SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	"Chemistry Climate Model Simulations for WMO Ozone Assessment" and "Simulations with an Atmosphere-Ocean-Chemistry- Climate Model for the development of a decadal climate prediction system"
Computer Project Account:	spdewmo3
Start Year - End Year :	2012 - 2014
Principal Investigator(s)	Prof. Dr. Ulrike Langematz
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Other Researchers (Name/Affiliation):	Janna Abalichin, Anne Kubin, Markus Kunze

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

Within this project Atmosphere-Ocean-Chemistry-Climate Model (AOCCM) simulations with the MA-ECHAM5/MESSy/MPIOM (EMAC-MPIOM) were conducted as contribution to the German research programme “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 in view of the development of a mid-term, i.e. decadal, climate prediction model. Furthermore the simulations were analysed in the projects SHARP and ISOLAA, both interested in the atmosphere-ocean interactions.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

In May 2014 we applied for additional resources to conduct another simulation with the atmosphere ocean CCM EMAC-O before the shut-down of the IBM system. The requested computing time resources were approved and allocated within only a few weeks. This was a very positive experience.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

We constrain our report to the last year of this special project and refer to our progress reports for earlier results. Two simulations with the Ocean-coupled Chemistry-Climate Model EMAC-MPIOM (hereafter EMAC-O) were completed on the ECMWF HPC Facility in 2014. The first one is a control simulation with perpetual boundary conditions representative for the year 1960 (e5ao_1960Ctl) but including the natural forcing by time-varying spectral solar irradiance. This simulation was run for 110 years. The other one was 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 (e5ao_rcp6.0). In the following we present the results of different ongoing analyses of the new simulations. First results have already been presented at conferences. The preparation of publications is underway.

The 11-year solar signal in the transient simulation

The 11-year solar influence on the atmosphere is extracted from the raw model output by means of a multiple linear regression approach. All results presented in this section are given per 100 units of the F10.7cm solar radio flux which is closely correlated with solar ultra-violet variations during the course of the solar activity cycle and which was used as basis function for solar variability in the regression. The analysis period is 1960 to 2007.

The annual mean solar signals in zonal mean short-wave heating rates, ozone and temperature are shown in Fig 1. An enhanced short-wave heating can be seen everywhere in the upper stratosphere and lower mesosphere which peaks at about 0.14 K/day near the tropical stratopause. Ozone is increased by about 1 to 1.5% over wide regions of the middle and upper stratosphere. These solar induced anomalies lead to an increase of temperature by about 0.7 K in the stratopause region. The vertical dipole signal at high northern latitudes with positive anomalies on top of negative anomalies in the lower atmosphere originates in the northern winter season.

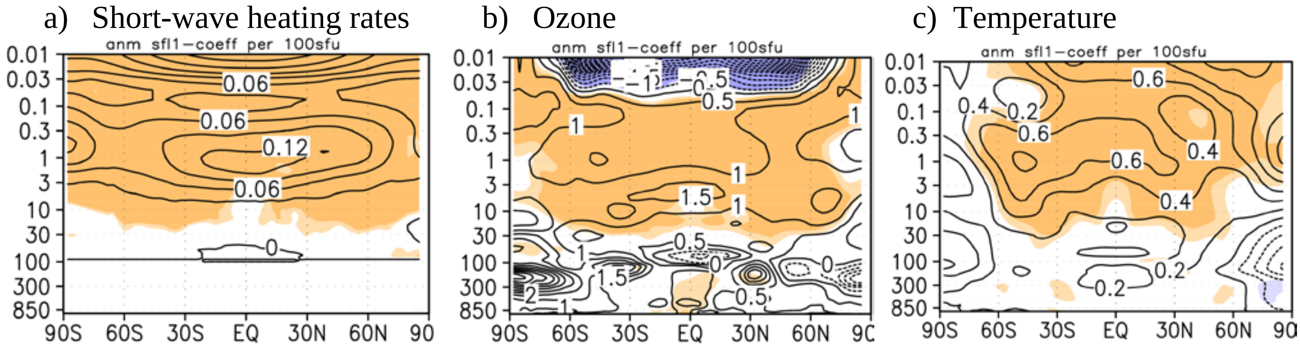


Figure 1: Annual mean solar signal in a) zonal mean short-wave heating rates in K/d, contour interval is 0.03 K/d, b) zonal mean ozone in %, contour interval is 0.5 % and c) temperature in K per 100 units F10.7 cm radio flux, contour interval is 0.2 K. Light (heavy) shading indicates statistical significance at the 95% (99%)-level.

