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Title: **NATHAN – Quantification of Natural Climate Variability in the Atmosphere-Hydrosphere System with Data Constrained Simulations**

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This two year reporting period covers the main research work that was performed within the “Helmholtz-University Young Investigators Group” NATHAN. Thanks to the generous regulations at DKRZ regarding CPU time in 2015 we were able to finish all our planned experiments. Analysis of most experiments has been started (see list of publications) and will continue throughout the next years. A detailed description of the work performed in 2014/2015 is given in the following sections. Table 1 provides an overview of the major computations performed in 2014 and 2015. All simulations were done with NCAR’s Community Earth System Model (CESM, Marsh et al, 2013).

1. Sensitivity studies to investigate the role of solar influence for long-term climate variability

1.1 Influence of Solar Variability

Observational and modeling studies have shown that the impact of solar variability on global climate is important (Gray et al., 2010), but there are different mechanisms (Kodera and Kuroda, 2002; van Loon et al., 2007) by which the Sun affects climate, and they all involve feedbacks between the solar forcing and the atmosphere-ocean system (Matthes et al., 2010; Matthes et al., 2011; Scaife et al., 2013). We investigated the effect of the 11-year solar cycle on climate, using NCAR’s Community Earth System Model (CESM), by comparing simulations with and without varying solar forcing. We particularly examined the influence of the solar forcing on the North Atlantic climate. We found that the experiment including solar variability (“natural”) can simulate a 1–2-year lagged solar/North Atlantic Oscillation relationship, consistent with the observations. Analysis of the experiment without varying solar forcing (“natural solarmean”) revealed a significant quasi-decadal NAO variability mode, internally generated by the coupled ocean-atmosphere system. Comparison of both experiments further suggested that the 11-year solar cycle synchronizes quasi-decadal North Atlantic Oscillation variability intrinsic to the model (Figure 1). The synchronization is consistent with the downward propagation of the solar signal from the stratosphere to the surface (Thiéblemont et al., 2015a).

1.2 Influence of the Quasi-Biennial Oscillation and Varying Sea Surface Temperature on the Stratosphere and Climate Variability (“NoQBO” and “FixedSST”).

To address this question we designed two sensitivity experiments, one without QBO (“noQBO”) and the second experiment were the atmosphere is forced with climatologically varying SSTs from the “natural” experiment performed in 2011.
A first study made use of these 55-year sensitivity experiments to examine the effect of natural variability factors on winter major stratospheric sudden warmings (SSWs) (Hansen et al., 2014). It is demonstrated that the QBO reduces the frequency of major SSWs, while the SST variability increases it. Hansen et al. (2014) further showed that the feedback between the ocean and the atmosphere is necessary to obtain a significant surface response over Europe after SSWs.
In 2014, the “NoQBO” and “FixedSST” experiments were extended from 55 to 145 years in order to improve the statistical representativeness of the results. The analysis of Hansen et al. (2014) has been extended within a Bachelor thesis where the statistically robustness of the results is now significantly improved in particular the tropospheric surface signal (Brieber, 2015).
The extended experiments are currently further analyzed to determine the effect of the QBO and varying SST on the Northern Hemisphere polar vortex. In comparison to the “Natural” experiment, the role of stratosphere-troposphere coupling, in particular the downward wave coupling and the importance of natural and anthropogenic factors is studied (Lubis et al., 2015a, Lubis et al., 2015c).

ID	Year	Time span	Details in Section	Comment
“natural solarmean”	**2013**	1955-2099	1.1	GHGs and ODs fixed to 1960 conditions; no solar variability
“transient solarmean”	**2013/2014**	1955-2099	1.1	no solar variability, observations until 2005, RCP8.5 scenario thereafter
“noQBO”	**2011/2014**	1955-2099	1.2	Same as “natural” but no QBO (i.e. climatological winds in tropical stratosphere)
“fixedSST”	**2011/2014**	1955-2099	1.2	Same as “natural” but fixed SST, using climatological averages from “natural” experiment
“GHG-ODS-2010”	**2014/2015**	1990-2030	2.1	GHG and ODS surface emissions fixed to 2010 levels
“GHG2010-ODS1960”	**2014/2015**	1990-2030	2.1	GHG (ODS) surface emissions fixed to 2010 (1960)
“GHG1960-ODS2010”	**2014/2015**	1990-2030	2.1	GHG (ODS) surface emissions fixed to 1960 (2010)
“GHG2080-ODS1960”	**2015**	2060-2100	2.1	GHGs(ODS) surface emissions fixed to 2080 (1960)
“GHG1960-ODS2080”	**2015**	2060-2100	2.1	GHG (ODS) surface emissions fixed to 1960 (2080)
“natural tendencies”	**2014/2015**	1955-2054	2.2	2^{nd} ensemble for “natural” with extra diagnostic output
“zonal O3”	**2014**	1955-2010	2.2	Same as “natural” but zonally averaged O_3 in radiation calculations
“zonal O3 stratosphere”	**2014/2015**	1955-2005	2.2	Same as “zonalO3” but zonally averaged O_3 only below 2hPa
“RCP8.5 extension”	**2014**	2100-2129	2.3	Extension of an RCP8.5 scenario run with repetitive year 2100 conditions
“sahara afforestation”	**2015**	1955-2004	4	Same as “natural” but assuming afforestation in the Sahara
“australia afforestation”	**2015**	1955-1984	4	Same as “natural” but assuming afforestation in central Australia
“natural”	2011	1955-2099	-	All forcings included except anthropogenic ones: GHGs and ODs fixed to 1960s state

