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Research proposal for GEOSIM scholar Tobias Spiegl

Solar cycle effects on climate and their modulation by decreasing solar activity and climate change

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Abstract

Is the sun passing into a period of lower magnetic activity, and will this decrease in solar activity lead to a cooling of Earth's climate in the near future, thus counteracting the greenhouse gas (GHG) induced global warming of the atmosphere? These questions are examples of an on-going public debate motivated by the recent, low and longer lasting minimum of the 11-year solar cycle 23 in 2008. The discussion has revealed the urgent need to better understand and identify on a scientific basis the respective roles of natural climate forcing by solar variability and of anthropogenic forcing by increasing GHG concentrations for the future development of climate. It is therefore the goal of the project to quantify the effects of 11-year solar variability on climate, in particular the role of long-term changes of solar activity for climate and weather in a changing atmosphere with continuously increasing GHG concentrations. Using a state-of-the-art chemistry-climate model with coupled ocean the project will provide new insight in the relevant processes responsible for a solar signature in climate, and disentangle the respective contributions of chemistry-climate interactions in the stratosphere ("top-down" or UV effect) and, in particular, of atmosphere-ocean interactions ("bottom-up" or TSI effect). Specific multi-decadal simulations will be carried out to investigate the modulation of the solar effect on climate by increasing GHG concentrations, and to quantify the impact of a long-term decrease in solar activity on global and regional climate.

Objective and problem

The project aims to quantify the effect of 11-year solar variability on climate, in particular the role of long-term changes of solar activity for climate and weather in a changing atmosphere with continuously increasing greenhouse gas concentrations.

The objectives are

- To improve the basic understanding of the mechanisms and processes leading to the solar signal in the troposphere, in particular the specific roles of chemistry-climate interactions in the stratosphere ("top-down" or UV effect) and of atmosphere-ocean interactions ("bottom-up" or TSI effect) for the solar contribution to climate change
- To assess the solar signal in a future climate with increased greenhouse concentrations
- To assess the effects of a potential future decrease of solar activity on the solar signal in the atmosphere and the ocean, in particular its effects on regional weather and climate.

'Top-down' versus 'bottom-up' solar effect?

One scientific objective is to identify the potential contribution of long-term solar activity and climate change to the resulting solar signature in climate and weather. This aim can only be achieved if the basic understanding of the underlying mechanisms leading to the observed solar signal in the atmosphere and its effects on climate is improved. An open question is still the respective roles of both chemistry-climate interactions in the stratosphere (‘top-down effect’) and the feedback between the atmosphere and the oceans (‘bottom-up effect’) on the long time scale. In spite of a number of observational analyses and studies with global climate and chemistry-climate models (CCMs) the magnitude of the tropospheric solar signal is still highly uncertain (e.g., Baldwin and Dunkerton, 2005; Gray et al., 2010). The stratospheric observational data series is short, and the associated processes are not very well incorporated in all atmospheric models, leading to a large spread in model results (Austin et al., 2008; SPARC CCMVal, 2010). The relevance of the stratospheric ‘UV-effect’ (variations in solar ultraviolet-radiation) compared to the tropospheric ‘TSI-effect’ (total solar irradiance variations that effect the surface and troposphere) is still discussed (Meehl et al., 2003; van Loon, 2007). An additive effect of the two mechanisms was found for the first time by Meehl et al. (2009) in a CCM and a general circulation model (GCM), both with coupled ocean module; however the magnitude of the observed solar signal could not be reproduced. Therefore, the first goal of SOMOSA is to systematically investigate the relative role of both suggested process chains using two state-of-the-art chemistry climate models (CCMs) that involve parameterizations of all necessary processes, i.e., model systems that allow for both a complete representation of relevant middle atmosphere processes (e.g., gravity wave dissipation, improved solar absorption, interactive chemistry) and the interaction of the atmosphere with the ocean. We will investigate the role of atmosphere-ocean interactions by comparing the oceanic and tropospheric responses to external solar variability by performing transient atmosphere-only and atmosphere-ocean simulations. This work package will deliver new insight in the mechanisms leading to the tropospheric solar signal and is the pre-requisite for the investigation of future changes of the solar signal.

Solar signal in a changing climate?