During northern winter and spring there is a solar induced enhancement of the zonal mean zonal wind which is initiated in the subtropical lower mesosphere and which travels poleward and downward as the winter proceeds. This behaviour is known from earlier studies (e.g. Kodera and Kuroda, 2002; Matthes et al., 2006). However, the timing of the wind anomalies is about one month delayed compared to studies with the same model but without interactively coupled ocean. We note also a longer persistence of the westerly anomalies into the spring season. From January to March statistically significant zonal wind anomalies can be detected in the troposphere which imply a latitudinal shift of the jet stream.

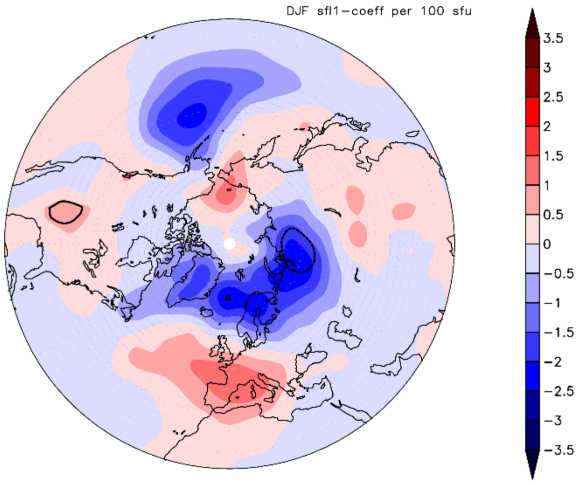


Figure 2: Solar induced changes in mean sea-level pressure in northern winter (DJF) in hPa per 100 units F10.7 cm radio flux. Anomalies enclosed by thick black contours are statistically significant at the 95% level.

The solar influence near the Earth' surface manifests itself in northern winter (DJF) in a tendency towards a more positive North Atlantic Oscillation (NAO), i.e. with negative mean sea level pressure anomalies near Iceland and positive anomalies farther south in the Azores region, depicted in Figure 2. However, both anomalies are statistically not significant. Consistent with these pressure anomalies higher temperatures can be detected downstream of the pressure anomaly dipole. Another characteristic solar induced anomaly in mean sea level pressure reported in literature (e.g. Hood and Soukharev 2012, Hood et al., 2013) is a weakening of the Aleutian low. EMAC-O does not really capture this behaviour. Instead it simulates a weakening on the north western flank of the Aleutian low and a strengthening on the south eastern flank which results in a shift of the Aleutian low.

For the above mentioned positive NAO phase at high solar activity sensitivity tests have been performed by varying the length of the data window. The last year considered is always 2007 but the start year was shifted backwards in time with a minimum length of the time series of ten years. It was found that including up to 25 years in the regression analysis the procedure yields a strong and statistically significant positive phase of the NAO. However, when more years are taken into account the signal becomes weaker and statistically insignificant. This is a strong indication for the need for long data series in order to obtain reliable results on decadal time scales. It also raises questions about results obtained from the analysis of only the satellite era, i.e. since 1979, which might be a too short period for solar cycle studies.

In recent studies Gray et al. (2013) and Hood et al. (2013) discuss a lagged response of DJF mean sea level pressure in the north Atlantic to solar forcing. They identify pressure anomaly peaks three to four years after the peak of solar activity. This has also been tested in EMAC-O by repeated regression analyses with the solar basis function shifted one to five years ahead with a one-year increment. In this way the sea-level pressure lags the solar forcing by one to five years. Investigating the lag-dependency in the centres of action of the NAO, i.e. picking grid points near Iceland and near the Azores the strongest signal arises with a one-year lag, however, it is statistically not significant, see Figure 3.

