SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	2010/2011
Project Title:	Chemistry Climate Model Simulations for WMO Ozone Assessment
Computer Project Account:	SPDEWMO3
Principal Investigator(s):	Prof. Dr. Ulrike Langematz
Affiliation:	Institut für Meteorologie, Freie Universität Berlin
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	2008
Expected end date:	2011

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	400 000	400 000	2 650 000	0
Data storage capacity	(Gbytes)	1000	1000	9900	0

Summary of project objectives

(10 lines max)

The objective within SPDEWMO3 is to perform a chemistry-climate-model simulation using the MAECHAM5/MESSy model system with the FUBRad radiation parameterisation (EMAC-FUB) (Nissen et al., 2007). The simulation covers the period 1960 to 2100. It contributes to the WMO/UNEP "Scientific Assessment of Ozone Depletion: 2010" and to the SPARC-CCMVal report on the evaluation of coupled chemistry climate models. The main focus lies on the validation of the model against observations as well as on the assessment of the future development of stratospheric ozone. At present ozone recovery is expected to take place until mid-century (WMO, 2007), so that column ozone reaches 1980 values in southern polar latitudes. For studies of the future development of stratospheric ozone it is of great importance to take into account interactions between radiation, dynamics and chemical composition of the atmosphere. Only CCMs can simulate the feedback of chemical processes on dynamics and transport of tracers.

Summary of problems encountered (if any)

(20 lines max)

Summary of results of the current year (from July of previous year to June of current year)

This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

Within this Special Project we performed a transient chemistry climate model (CCM) simulation to contribute to the SPARC-CCMVal report and to the WMO/UNEP "Scientific Assessment of Ozone Depletion: 2010". The experiment carried out is the CCMVal-SCN-B2d-simulation (Eyring et al., 2008). It is designed as a sensitivity simulation in addition to the transient REF-B2 run covering the period from 1960 to 2100. Whereas in REF-B2 only forcings by emissions of greenhouse gases (GHGs) and ozone depleting substances (ODSs) are taken into account, SCN2-B2d in addition considers natural forcings such as solar variability, the quasi biennial oscillation (QBO) and volcanic eruptions. The lower boundary conditions are set by prescribed modelled sea surface temperatures and sea-ice taken from an A1B-scenario IPCC AR4 simulation to ensure consistency between the past and the future part of the simulation.

The analysis is done within the approved projects "Project on Solar Effects on Chemistry and Climate Including Ocean Interactions" (ProSECCO), part of the DFG Priority Program "Climate and Weather of the Sun-Earth-System" (CAWSES), and "The Shift of Southern Hemisphere Storminess under Anthropogenic Climate Change around Antarctica and ist Impacts" (SACAI), part of the DFG priority programme on Antarctica. Moreover, the results provide the basis for research within the approved DFG-Research unit "Stratospheric Change and its Role for Climate Prediction" (SHARP, FOR1095), coordinated by Ulrike Langematz.

Initial results of the SCN-B2d simulation have been described in our progress report of the period 2009/2010. The simulation has been further analysed within the DFG-Research unit SHARP with respect to the evolution of ozone and the future development of the Brewer-Dobson circulation. Results have been presented at the IUGG conference 2011 in Melbourne (poster *"The impact of anthropogenic activity on the evolution of stratospheric ozone – a model study with EMAC-FUB"* by U. Langematz, S. Meul, S. Oberländer, J. Abalichin and A. Kubin) as well as at the EGU General Assembly 2011 in Vienna (poster *"The Brewer-Dobson Circulation in sensitivity simulations for the past and future with the Chemistry Climate Model EMAC-FUB"* by S. Oberländer, S. Meul, U. Langematz and A. Kubin). The simulation has been further analysed within the DFG project CAWSES-ProSECCO with respect to the 11-year solar cycle influence on ozone and temperature.

Part I: The 11-year solar signal in SCN-B2d

The 11-year solar signal in ozone and temperature has been extracted from the SCN-B2d simulation model output of the period 1960 to 2005 by a multiple linear regression approach (Bodeker et al., 1998). The signal in the zonal and annual mean is shown in Figure I.1. It is given per 100 units F10.7 solar radio flux. Ozone volume mixing ratio is enhanced during high solar activity by about 2.5% per 100 units of the F10.7 cm solar radio flux in the upper stratosphere (~3 hPa) at mid-latitudes (cf. Figure I.1, left). The temperature response is strongest at the stratopause level (50 km, ~1 hPa) where it exceeds values of 0.6 K per 100 units F10.7 (Figure I.1, right). The solar signals in ozone and temperature are statistically highly significant as is indicated by the shading in Figure I.1.

