

Sea-Ice and Stratospheric Ozone – Links and Impacts in the Arctic and Antarctic (in Hellmer et al., 2016)

The trends of sea ice extent (SIE) during the last decades are different for both hemispheres. Arctic sea ice has dramatically decreased in the recent past. Estimates from satellite measurements find a negative trend of about 10 % per decade since 1979 (Comiso et al., 2008). In contrast, annual mean Antarctic sea ice increased by about 1 % per decade for the years 1978–2006 (Turner et al., 2009). While the Arctic sea-ice retreat has been associated with the warming of the troposphere caused by increasing greenhouse gas (GHG) concentrations (IPCC, 2013), the ozone depletion by man-made halogens in the polar stratosphere and its impact on tropospheric circulation have been suggested as the driving mechanism to explain the observed Antarctic changes (e.g. Thompson and Solomon, 2002). However, there is still low confidence in the scientific understanding of the observed increase in Antarctic SIE since 1979, due to missing knowledge of internal variability and competing explanations for the causes of change (IPCC, 2013). With further increasing GHGs and an expected recovery of polar ozone at the end of the twenty-first century, projections of future polar climate and its hemispheric differences are highly uncertain. To understand and project the interactions between the atmosphere, oceans and the cryosphere as well as the chemical and radiative effects of natural and anthropogenic climate gases throughout the troposphere and stratosphere, the atmosphere-ocean version of the ECHAM/MESSy Atmospheric Chemistry (EMAC) chemistry-climate model which combines the EMAC model was used.

Figure 5 shows the evolution of Antarctic SIE between 1960 and 2100, as simulated with the EMAC model assuming a continuing future increase of GHG concentrations according to the RCP6.0 scenario (IPCC 2013) and projected emissions of ozone depleting substances following the WMO A-1 scenario. During the period of strongest Antarctic ozone depletion (about 1980–2007), the SIE shows considerable interannual variability but no indication of a retreat comparable to the Arctic. The local changes in sea ice concentration (SIC) around Antarctica in this period agree with observations (e.g., Turner et al., 2009): Consistent with an intensification of the Amundsen-Bellingshausen Sea (ABS) low, enhanced northerly winds induce a reduction of SIC in the ABS, while stronger southerlies lead to a larger SIC in the Ross Sea. An even stronger SIC enhancement was found in the Weddell Sea (left panel in Fig. 5). These changes arise from two contributions: (a) an increase of the SAM associated with the intensification of the stratospheric polar vortex during Antarctic ozone depletion and a concurrent reduction in planetary wave activity and (b) enhanced synoptic activity due to climate change. In the upcoming decades (2008–2054, middle panel in Fig. 5b), i.e. a period with increasing climate change and declining yet still relevant ozone depletion, the SIC increases over the Ross and Weddell Seas are weaker. However, in the second half of the twenty-first century (2055–2096, right panel in Fig. 5b), when total column ozone is projected to recover, the GHG induced climate change will dominate and Antarctic SIC is projected to reduce, similar to the Arctic.