Table 1: Overview on model experiments performed within NATHAN in 2014 and 2015 with CESM (GHG: greenhouse gases, OD: ozone depleting substances, SST: sea surface temperature, CESM: Community Earth System Model).

Both experiments are also currently used to examine the interannual variability of Northern Hemisphere stratospheric vortex breakup. We find that while the SST variability does not seem to play a major role in this springtime transition, the QBO strongly modulates its characteristics and variability (Thiéblemont et al., 2015b).

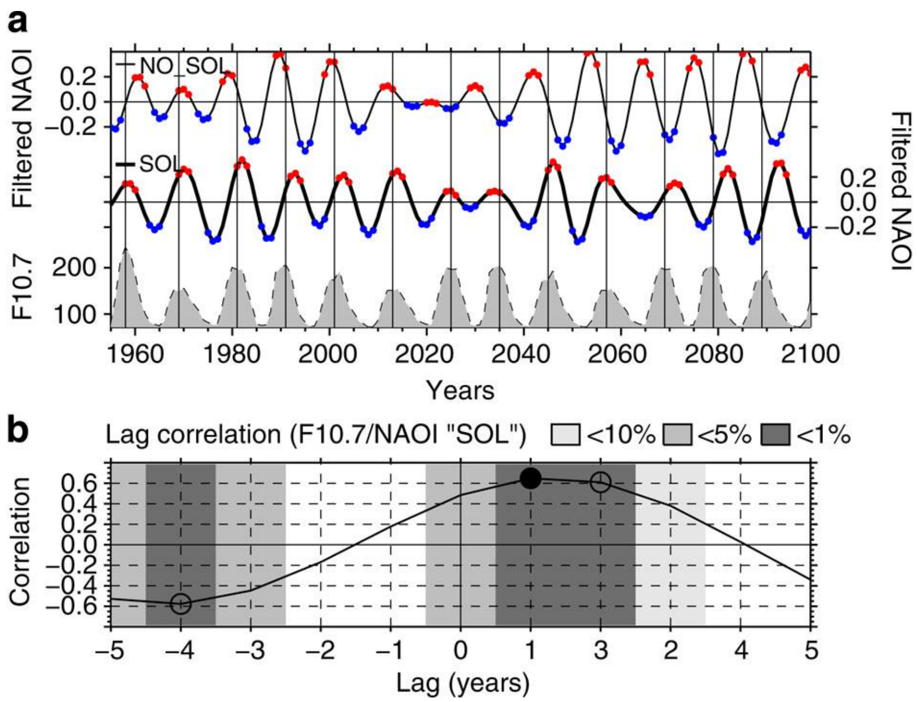

Figure 1: (a) Time series of 9–13-year band-pass filtered NAO index for the NO_SOL ("Natural solarmean", solid thin) and SOL ("Natural", solid thick) experiments, and the F10.7 cm solar radio flux (dashed black). Red and blue dots define the indices used for NAO-based composite differences at lag 0 (see the Methods section). For each solar cycle, maximum are marked by vertical solid lines. (b) Lag correlation between F10.7 cm solar radio flux and NAO index of the SOL experiment. Significance levels are indicated by empty (90%) and filled (95%) circles. Grey shades coloured stripes indicate the likelihood (<10, 5 and 1%) that the correlation coefficient between the filtered NO_SOL NAO and the F10.7 time series is higher than between the filtered SOL NAO and the F10.7 ones. All calculations are shown for DJF. From Thiéblemont et al. (2015a).