Solar activity varies on different time scales, from short-term solar storms to centennial variations. A prominent example of solar variability is the 11-year solar cycle that constitutes an important component of natural climate variability. Observational and model studies find a high correlation of tropospheric climate variability patterns, like the NAO- and Arctic Oscillation- (AO) indices, with the 11-year solar cycle, with stronger stratospheric polar vortices and stronger tropospheric cyclone activity over the North Atlantic during solar maximum (Kodera, 2002; Matthes et al., 2006). With continuously increasing greenhouse concentrations (see e.g., IPCC, 2007) the question arises if and how the decadal solar impact in the stratosphere and surface climate and weather will change in the future.

Starting with Kodera and Kuroda (2002) a number of publications showed that the initial radiative solar signal - due to absorption of UV irradiance by ozone and molecular oxygen in the upper stratosphere and lower mesosphere - is dynamically transferred downward and poleward in the winter season by the interaction of planetary waves and the climatological background circulation. This implies that the solar signal reaching the troposphere might be affected by both changes in the planetary wave driving from the troposphere and a change in the stratospheric background circulation. In a future climate, both factors may change: the planetary wave driving from the troposphere may increase due to the GHG induced warming of the troposphere and oceans, as well as the stratospheric background circulation with a more stable polar vortex due to the GHG induced stratospheric cooling. This implies that the solar signal reaching the troposphere and Earth’s surface might be affected, too. Kodera et al. (2008) suggested that the GHG induced stratospheric cooling effect manifests itself in the troposphere through a non-linear interaction with the solar cycle. Figure 1 shows the solar signature in the mid- troposphere geopotential height of the northern hemisphere in winter for the past (years 1960-2000, left) and the future (years 2060-2099, right) from a transient simulation with the ECHAM5-MESSY Atmospheric Chemistry (EMAC) chemistry-climate model (CCM) performed at FUB (Langematz et al., 2012a; Kubin, personal communication).

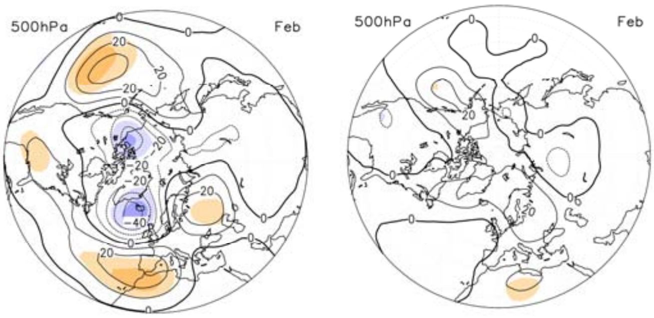

Figure 1: The February 11-year solar signal in geopotential height in m per 100 units F10.7 cm solar radio flux from 20°N to 90°N at 500 hPa in the past (1960-2005, left), and the future (2055-2100, right). Light (heavy) shading denotes statistical significance at the 95% (99%)-level.

The well-known change towards the positive phase of the Northern Annular Mode with increasing solar activity seems to vanish in the future. This result implies a decreasing contribution of solar variability to climate variability in the future. However, as shown in the Chemistry Climate Validation CCM intercomparison (SPARC CCMVal, 2010) the dynamical variability in current CCMs varies considerably. Particularly the models do not agree in the degree of the future change in northern winter dynamics with some models simulating more sudden stratospheric warmings (SSWs) in the future, while other models do not see an increase in the SSW occurrence (e.g. McLandress and Shepherd, 2009; Mitchell et al., 2012). There are also indications that future simulations of CCMs differ from similar simulations with atmosphere-ocean climate models (AOGCMs) performed within the CMIP5 model intercomparison for the upcoming IPCC assessment. In contrast to the CCMs, AOGCMs tend to show an increase in future SSW occurrence (e.g. Huebener et al., 2007; Langematz et al., 2012b). It is the goal of SOMOSA to provide an assessment of the solar effect on climate in a future climate by making use of two improved CCMs that include state-of-the-art parameterizations of the relevant processes affecting the solar signal. The CCMs are coupled to interactive ocean modules hence allowing us to take the direct effects of the ocean response to total solar irradiance (TSI) variations into account. Coordinated transient and supporting sensitivity simulations will be performed using different GHG scenarios and the same solar cycle variability to systematically analyze the dependence of the solar climate effect on the GHG concentration.

Long-term solar activity change?