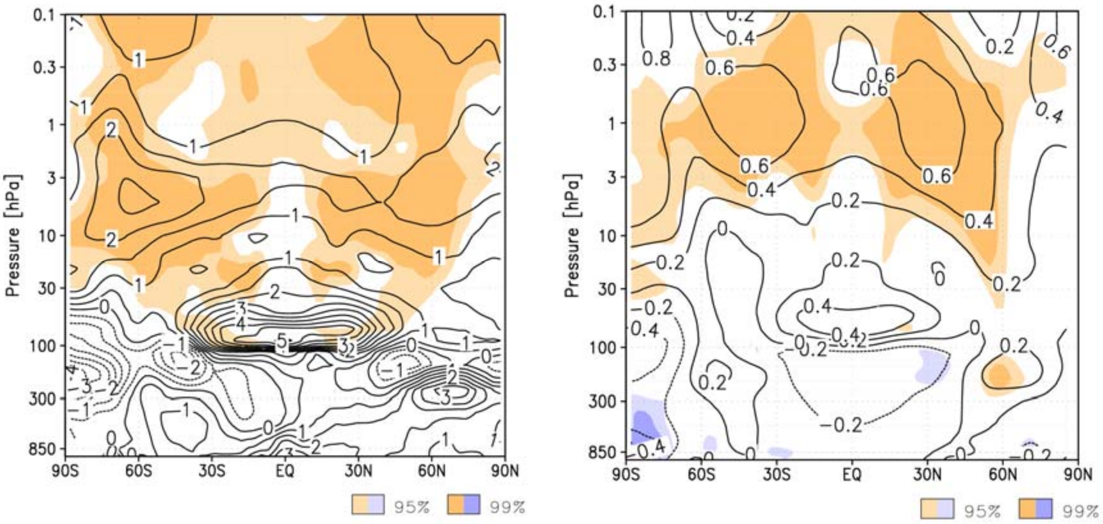


Figure I.1: Latitude-height sections of 11-year solar influence on ozone (left, in % per 100 units F10.7) and on temperature (right, K per 100 units F10.7) in the past (1960-2005).

In the tropical lower stratosphere secondary maxima of the ozone and temperature responses appear in the SCN-B2d simulation (Figure I.1). A comparison between the annual mean 11-year solar signal in the SCN-B2d simulation with the signal obtained from a reference CCMVal REF-B1 simulation (not shown) of the period 1960 to 2005 (Eyring et al., 2008) shows overall similarity of the results but also a remarkable difference, in particular, in the tropical lower stratosphere. The secondary maxima in the ozone and temperature responses to 11-year solar variability are not present in the REF-B1 results. A plausible explanation for this is a bias towards cold extremes of the El Nino Southern Oscillation (ENSO) phenomenon in the modelled sea surface temperatures (SSTs) and sea ice conditions that are prescribed to the model for the SCN-B2d simulation in contrast to observed SSTs and sea ice data which are used to force the reference REF-B1 simulation. ENSO cold events favour the development of the tropical lower stratospheric maxima in the ozone and temperature response to the 11-year solar cycle forcing (Kubin, 2011).

The period 1960 to 2100 covered by the SCN-B2d simulation allows to investigate whether the 11-year solar signal in ozone and temperature changes under a changing climate. By the end of the 21st century the CO_2 concentration will have more than doubled compared to the 1960 level. Polar stratospheric ozone is projected to have returned to 1980 values but not to have fully recovered from the influence of chlorofluorocarbons whereas tropical ozone continuously declines due to a projected increase in tropical upwelling (Eyring et al., 2010). Thus, the basic state of the atmosphere is modified.