2. New Model Runs

2.1 GHG/ODS Timeslice Experiments

In 2014 and 2015, we ran five timeslice simulations (40 years each) with different combinations in prescribed surface emissions of ozone-depleting substances (ODSs) and greenhouse gases (GHGs) as described in Table 1. We set the timeslices to 2010 and 2080 to cover the ozone hole period and the recovered ozone hole state, respectively.
The combination of these timeslice simulations are used to understand the effects of ozone depletion/recovery and future climate change on the downward wave coupling (DWC) in the southern and northern hemisphere. The results show that increased DWC in the southern hemisphere maximizes around the period of the maximum stratospheric ozone depletion due to increased ODS concentration, while in the northern hemisphere the significant changes in DWC occur mainly in the future over the last few decades due to high GHGs (Lubis et al., 2015d). In addition, some of the timeslice experiments are used to investigate the vertical coupling of the stratosphere and mesosphere-lower-thermosphere (MLT) system during the period of the Antarctic ozone hole. The results show that both dynamical and radiative processes (induced by decreased ODSs and increased GHGs concentrations) are important for the MLT responses to the Antarctic ozone hole (Lubis et al., 2015b).

2.2 Zonally Symmetric and Asymmetric Ozone Experiments

In 2014 and 2015, we ran three experiments in a "Natural" (see Table 1) configuration with different representations of ozone fields in the radiation code. The first experiment ("Natural tendencies") is exactly the same as the "Natural" experiment except for additional diagnostic output necessary for the analysis described below. The other two experiments used zonally averaged ozone fields in the radiative transfer calculations, and only differ in the number of vertical levels where this method is applied ("zonal O3 stratosphere" and "zonal O3" experiment, respectively). This set of experiments is used to examine the radiative effects of ozone waves on the seasonal cycle of the polar vortex and on extratropical QBO signals. Comparison between the "Natural tendencies" and the "zonal O3 stratosphere" experiment show that the radiative effects of ozone waves are found during the westerly phase QBO conditions from November to December. These effects need to accumulate over the winter to influence the wave fluxes and correspondingly the polar vortex in spring (Silverman et al., 2015, in preparation).

The 3DO3 experiment is also used to study the impact of DWC on the variability of winter and springtime Arctic ozone levels. The results indicate that multiple DWC events during NH midwinter contribute to springtime ozone loss via a weakening of the residual circulation, which leads to weakened ozone transport, a lowering of Arctic temperatures, a strengthening of the polar vortex, and thus a delayed final warming (Lubis et al., 2015d, in preparation).

2.3. Extended RCP8.5 Experiment

In 2014, we performed one extended RCP8.5 scenario experiment where the anthropogenic GHGs and ODSs were kept constant at the year 2100 conditions. This experiment is used to estimate the influence of future anthropogenic forcing levels (i.e., future ozone recovery and global warming) on the variability of DWC between the stratosphere and the troposphere in the southern and northern hemisphere. From this experiment we find no significant changes in DWC between the stratosphere and troposphere in both hemisphere, which might be related to the competing effects on the mean states between increasing greenhouse-gas concentrations and ozone recovery.

2.4 Test Simulations

A total of approximately 50,000 CPUhs were used for test simulations with CESM1-WACCM. The first test run (30 years) used an atmosphere-only configuration of CESM with interactive chemistry, using the reference solar spectrum RSSV1-ATLAS3 (Thuillier et al., 2004) as spectral solar irradiance forcing. The standard setting for CESM1 is to employ the spectral irradiance forcing of Wang et al. (2005) or derivatives of this spectrum. The motivation for this test is the analysis of uncertainties of solar induced climate variability which is the focus of the BMBF-funded project ROMIC-SOLIC (FKZ: 01 LG 1219A).

A second test included a 55-year long fully-coupled specified chemistry run using a GHG forcing input, produced from output of our "Natural" simulation. The setting of the specified chemistry (SC) run is based on a SC-WACCM configuration (Smith et al., 2014) and adapted to the design of our Natural experiment. The specified chemistry run will be used to estimate the relative importance of stratospheric chemistry on tropospheric dynamics, and is part of the PhD work of S. Haase.