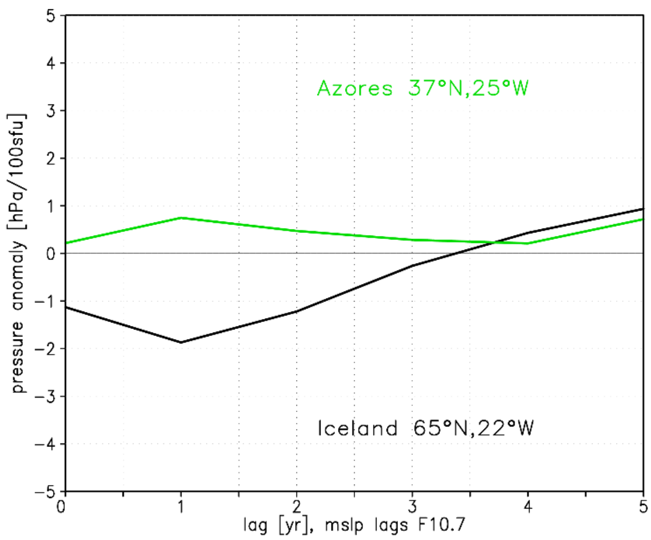


Figure 3: Solar induced changes in mean sea-level pressure in northern winter (DJF) in hPa per 100 units F10.7 cm radio flux as a function of lag time. The green curve shows the pressure anomaly near the Azores (37°N, 25°W) and the black curve the anomaly near Iceland (65°N, 22°W).

The response of the modelled sea surface temperatures (SSTs) in the equatorial Pacific to the 11-year solar forcing has a non-uniform character. It neither resembles an El-Nino nor a La-Nina signal as has been discussed in literature (Van Loon and Meehl, 2008; Meehl et al. 2009; Roy and Haigh, 2010, 2012; Zhou and Tung, 2010; Tung and Zhou, 2010). Also, there is no basinwide warming in EMAC-O as was described by Misios and Schmidt (2012) from another model of the ECHAM-MPIOM family. In the north Pacific the 11-year solar signal is comparable in shape to the signal derived from a long observational data set (Hood et al., 2013) but it is considerably stronger.

Currently, a detailed investigation of the North Atlantic signal is done, involving sub-surface ocean temperature reactions to the solar forcing. It is known that the NAO index when correlated with the Atlantic SSTs yields a tripole pattern with higher temperatures off the North American coast, lower temperatures off the coast of western Africa and another region of lower temperatures near Iceland (e.g. Visbeck et al., 2003). This correlation is also found in EMAC-O results, using the pressure difference between two grid points near the Azores and near Iceland (coordinates as given above) as NAO index. Near the node of the correlation between its positive pole and the northern negative pole statistically significant solar induced anomalies in the SSTs as well as in the ocean heat content of the upper 700m of the water column are detected. Thus, the solar influence seems to act in the same sense as the NAO, i.e. cooling the central Atlantic near 40°N and warming it near 35°N. At the same time a strong warming is found stretching from the Caribbean to the north western coast of Africa. As yet this is work in progress. Further analyses are necessary.

The above summarised results have been presented at several conferences:

U. Langematz, A.Kubin, J. Abalichin, J. Scheffler, M. Dameris, D.S Cai and K. Matthes, 2015: The role of the stratosphere for decadal climate prediction, MiKlip Status Seminar, 23-25 February 2015, Offenbach, Germany.

A. Kubin, J. Abalichin, and U. Langematz, 2015: The 11-year solar signal in ocean-coupled climate models with and without interactive chemistry, Conference on Sun-Climate Connections, 15-19 March 2015, Kiel, Germany.

A. Kubin, J. Abalichin and U. Langematz, 2015: The 11-year solar signal in the troposphere in ocean-coupled climate models with and without interactive chemistry, 26th IUGG General Assembly, 22 June-2 July 2015, Prague, Czech Republic.