Figure I.2 shows the 11-year solar signal as computed from a multiple linear regression analysis of the period 2055-2100. The annual mean ozone response to 11-year solar variability in the future is in its main features similar to the response in the past (cf. Figure I.2, left). A difference can be noted in the tropical lower stratosphere. Where in the past period a strong and significant maximum is seen there is a very weak and insignificant response in the future period. The temperature signal near the stratopause is comparable in magnitude to the signal in the past (cf. Figure I.2, right), but it is situated at a lower altitude. The changes are highly significant in the extratropics At high northern latitudes a dipole pattern with a significant warming at the stratopause and in the lower mesosphere and a cooling in the middle stratosphere appears. This signal was absent in the past analysis period, but was also seen in the reference simulation of the past with observed SSTs. The secondary maximum in the tropical lower stratosphere that was found in the past period is weaker in the future period. It is also noted that the area with statistically significant changes has shrinked from the past to the future period. This points towards an increased variability in the atmosphere in a warming climate.

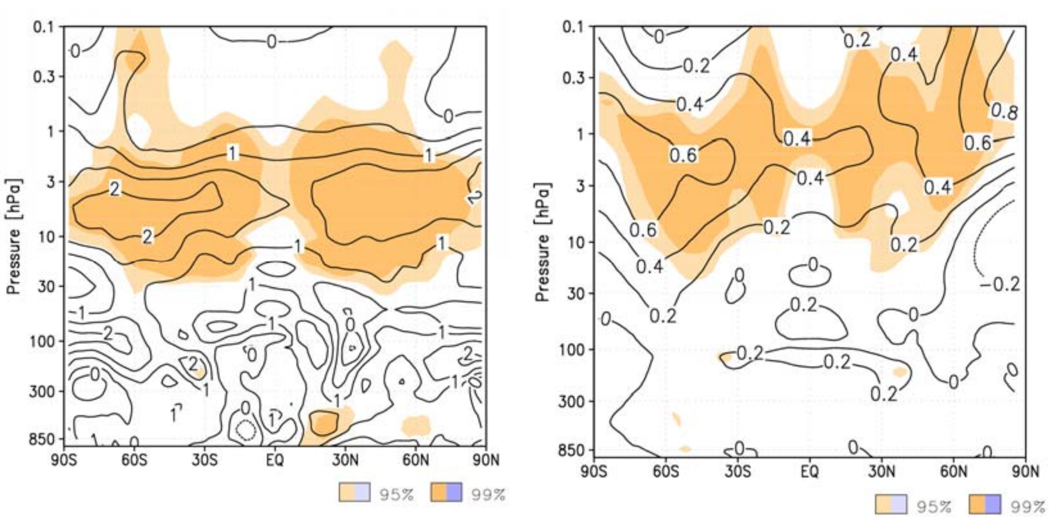


Figure I.2: Latitude-height sections of 11-year solar influence on ozone (left, in % per 100 units F10.7) and on temperature (right, K per 100 units F10.7) in the future (2055-2100).

However, these results for the future period are subject to a substantial uncertainty associated with the imposed solar irradiance changes. The solar cycles 20 to 23 (1962-2004) were repeated several times to continue the solar irradiance time series for the model input. As the solar activity will not necessarily remain on the present relatively high level this assumption may be unrealistic, particularly, since there are indications for a decrease of solar activity in the future (e.g., Abreu et al., 2008).

Part II: Stratosphere-Troposphere coupling in SCN-B2d

A high correlation between the intensity of the stratospheric polar vortex and tropospheric variability modes like the Northern and Southern Annular Mode (NAM/SAM) could be shown through statistical analyses of long term observations and numerical model simulations. NAM is a key index for weather and climate in Europe. Stratospheric NAM anomalies associated with anomalously strong or weak stratospheric polar vortices propagate downward into the troposphere with a time lag of several weeks showing up as anomalies of surface meteorological fields. Similarly, anomalously strong Antarctic stratospheric polar vortices during periods with severe ozone depletion were found to be associated with anomalous positive phases of the SAM and related to changes in tropospheric polar climate.

Especially on climate time scales changes in tropospheric variability are associated with stratospheric variability. In a future climate with increasing greenhouse gas (GHG) concentrations and an expected stratospheric ozone recovery changes in stratospheric temperatures and dynamics will affect the tropospheric climate. However, future climate projections performed with chemistry – climate models which resolve also the stratosphere do not agree on the evolution of stratospheric variability in winter.

Data from the CCMVal SCN-B2d simulation with increasing GHG conditions covering the period 1960-2100 performed with the ECHAM5/MESSy (EMAC-FUB) chemistry-climate model have been used in order to assess the model's ability to reproduce the stratosphere-troposphere-coupling through the analysis of observed and simulated NAM and SAM-patterns for the period from 1960 to 2000. These results have been presented on the II. SHARP Annual Meeting in Karlsruhe, Germany, 25-27 May 2011, and have been summarised in the Bachelor-Thesis of Stefan Metzner (Metzner, 2011).