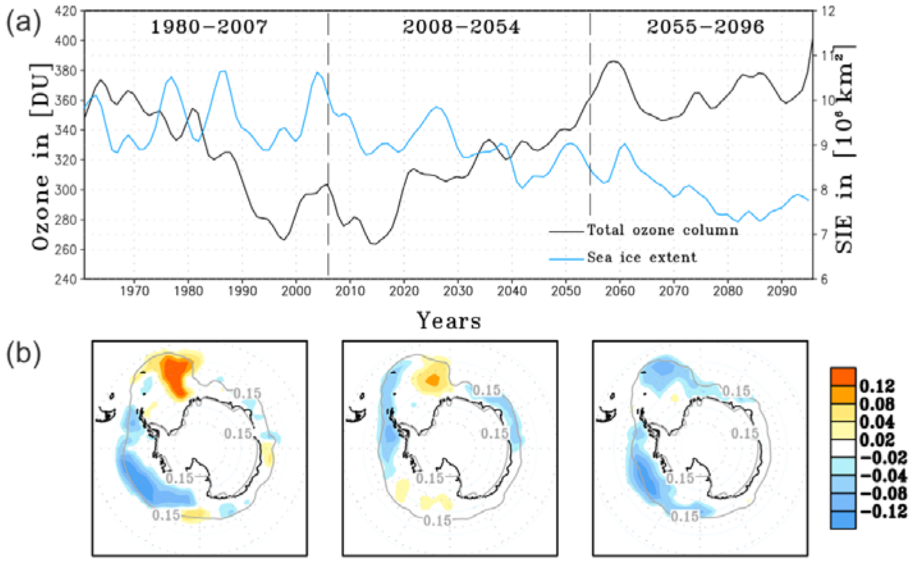

Figure 5: Evolution of the Antarctic total ozone column (in Dobson Unit, DU, 60° S–90° S mean, black) in October and Antarctic sea ice extent (SIE, in km2, blue) in December between 1960 and 2100, simulated with the EMAC chemistry-climate model, assuming the RCP6.0 greenhouse gas scenario and the WMO-A1 scenario for ozone depleting substances. The time series have been smoothed by applying three times a 1-2-1 filter. b Decadal trends in sea ice concentration (SIC) in October for the periods 1980–2007 (left), 2008–2054 (middle), and 2055–2096 (right). Grid boxes with SIC >0.15 are considered as covered with sea ice.

Identifying 21st century climate change hotspots and their response to a potential solar downturn

(Spiegl and Langematz, to be submitted 2018)

Observations as well as model-based climate reconstructions and projections suggest heterogeneous warming patterns due to the rise of anthropogenic greenhouse gases, revealing different degrees of regional climate vulnerability. However, the climate vulnerability in a certain region is not only defined by changes in absolute values, e.g. the rise in near surface temperature, but also depends on seasonal changes in the variability and the occurrence of extreme events. Even though the magnitude of 21st century climate change will be determined by the amount of anthropogenic carbon dioxide emissions, it is possible that external climate forcings will amplify or dampen the human induced signal. The main source of external variability in the terrestrial climate system is the internal variability of the Sun. Satellite measurements over the last three decades show a gradual decrease in solar output. This development raises the questions whether a longer-lasting downturn in solar variability and an associated hypothetical solar induced global cooling might counteract the proposed human induced global warming. Just like the anthropogenic imprints the effects of a solar downturn are multidimensional. To address this fact we apply a metric which allows us to quantify the aggregate climate change due both, the future anthropogenic and solar forcing, in multidimensional climate space.

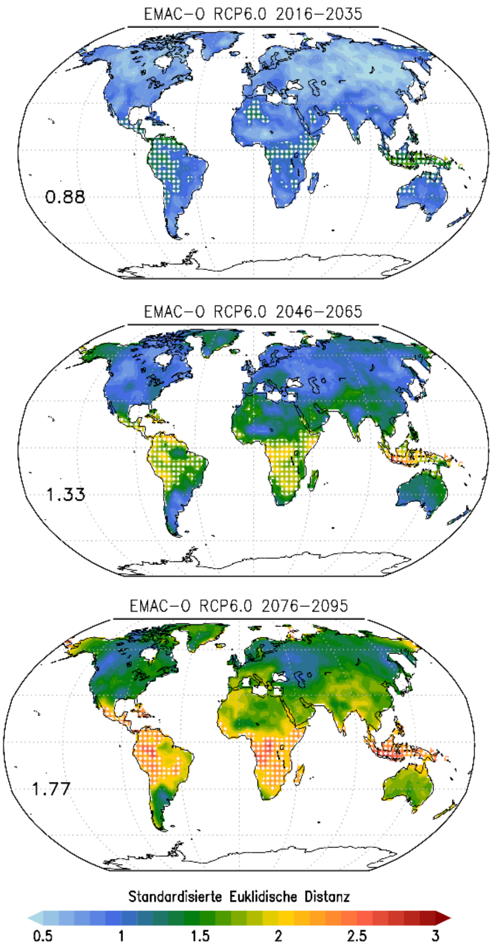

Figure 6: The development of aggregate climate change within the reference simulation represented by standard Euclidean distances. a) 2016-2035, b) 2046-2065 and c) 2076-2095.