Total ozone in the transient simulation

The evolution of the maximum Antarctic ozone hole area per year in the past and the projection until 2100 in the e5ao_rcp6.0 simulation is shown in Figure 4 (purple curve). For comparison observations (light blue) as well as various model simulations with different model setups (without interactive ocean) and different GHG scenarios are included. Although all model simulations substantially underestimate the observed ozone hole area in the recent past, the qualitative development is represented with low values before 1980 and maximum values around the year 2000. The simulation with interactive ocean lies well in between the other model experiments. In the future, the stratospheric halogen loading is projected to decline which leads to a reduction of the ozone hole area. This decrease differs between the different simulations due to the impact of changing dynamics. In the simulation with atmosphere-ocean coupling the decline is relatively slow compared to the other simulations except for the non-climate change simulation (NCC, red). This indicates that the effect of increasing GHGs on stratospheric dynamics and thus on the evolution of the ozone hole area is damped if the ocean is allowed to react on atmospheric changes.

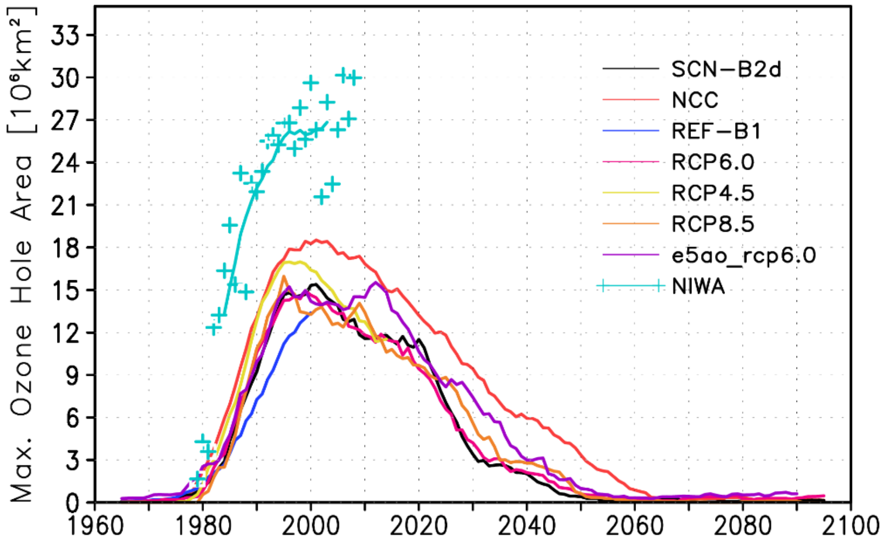


Figure 4: Temporal evolution of the maximum Antarctic ozone hole area [million km²] in each year for the observations (light blue) and various model simulations. The ozone hole area is calculated by integrating the corresponding area of each model grid point south of 30°S at which the total column ozone is lower than 220 DU. The data are smoothed with an 11-year running mean (solid lines). For the observations also the unsmoothed data (crosses) are shown.

<u>Brewer-Dobson circulation in the transient EMAC-O simulation</u>

In this subsection the Brewer-Dobson circulation (BDC) in EMAC-O is compared to two other model simulations under the greenhouse gas (GHG) scenario RCP6.0 with different treatments of sea surface temperatures (SSTs) and sea ice concentrations (SICs). The EMAC-O simulation run with the interactively coupled ocean model, whereas the simulations EMAC-SST-O and EMAC used prescribed SSTs/SICs as lower boundary condition. For the EMAC-SST-O SSTs/SICs are taken from the coupled simulation with EMAC-O, whereas for the EMAC run the SSTs/SICs from a coupled simulation performed at the Met Office Hadley Centre (HadGEM) are used. The three RCP6.0 simulations are compared to ERA-Interim reanalysis data and observations from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS, provided by G. Stiller, KIT).

The BDC is the middle-atmospheric meridional circulation which includes the large scale residual circulation (RC) in the stratosphere and mesosphere as well as small scale mixing processes. Here we introduce two measures of the BDC, i.e. the mean age of stratospheric air (AoA) and the tropical upward mass flux. The AoA is the travel time of an air parcel within the stratosphere and includes both components of the BDC – RC and mixing. The tropical upward mass flux is a measure of the RC and corresponds to the mass transport at a specific level in the stratosphere (here: 70 hPa).