Combined EOF-analyses of lowpass-filtered winter geopotential heights (gph) on 5 pressure levels have been performed to calculate the annular mode (AM) signatures. Composites of strong and weak polar vortices were associated to AM-indices exceeding on the 10 hPa-level 2 and -3 standard-deviations, respectively, for the Northern Hemisphere (NH), and 1.5 and -2 standard deviations, respectively, for the Southern Hemisphere (SH). Figure 1 shows the obtained vertical profiles of the annular modes for A strong and B weak stratospheric vortex events in the northern (left) and southern (right) hemisphere. NH gph anomalies at 10 hPa propagate downward and reach the surface on average after 30 days for perturbed polar vortex condi-

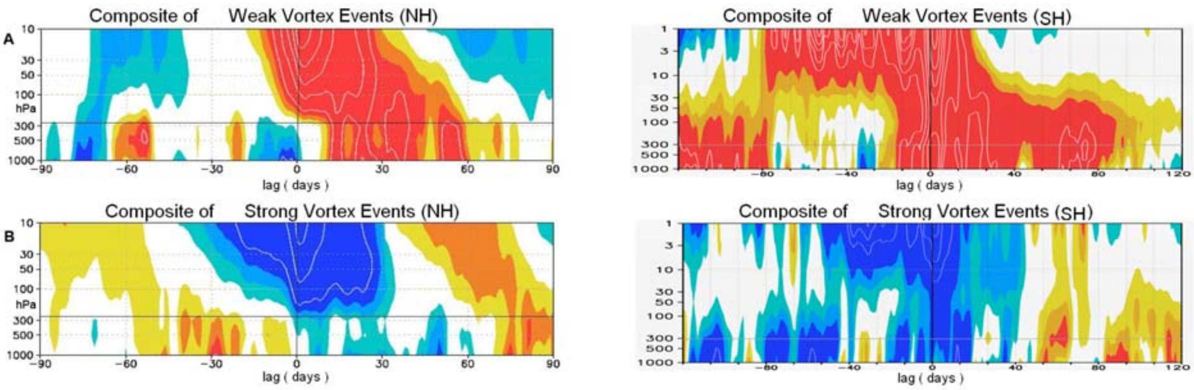


Figure II.1 Composite of standardised AM-indices associated to weak (A) and strong (B) vortex events AM-index on the northern hemisphere (NH) (left) and southern hemisphere (SH) (right).

tions (weak events) and approximately between 1 and 4 weeks after a strong polar vortex event. Weak vortex events associated NAM propagation can reach the surface after maximum 60 days. SAM-downward propagation, associated to strong vortex events, is faster and more apparent than NAM-propagation. The gph-anomalies propagate within maximum 2 weeks from 10 hPa down to the surface. SH weak polar vortex events are less frequent than in the Arctic region. Nevertheless, the time-lag of influence for SAM-index downward propagation associated to SH weak vortex events is up to 80 days. This behaviour is in very good agreement with observed downward propagation of NAM (Baldwin et al., 1999) and SAM (Thompson et al., 2005) indices.

The next step will be to investigate to which extent the dynamical coupling between the stratosphere and the troposphere is affected by changes in the stratosphere, analysing in detail the future (2000-2100) development of the stratospheric northern and southern polar vortices from the SCN-B2d simulation. Special attention will be paid to frequency and intensity of sudden stratospheric warmings and occurrence of weak and strong vortex years. The related NAM/SAM-variability can then be related to changes in tropospheric climate.

Part III: Antarctic climate change and the development of cyclones

In this part the ability of the EMAC-FUB model to simulate the development of the Antarctic climate during the 21st century in the CCMVal SCN-B2d run is addressed. Since the model is able to resolve the middle atmosphere and with an interactive chemistry module included, EMAC-FUB is capable to produce the ozone hole, which is a prominent part of the Antarctic climate change, and also to simulate the recovery of the ozone layer.

As published by Eyring et al. (2010) and by Austin et al. (2010), the simulated ozone hole in EMAC-FUB is smaller than observed and also smaller than simulated by the most part of other CCMVal models. The ozone recovery proceeds to fast, thus, the return year to the ozone values equivalent to 1980 is 2034 in the Southern Hemisphere, while it is estimated to be 2045 by the multi-model mean of the CCMVal models.