3. Climate Engineering Experiments

The CESM model is applied to investigate the impact of large-scale afforestation on the global and the local climate. The irrigation of the Sahara and the Australian Outback is realized by the implementation of an interactive irrigation scheme in the Community Land Model (CLM4) which is part of CESM. A comparison between the "natural" and the "sahara afforestation" shows an intensification and extension of the West African Monsoon (Figure 2). The details of the physical mechanisms for this modification are still under investigation, and preliminary results reveal complex interactions between the local circulation, moisture advection, cloudiness, and the atmospheric radiation budget (Kemena et al., 2015).
Besides the strong regional response to the afforested Sahara with an intensification of the West African monsoon, global teleconnection patterns with an effect on ENSO occur that are currently

under investigation. In comparison to the “sahara afforestation” experiment the afforestation of the Australian Outback shows less influences on global and local precipitation patterns (not shown).

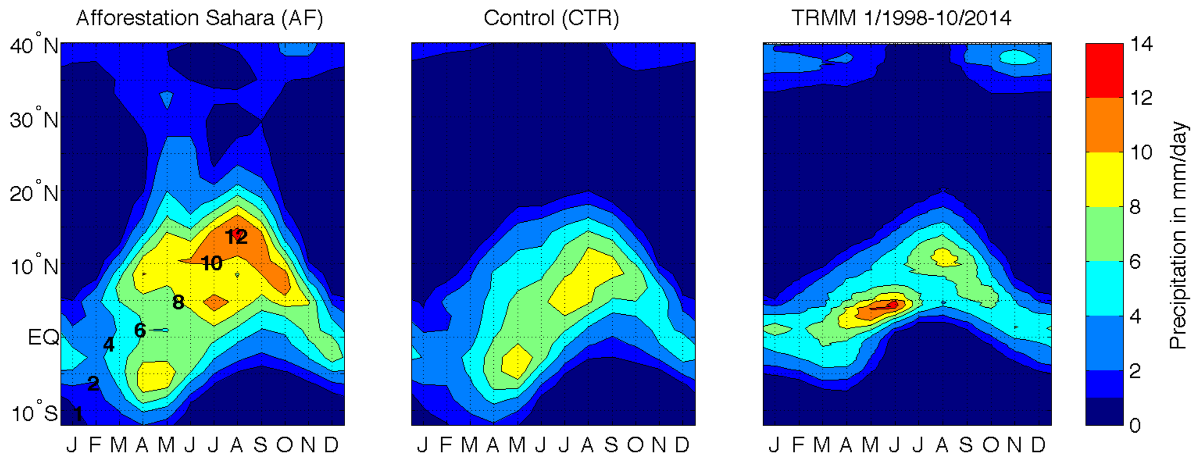

Figure 2: Seasonal cycle of zonally averaged precipitation from 10°W to 10°E for the “sahara afforestation” experiment(left), the “natural solarmean” experiment with fixed CO2 concentration (middle) and diagnosed from observations of the Tropical Rain Measuring Measuring Mission (TRMM) observations (right) in mm/day. Kemena et al. (2015; in preparation).

4. Data Assimilation Experiments

Approximately 300.000 CPU hours were used to test the data assimilation system DART-WACCM, i.e. running the high-top atmosphere component of the CESM (WACCM) in standalone mode while assimilating data using the Data Assimilation Research Testbed (DART, Anderson, 2001; Anderson et al., 2009), a community software facility for ensemble data assimilation. A beta version of the code interface between WACCM and DART was introduced in Pedatella et al. (2013), and shared with our research group in early 2014 in exchange for further testing of the code. We ran several so-called Observing System Simulation Experiments (OSSEs), wherein the model is run once to generate synthetic “observations”, which are then assimilated back into an N-member ensemble of model simulations, in order to test how well the assimilation system can recover the true state of the atmosphere. Individual tests varied in length from one to 31 simulation days, always with an ensemble of 40 WACCM simulations. The tests identified several difficulties associated with data assimilation into highly complex, high-top models, most notably that vertical localization of observations has to be chosen very judiciously in order to avoid generating spurious gravity waves at high model levels, where there are few observations to constrain the model variable fields. These tests led to significant code improvements of the DART-WACCM interface by our colleagues at the National Center for Atmospheric Research (NCAR) in the United States, and established a framework for the observation of real observations into WACCM, which is currently ongoing (Neef et al., 2015).