Figure 5a shows the lower stratospheric (50 hPa, ~ 22 km) mean AoA from 90°S to 90°N for the 1980 to 2000 average of the model simulations in comparison with MIPAS observations averaged between 2002 and 2004. All model simulations show a lower mean AoA by about one year in the tropics and up to four years at high latitudes. This corresponds to a faster transport in the model simulations compared to observations and is a well-known feature of many general circulation models (GCMs) and CCMs. The general transport characteristics are reproduced in all simulations, i.e. the lowest mean AoA is found in the tropics, where air enters the stratosphere and the highest mean AoA occurs at high latitudes. All model simulations look similar, but the simulations EMAC-O with coupled ocean and EMAC-SST-O with SSTs/SICs from the coupled simulation show the lowest mean AoA, i.e. the strongest transport, at all latitudes.

The time evolution of the tropical upward mass flux at 70 hPa (~18 km) is shown in Figure 5b for all model simulations and reanalysis data. Compared to ERA-Interim reanalysis, the model simulations show a higher tropical upward mass flux, i.e. a stronger BDC. Both simulations with SSTs/SICs from EMAC-O show the strongest tropical upward mass flux, in agreement with the

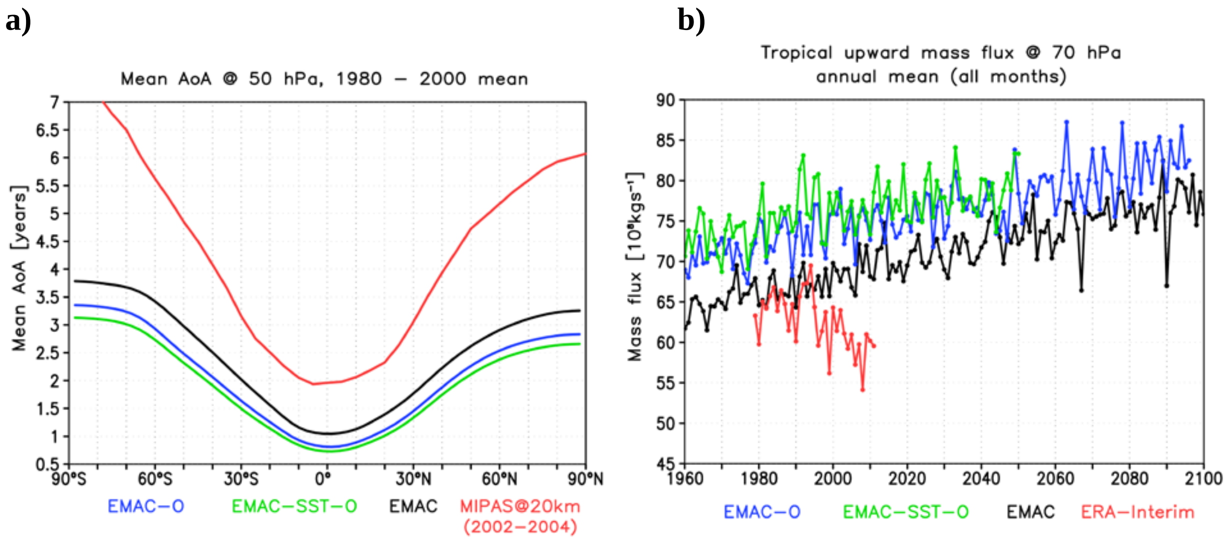


Figure 5: a) Mean Age of Air (AoA) at 50 hPa in years averaged over the period 1980 to 2000 along with the MIPAS measurements (red) at 20 km averaged over the period 2002 to 2004. b) Temporal evolution of the annual mean tropical upward mass flux at 70 hPa in 10^8 kgs^{-1}.

lowest mean AoA (Fig. 5a). For the future all model simulations predict a rising tropical upward mass flux with increasing GHG concentrations. The decline in upward tropical mass flux in ERA-Interim reanalyses around 2000 is currently under debate.

Future changes in wintertime polar stratospheric variability

Major stratospheric warmings (MSWs) are the most abrupt events of boreal wintertime polar stratospheric variability, whose influence extends down to the troposphere. Thus, the analysis of these phenomena and their possible variations in the future is also important for the future climate change projections of surface climate. In the framework of a Chemistry Climate Model Initiative (CCMI) project, an analysis of future changes of these phenomena has been carried out by means of transient runs of different CCMs under RCP6.0 future scenario, one of these CCMs being EMAC-O. All of these runs extend from 1960 to 2100 and include natural and anthropogenic forcings and natural variability following the specifications by the CCMI initiative (Eyring et al., 2013). Future changes in MSWs characteristics are assessed by comparing the last 40 winters of each run with the first 40 ones.