In Figure III.1 a decadal trend in Southern Hemisphere ozone concentrations for the years 2000-2099 is presented as a percentaged change to the ozone values of 2000 in a time-height projection. The maximum relative change is seen in the lower springtime stratosphere with values exeeding 30%/decade between 70 and 50 hPa in October due to reduced concentrations of chlorofluorocarbons (CFC’s) in the polar regions, especially in the Antarctic stratosphere, since 2000. The time and the dimension of this maximum are in very good agreement with multi-model results, presented in Son et al., 2009.

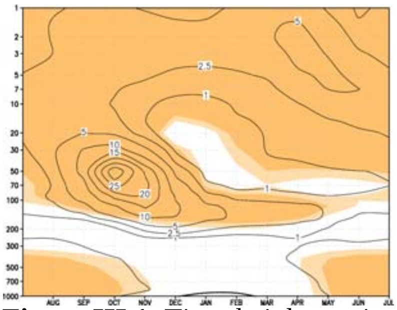


Figure III.1: Time-height section of decadal ozone trend for the years 2000-2099.

Despite the recovery of the Southern Hemisphere springtime ozone, the temperature trend in the most part of the stratosphere and the mesosphere is negative for the 21st century, as expected due to the radiative cooling of the stratosphere caused by increasing greenhouse gas concentrations just beneath the tropopause. The Southern Hemisphere ozone recovery has an effect only on the lower stratospheric temperatures at southern high latitudes.

This is presented in Fig III.2, showing decadal trends in September – November ozone concentrations (left), temperatures (middle) and zonal wind (right) for the years 2000-2099 in a latitude-height projection:

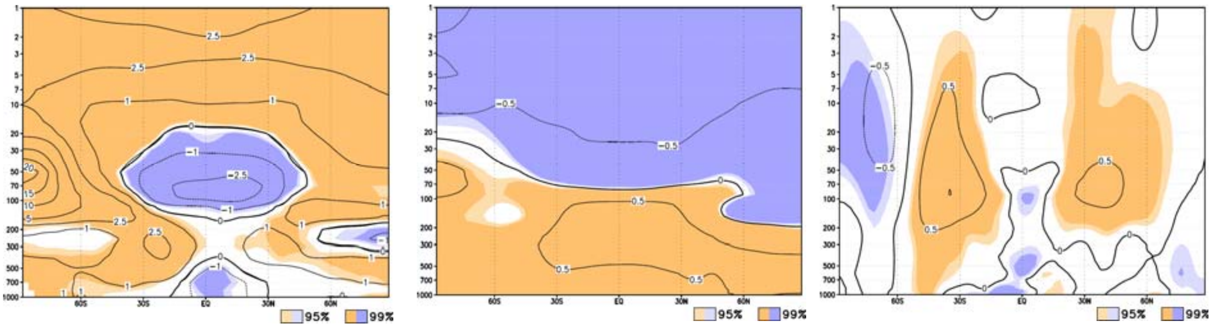


Figure III.2: Latitude-height sections of decadal trends in September – November ozone concentrations in percent (left), temperature (middle) and zonal wind (right) for the years 2000-2099.

While there is a visible positive trend of more than 20%/decade in the lower stratospheric September-November ozone concentrations over the Southern Hemisphere polar cap, slightly negative trends in ozone concentrations are located over the tropics, caused (in all probability) on the one hand by an enhanced Brewer-Dobson circulation, on the other hand by decreasing photolysis rates of ozone due to the cooler tropical stratosphere (Fig III.2 middle).

The zonal wind (Fig III.2 right) decreases by 0.5 ms^{-1}/decade in the direct vicinity of the polar cap as an immediate consequence of polar stratospheric warming. The increase of zonal wind over the mid-latitudes is due to an increasing meridional temperature gradient between the tropics and the mid-to-polar latitudes in the most part of the troposphere and the lower stratosphere.