4. CPU Time Summary

Section 1 (Solar radiation sensitivity experiments):	310 000 CPUh
Section 2.1 (Time slice experiments):	170 000 CPUh
Section 2.2 (Zonal O3 experiments):	265 000 CPUh
Section 2.3 (RCP8.5 extension):	30 000 CPUh
Section 2.4 (Test runs):	46 000 CPUh
Section 3 (Climate engineering runs):	63 000 CPUh
Other (Testing, data assimilation experiments)	425 000 CPUh
Expired resources	100 000 CPUh
SUM	**1 410 000 CPUh**

Publications within NATHAN 2014/2015:

Note, not all publications are explicitely mentioned above (only those highlighted in black), but all publications use model experiments performed at DRKZ in 2014/2015.

Adolphi, F., Muscheler, R., Svensson, A., Aldahan, A., Possnert, G., Beer, J., Sjolte, J., Björck, S., Matthes, K. und Thieblemont, R. (2014) Persistent link between solar activity and Greenland climate during the Last Glacial Maximum, Nature Geoscience, 7 (9). pp. 662-666. DOI 10.1038/ngeo2225.

Brieber, A., 2015: Wie robust ist der Einfluss von QBO und variable SSTs auf Plötzliche Stratosphärenerwärmunen, Bachelor thesis at the Christian-Albrechts Universität zu Kiel.

Hansen, F., (2015), The Importance of Natural and Anthropogenic Factors for the Coupling Between the Stratosphere and the Troposphere, PhD thesis at Christian-Albrechts Universität zu Kiel.

Hansen, F., Matthes, K., Petrick, C. and Wang, W. (2014) The influence of natural and anthropogenic factors on major stratospheric sudden warmings Journal of Geophysical Research - Atmospheres, 119 (13). pp. 8117-8136. DOI 10.1002/2013JD021397.

Lubis, S., K. Matthes, N. Omrani, N. Harnik, and S. Wahl (2015a), Influence of the QBO and Atmosphere-Ocean Interactions on Downward Wave Coupling in the Northern Hemisphere, J. Atmos. Sci., under review.

Lubis, S.W., N-E. Omrani, K. Matthes, and S. Wahl. (2015b): Impact of Antarctic Ozone Hole on the Vertical Coupling of the Stratosphere-Mesosphere-Lower Thermosphere System, J. Atmos. Sci., under review.

Lubis, S.W., K. Matthes, N-E. Omrani, N. Harnik, and S. Wahl. (2015c): Effects of Stratospheric Climate Change on Downward Wave Coupling in the Northern and Southern Hemisphere, to be submitted.

Lubis, S.W., K. Matthes, V. Silverman, N. Harnik, N-E. Omrani, and S. Wahl. (2015d): On the Control of Stratospheric Ozone in the Arctic by Downward Planetary Wave Coupling, in preparation.

Neef, L., K. Matthes, K. Reader, and J. Anderson (2015), Assimilation of Earth Rotation Parameter observations to constrain and evaluate atmospheric models, to be submitted to JGR-Atmosphere

Offermann, D., O. Goussev, R. Koppmann, K. Matthes, H. Schmidt, W. Steinbrecht, and J. Wintel (2015): A case study of multi-annual temperature oscillations in the atmosphere: Preliminary results in Middle Europe, special issue of Journal of Atmospheric and Solar-Terrestrial Physics, doi:10.1016/j.jastp.2015.10.003, in press.

Petrick, C., Dobslaw, H., Bergmann-Wolf, I., Schön, N., Matthes, K. und Thomas, M. (2014) Low-frequency ocean bottom pressure variations in the North Pacific in response to time-variable surface winds, Journal of Geophysical Research - Oceans, 119 (8). pp. 5190-5202. DOI 10.1002/2013JC009635.

Silverman, V., N. Harnik, K. Matthes, S. W. Lubis, and S. Wahl. (2015): Radiative effects of ozone waves on polar vortex seasonal cycle and extratropical QBO signals, in preparation.

Thiéblemont R., K. Matthes, N.-O. Omrani, K. Kodera and F. Hansen (2015a), Solar forcing synchronizes decadal North Atlantic climate variability, Nature Communications, 6, 8268, doi:10.1038/ncomms9268.

Thiéblemont R., K. Matthes, Y. Orsolini and N. Huret (2015b), Frozen-In Anticyclones representation in CESM1-WACCM, in preparation.

Wang, W., K. Matthes, T. Schmidt, 2015: Quantifying contributions to the recent temperature variability in the tropical tropopause layer, Atmos. Chem. Phys., 15, 5815–5826, doi:10.5194/acp-15-5815-2015.

Wuke, W. (2015), The Tropical Tropopause Layer – Detailed Thermal Structure, Decadal Variability and Recent Trends, PhD thesis at Christian-Albrechts Universität zu Kiel.

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