As a first step, variations in the frequency of these phenomena have been studied. By applying the standard criterion for the identification of 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, no statistically significant future changes in the frequency of MSWs are found except for NIWA-UKCA (Table 1). However, the statistically significant result for NIWA-UKCA could be due to the unrealistically low frequency of these phenomena in the past period in comparison with observations (0.8 MSWs/decade in NIWA-UKCA vs. 5.5 MSWs/decade in NCEP/NCAR reanalysis).

As a second step, the sensitivity of the results to different MSW diagnostics has been tested by using other criteria for the identification of MSWs such as the reversal of zonal mean zonal wind at 10 hPa averaged over the polar cap or exceeding of polar-cap averaged 10-hPa Z anomalies by more than 3 standard deviations (Butler et al., 2015). The results associated with different SSWs diagnostics confirm the lack of statistically significant future changes.

Finally, a possible change in the seasonality of MSWs has been examined. However, as the number of MSWs in some models is very low, we have rather focused on the intensity of the polar night. Thus, future changes in the daily climatology of the zonal-mean zonal wind at 10 hPa have been

Table 1: Frequency of major stratospheric warmings in RCP6.0 simulation of CCMI models for the past (1960/61-1999/2000) and the future (2060/61-2099/2100) along with the frequency obtained from NCEP/NCAR reanalysis data. The MSWs have been identified according to the standard criterion.

Model	Past (MSWs/dec)	Future (MSWs/dec)
CCSRNIES-MIROC3.2	2.3	3.0
NIWA-UKCA	0.8	3.3
GEOS-CCM	1.8	1.8
CNRM-CCM	7.5	7.5
EMAC-O	9.3	7.5
ACCESS	10.0	9.3
NCEP/NCAR reanalysis	5.5	

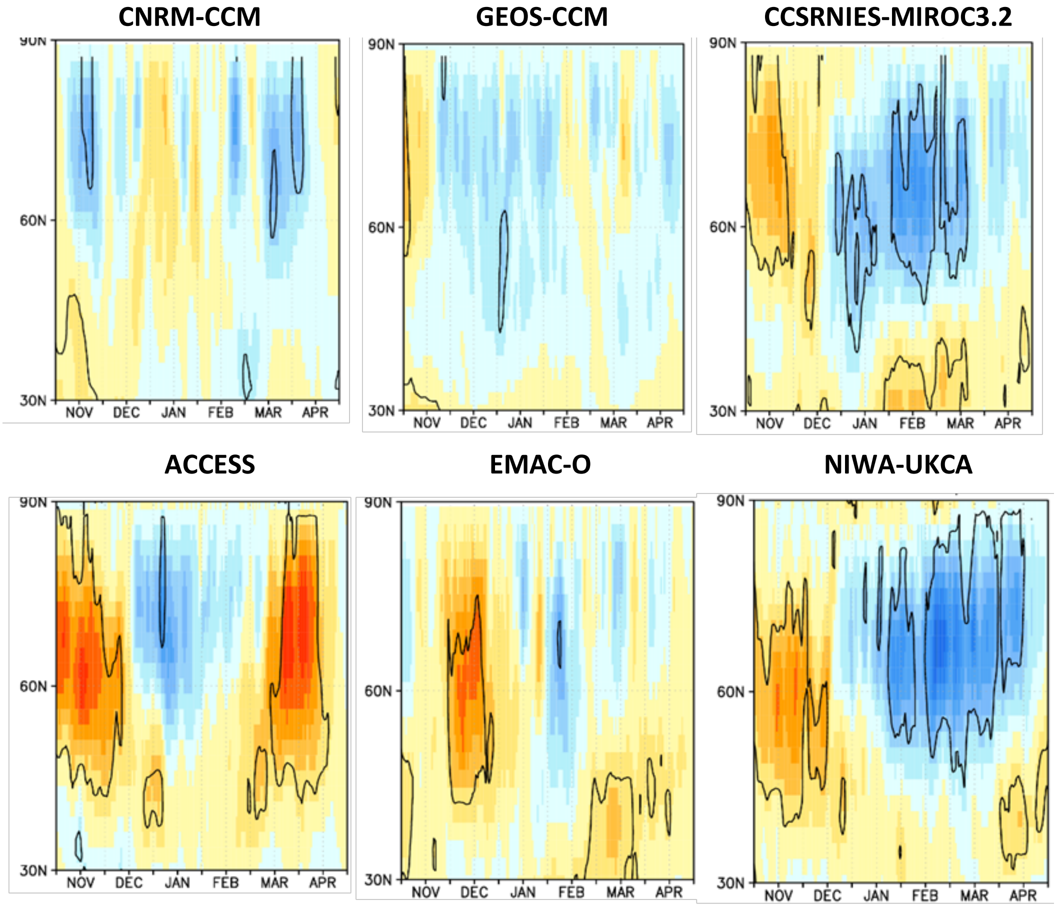
studied (Figure 6). Most of the models (CCSRIES-MIROC3.2, NIWA-UKCA, EMAC-O & ACCESS) show a future weakening of the polar stratosphere in midwinter and a future strengthening in early winter (Figure 6, upper and middle row). The other two models (CNRM-CCM and GEOS-CCM) do not show any statistically significant change.