The tropical regions will severely be affected by anthropogenic climate change already during the first third of the 21st century. Tropical Southeast Asia, large parts of the Amazon Basin, Central America and Equatorial / Southern Africa can be identified as 21st century climate change hotspots. Those areas are particularly affected by a stronger increase in near surface temperature and the occurrence frequency of extreme events. With respect to the magnitude of a possible future GSM, the regional anthropogenic influences might be mitigated to a certain degree by a solar downturn. However, at the end of the GSM core period climate change quickly catches up to reference conditions.

The 11-year solar signal in the troposphere and the role of ocean-atmosphere coupling (Kubin, Langematz, Abalichin et al., to be submitted, 2018)

Effects of the 11-year solar cycle on the tropospheric climate are studied by analysing integrations of the chemistry climate model EMAC that has been coupled to the MPIOM ocean model. A series of experiments has been tailored to investigate the role of atmosphere-ocean coupling for the formation of the near-surface response to the 11-year solar irradiance variability. The focus is on the north Atlantic region and the tropical Pacific region in the northern winter season. The model output is analysed with a multiple linear regression technique. There is a tendency towards a positive phase of the North-Atlantic Oscillation (NAO) at maxima of the sunspot cycle. The signal is enhanced when the atmosphere-ocean interaction is suppressed by prescribed SSTs. Additional sensitivity simulations with either the sea surface temperatures (SSTs) or the middle atmosphere being free from 11-year solar influence reveal a key role for the stratospheric forcing in shaping the tropospheric response in the North Atlantic-European region. For the equatorial Pacific the results suggest a strong influence of the underlying sea surface temperatures and the decadal variability contained therein on the atmospheric circulation. The robustness of the signals is tested by varying the length of the analysed time series as well as by varying the set of basis functions used in the regression. The Pacific solar signals proofs to be primarily insensitive to changes in the regression approach, whereas the NAO response shows substantial variation of magnitude and even sign when subsets of the analysis period are examined. The sub-surface response of equatorial (5°N to 5°S mean) water temperature displayed in **Figure 7a** reveals that the surface warming does not penetrate deep into the Pacific but is confined to the upper 50 to 150m. However, there is a strong and statistically significant cooling in the region of the climatological thermocline, which implies a lifting of the thermocline. This signal is very different from El Niño conditions, which are characterized by an almost basin-wide warming of the upper layers down to about 50m to 120m and a cooling below with a maximum in the western Pacific (**Figure 7b**). During an El Niño event the thermocline shoals in the western Pacific, whereas it is lifted in the region of its maximum east-west slope in the central and eastern Pacific at high solar activity.

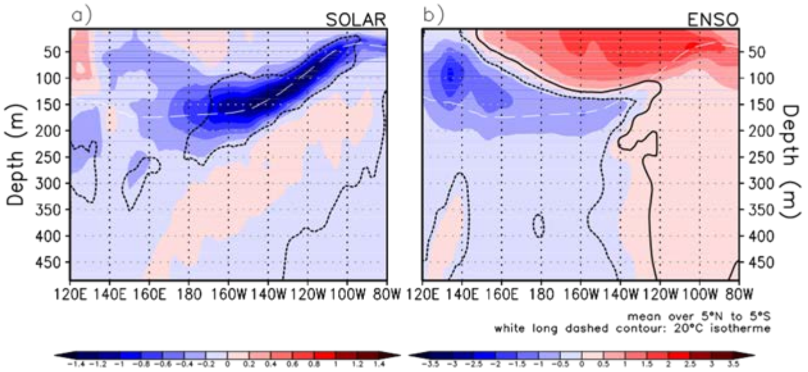

Figure 7: a) Solar signal in DJF seawater potential temperature in K per 100 units F10.7cm solar radio flux and b) ENSO signal in K per unit Niño3.4 index. Data in a) and b) are averaged between 5°N and 5°S. Statistically significant anomalies at the 95% confidence level are enclosed by black contours (solid for positive and dashed for negative anomalies). The 20°C isotherm is indicated by a white long-dashed line. Note the different color coding in sub-figures a) and b).

References:

Bellenger, H., Guilyardi, E., Leloup, J., Lengaigne, M., and Vialard, J., 2014: ENSO representation in climate models: from CMIP3 to CMIP5, *Climate Dynamics*, 42(7), 1999–2018.