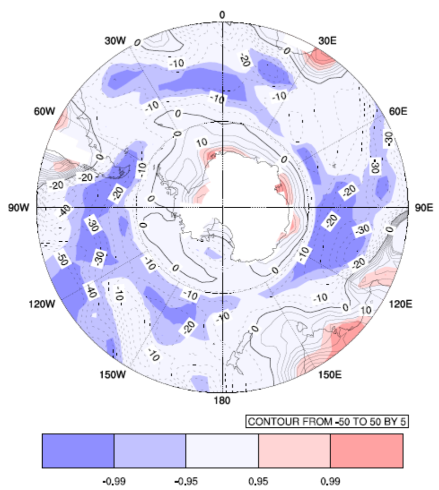


Figure III.3: Difference in cyclone track density in percent between 2080-2099 and 1980-1999

In Figure III.3 percentaged changes in October – April cyclone track density, described by the Laplace of mean sea level pressure (Murray and Simmonds, 1991), are expressed as difference of the years 2080-2099 and 1980-1999, showing a significant increase of cyclonic activity of more than 20% around the Antarctic coast, a slight weakening of the Ross Sea cyclone at 180°W, and a significant decrease of cyclonic activity of about 20 %, with peak values of 40-50% at mid-latitudes, which implies a diminishment by up to 20 cyclones per season.

A direct consequence for the Antarctic continent is an enhancement of the off-coast cyclones, causing increased poleward heat and moisture fluxes, accumulation of moisture over the continent, and increased precipitation.

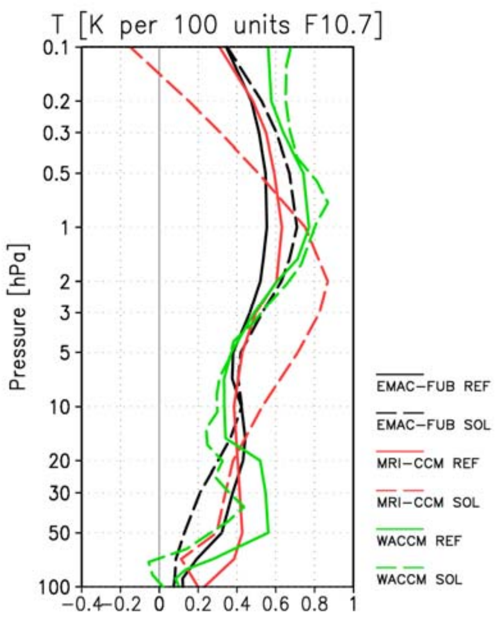
The Antarctic continent itself is experiencing a considerable overall warming during the 21st century. The differences, characteristic for the 20th century, expressed in differential warmig of the Antarctic Peninsula, and cooling of the East Antarctica, are no more present. By taking into account additional (regression) analyses the positive temperature trend and the increase of cyclone track density around the Antarctic coast is most probably attributable to increasing sea surface temperatures, which were prescribed in this experiment.

Part IV: SPARC-SOLARIS simulation with linearly independent forcings

From observations a double peak structure of the tropical ozone and temperature response to 11-year solar variability is known. However, chemistry-climate models still have difficulties to reproduce the observed maximum in the tropical lower stratosphere (SPARC CCMVal, 2010).

It is a matter of debate whether the observed tropical lower stratospheric maxima in the ozone and temperature 11-year solar signal are due to interactions between the 11-year solar irradiance variations and the QBO and ENSO, respectively. The observed tropical winds and the sea surface temperatures are themselves subject to an 11-year solar influence. Using these observed forcings may lead to an aliasing and to a possible amplification of the 11-year solar signal in the tropical lower stratosphere.

In 2010 a transient simulation of the period 1960 to 2005 has been performed, similar to the CCMVal REF-B1 simulation but with linearly independent solar irradiance, QBO and SST data. Linear independence has been achieved by a band-pass filtering of the QBO and the SSTs and sea ice data. Thus, the original QBO period is retained in the tropical winds whereas longer periods are suppressed. The filtered SSTs and sea ice data contain the annual cycle and the typical ENSO time scale but periods longer than seven years have been filtered out. With this simulation the EMAC-FUB model takes part in an international CCM intercomparison coordinated by SPARC SOLARIS (Solar Influence for SPARC) together with the Japanese MRI-CCM and NCAR's WACCM.



The 11-year solar signal in tropical temperature averaged between 25°N and 25°S as obtained by multiple linear regression from the SOLARIS simulations with filtered forcings is shown by the dashed lines in Figure IV.1. For comparison the results from the corresponding REF-B1 simulations (with unfiltered forcings) are shown as solid lines. There is a clear tendency towards a reduced magnitude of the lower stratospheric maximum when the linearly independent forcings are employed.