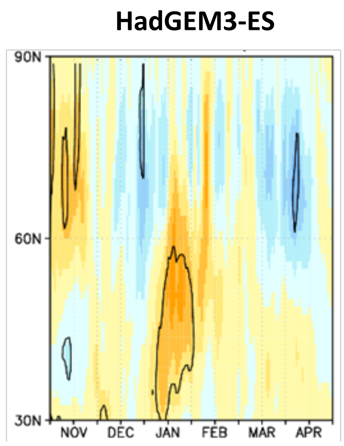
Results have been presented at the 2015 AMS Annual Meeting in Phoenix, Arizona, United States, 7 January 2015 (oral presentation "Future changes in Major Stratospheric Warmings in CCMI models" by Blanca Ayarzagüena, U. Langematz, L. M. Polvani, J. Abalichin, H. Akiyoshi, A.Klekociuk, M. Michou, O. Morgenstern, L. Oman and K. Shibata).

Relationship between stratospheric weak polar vortex events and cold air outbreaks over Northern Europe under different climate change scenarios in EMAC

The relationship between stratospheric weak polar vortex events (weak vortex days, WVDs) and cold air outbreaks (CAO) over Northern Europe in the future has been investigated in the output of EMAC and EMAC-O simulations run under different climate change scenarios (i.e., RCP4.5, RCP6.0 and RCP8.5). We followed the methodology of Kolstad et al. (2010) and Tomassini et al. (2012) who analyzed this relationship in NCEP/NCAR reanalysis and pre-industrial model simulations, respectively. These authors identified a negative phase of the NAO after the occurrence of WVDs leading to cold anomalies over northern Europe. This NAO phase weakens with time thereby intensifying the cold anomalies over Asia.

Analyzing the tropospheric circulation around the occurrence of stratosphere-related cold air outbreaks we found EMAC(-O) to reproduce qualitatively well reanalysis results in the 1960-2000 period. In the future, a weaker relationship between cold air outbreaks over Northern Europe and changes in the polar vortex is detected, being, however, only statistically significant under an extreme climate change scenario (RCP8.5 scenario).





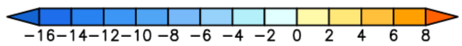


Figure 6: Differences future-minus-past of the daily climatology of 10-hPa zonal-mean zonal wind from November to April in the Northern Hemisphere. Shading interval: 2 m s-1. Statistically significant changes at a 95% confidence level (two-tailed Student's t-test) are enclosed by black contours.

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List of publications/reports from the project with complete references

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Since 2015 our new special project "Ocean-Atmosphere Chemistry Climate Model Simulations for new WMO-SPARC-Chemistry Climate Model Initiative (CCMI)" is running. We plan to continue the special project also in 2016 and apply for computing time accordingly.