Charlton, A. J., L.M. Polvani, J. Perlwitz, F. Sassi, E. Manzini, S. Pawson, J.E. Nielsen, K. Shibata and D. Rind, 2007: A new look at stratospheric sudden warmings. Part II. Evaluation of numerical model simulations, *J. Climate*, 20, 470-488.

Comiso, J. C., C. L. Parkinson, R. Gersten and L. Stock, 2008: Accelerated decline in the Arctic sea ice cover, *Geophys. Res. Lett.*, 35, L01703, doi: 10.1029/2007GL031972.

Eyring, V. et al., 2013: Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments, *SPARC Newsletter*, 40, 48-66.

IPCC 2013 Climate change, 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Cambridge University Press, Cambridge. 1535 pp. doi:10.1017/CBO9781107415324 Ocean Dynamics

Rasmusson, E. and Carpenter, T., 1982: Variations in tropical sea surface temperature and surface wind fields associated with the southern oscillation/El Niño. *Monthly Weather Review*, 110(5):354–384.

Thompson, D.W.J. and S. Solomon, 2002: Interpretation of recent southern hemisphere climate change, *Science*, 296, 895-899.

Turner, J., J. C. Comiso, G. J. Marshall, T. A. Lachlan-Cope, T. Bracegirdle, T. Maksym, M. P. Meredith, Z. Wang and A. Orr, 2009: Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophys. Res. Lett.*, 36, L08502, doi: 10.1029/2009GL037524.

List of publications/reports from the project with complete references

The following publications/ theses have used data from EMAC and EMAC-O simulations carried out in this project:

Abalichin, J. (2016), Natural variability and anthropogenic impact in simulations with the coupled CCM EMAC-O: atmosphere-ocean interactions in the Antarctic climate change. PhD thesis, Freie Universität Berlin.

Hegedüs, A. (2017), Auswirkungen eines zukünftigen Grand Solar Minimum auf die Klimaentwicklung und Klimavariabilität der Südhemisphäre, Master thesis, Eötvös Loránd University Budapest and Freie Universität Berlin.

Hellmer, H.H., Rhein, M., Heinemann, G., Abalichin, J. Langematz, U., et al. (2016), Meteorology and oceanography of the Atlantic sector of the Southern Ocean—a review of German achievements from the last decade, *Ocean Dynamics*, 66: 1379. https://doi.org/10.1007/s10236-016-0988-1.

Kubin, A., U. Langematz and J. Abalichin (2018), The 11-year solar signal in the troposphere and the role of ocean-atmosphere coupling, to be submitted to *J. Geophys. Res*.

Meul, S., M. Dameris, U. Langematz, J. Abalichin, A. Kerschbaumer, A. Kubin, and S. Oberländer-Hayn (2016), Impact of rising greenhouse gas concentrations on future tropical ozone and UV exposure, *Geophys. Res.Lett*., 43, doi:10.1002/2016GL067997.

Oberländer-Hayn, S., E. P. Gerber, J. Abalichin, H. Akiyoshi, A. Kerschbaumer, A. Kubin, M. Kunze, U. Langematz, S. Meul, M. Michou, O. Morgenstern, and L.D. Oman (2016), Is the Brewer- Dobson circulation increasing or moving upward?, *Geophys. Res. Lett.,* 43, 1772-1779.

Spiegl, T. (2017), Die Auswirkungen eines potentiellen Grand Solar Minimum auf das Klimasystem vor dem Hintergrund des anthropogenen Klimawandels, PhD thesis, Freie Universität Berlin.

Spiegl, T., and U. Langematz (2018), Quantifying the Regional Effects of a potential 21st century Grand Solar Minimum on aggregate climate change using Euclidean Distances, to be submitted to *Nature Climate Change*.

Thieblemont, R., B. Ayarzagüena, K. Matthes, S. Bekki, J. Abalichin, and U. Langematz (2018), On the drivers of the inter-annual variability of Northern Hemisphere stratospheric final warmings simulated in CESM1(WACCM), to be submitted.

Wunderlich, F. (2016), Darstellung der Madden-Julian Oszillation und deren Einfluss auf die boreale Stratosphäre im Winter durch das Klima-Chemiemodell EMAC-O, Master thesis, Freie Universität Berlin.

Future plans

There are currently no concrete plans for a continuation of the project. However, we consider to apply for a special project in the case that a new research proposal submitted recently will be evaluated positively.