A similar but weaker tendency is found in the ozone response (not shown). This is an indication for a pure solar origin of the lower stratospheric signal. However, it cannot be ruled out that non-linear interactions of the forcings play a role for the appearance of the signal, since these are not suppressed by the filtering procedure.

Figure IV.1: Profiles of tropical (25°S to 25°N) temperature change due to 11-year solar irradiance variation from three CCMs forced with observed unfiltered (solid) and with filtered QBO and SST data (dashed).

Results from this simulation have been presented at the SCOSTEP STP12 conference in Berlin 2010 (oral presentation "*Comparison of the 11-year solar signal in coordinated SPARC/SOLARIS experiments using filtered forcings*" by A. Kubin, K. Matthes, K. Shibata, K. Kodera and U. Langematz) and at the IUGG conference in Melbourne 2011 (poster: "*The influence of the sea surface temperatures on the appearance of the 11-year solar signal in the Indian Monsoon circulation*" by A. Kubin, U. Langematz and P. Jöckel).

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Eyring,V., M.P. Chipperfield, M.A. Giorgetta, D.E. Kinnison, E. Manzini, K. Matthes, P.A. Newman, S. Pawson, T.G. Sheperd and D. W. Waugh: Overview of the New CCMVal Reference and Sensitivity Simulations in Support of Upcoming Ozone and Climate Assessments and the Planned SPARC CCMVal, SPARC Newsletter, 30, 20-26, 2008.

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Kubin, A.: A model study on the influence of the 11-year solar cycle on the atmosphere, PhD thesis, Institut für Meteorologie, Freie Universität Berlin, 2011.

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Murray, R.J. and I. Simmonds: A numerical scheme for tracking cyclone centres from digital data part I: developement and operation of the scheme, Australian Meteorological Magazine, 39:155–166, 1991.

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Son, S.-W., N. F. Tandon, L. M. Polvani, and D. W. Waugh: Ozone hole and Southern Hemisphere climate change, Geophys. Res. Lett., 36, L15705, 2009.

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List of publications/reports from the project with complete references

Projections of UV radiation changes in the 21st century: impact of ozone recovery and cloud effects

Bais, A. F., K. Tourpali, A. Kazantzidis, H. Akiyoshi, S. Bekki, P. Braesicke, M. P. Chipperfield, M. Dameris, V. Eyring, H. Garny, D. Iachetti, P. Jöckel, **A. Kubin**, **U. Langematz**, E. Mancini, M. Michou, O. Morgenstern, T. Nakamura, P. A. Newman, G. Pitari, D. A. Plummer, E. Rozanov, T. G. Shepherd, K. Shibata, W. Tian, and Y. Yamashita, *Atmos. Chem. Phys. Discuss.*, 11, 10769-10797, 2011.

Solar Effects on Chemistry and Climate Including Ocean Interactions

U. Langematz, **A. Kubin**, C. Brühl, A. J. G. Baumgaertner, U. Cubasch and T. Spangehl, under review, to be published in a book summarizing results of the DFG priority programme CAWSES, 2011.

Climate Change Projections and Stratosphere-Troposphere Interaction

Scaife A. A., T. Spangehl, D. R. Fereday, U. Cubasch, **U. Langematz**, H. Akiyoshi, S. Bekki, P. Braesicke, N. Butchart, M. P. Chipperfield, A. Gettelman, S. C. Hardiman, M. Michou, E. Rozanov and T. G. Shepherd, *Journal of Climate*, accepted, 2011.

The Brewer-Dobson circulation and total ozone from seasonal to decadal time scales

M. Weber, S. Dikty, J. P. Burrows, H. Garny, M. Dameris, **A. Kubin**, **J. Abalichin**, **and U. Langematz**, *Atmos. Chem. Phys. Discuss.*, 11, 13829-13865, 2011.

Scientific Assessment of Ozone Depletion: 2010

WMO (World Meteorological Organization), Global Ozone Monitoring Project – Report No. 52, Geneva, Switzerland, 2011.

Summary of plans for the continuation of the project

(10 lines max)

Within this project another Chemistry-Climate Model (CCM) simulation with the ECHAM5-MESSy (EMAC-FUB) will be conducted as contribution to the new phase of the SPARC-CCMVal initiative of WMO. This simulation will cover the period 1960 to 2100 and it will use an enhanced greenhouse gas scenario other than the formerly used SRES A1B scenario. The input data for this simulation are currently in preparation and the simulation will start as soon as possible.