Another reason for a potential future change of the atmospheric solar signal is changes in solar activity itself. The periodic 11-year oscillations in solar forcing vary in amplitude on a longer time scale and might cause stratospheric temperature and dynamical changes that contribute to tropospheric climate change within the coming decades. A recent analysis of the cosmogenic ^{10}Be abundances in the GRIP ice core from Greenland revealed that the current grand maximum of solar activity that has existed for at least the last eight cycles, is expected to end within the next three decades (Abreu et al., 2008). The authors predict a decline in solar activity within the next two or three cycles. Similarly, de Jager and Duhau (2009), using a dynamical-statistical model to predict variations of the solar internal dynamo, predicted the beginning of a period of lower solar activity following the next maximum around 2014. This episode of low-to-moderate solar activity is assumed to last for at least one Gleissberg cycle (60 to 100 years). Lockwood (2010) found that average solar activity has declined rapidly since 1985 and cosmogenic isotopes suggest an 8% chance of a return to Maunder minimum conditions within the next 50 years. The quantification of the implications of such a projected decrease in solar forcing is of ultimate importance, given the on-going public discussion of the role of carbon dioxide emissions for global warming (e.g., SPIEGEL-online on February 8, 2012), and the possible role a cooling due to decreasing solar activity could be ascribed to.

Surface climate change during the Maunder Minimum, a period with low solar activity in the past (~1615-1745), has been documented in a number of historical reconstructions from proxy data such as tree rings or ice cores. Negative temperature anomalies reached 0.6 K in the annual mean compared to the first half of the 20th century (e.g., Esper et al., 2002) and the winters and springs in continental western Europe were cold and dry with temperatures locally reduced by 1–1.5 K (e.g., Pfister, 1992). Wanner et al. (1995) showed that during that period blockings over north-west Europe were quite frequent in winter, leading to southward outbreaks of cold, continental air, corresponding to a low North Atlantic Oscillation (NAO) index (e.g., Appenzeller et al., 1998). Motivated by the recent decline in solar activity and several cold winters in the UK, Lockwood et al. (2011) find that cold winter excursions from the hemispheric temperature trend occur more commonly in the UK during low solar activity, consistent with the solar influence on the occurrence of persistent blocking events in the eastern Atlantic. They conclude that because of the connections between solar activity and regional temperature anomalies, despite hemispheric warming, Europe could experience more frequent cold winters in the near future than during recent decades. These results are consistent with a recent model study of Ineson et al. (2011) for solar minimum conditions. The conclusions on the surface climate impact of solar activity trends from historical reconstructions could partly be reproduced in model simulations (e.g. Cubasch et al., 1997; Rind et al., 1999). A General Circulation Model (GCM) simulation with prescribed changes in solar UV irradiance, stratospheric ozone and carbon dioxide concentrations found similar temperature and precipitation changes during Maunder Minimum, with a more negative NAO index (Langematz et al., 2005). However, existing model simulations suffer from simplifications in the included parameterizations (e.g., no spectral radiation scheme), missing coupling with ocean models, or too low model tops (e.g., at 10 hPa, without resolving the stratosphere). It is the goal of SOMOSA to simulate and quantify the solar signature in climate parameters for a decrease in solar activity using two state-of-the-art CCMs that include the relevant physical and chemical processes and are coupled to ocean models. Updated estimates of potential spectral reductions in solar irradiance as well as idealized reductions in solar irradiance will be prescribed to derive the potential range of solar signal change.

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Research activities

In SOMOSA multi-decadal simulation will be performed and analysed with:

- **EMAC**

  The ECHAM5-MESSy Atmospheric Chemistry (EMAC) CCM is based on the ECHAM5 general circulation model developed at Max-Planck-Institute (MPI) for Meteorology (Röckner et al., 2006) and has been extended to a modular CCM at MPI for Chemistry (Jöckel et al., 2006). EMAC has been locally implemented at FUB and is successfully applied in different projects. EMAC is specifically qualified for the goals of SOMOSA as EMAC has been extended by a short-wave radiation scheme with improved spectral resolution in the ultraviolet (UV) part of the solar spectrum (Nissen et al., 2007). The scheme is essential to capture the spectral dependence of solar irradiance variations over the 11-year solar cycle in the UV. EMAC includes a complex chemistry module (Sander et al., 2005) which is essential to capture the potential response of stratospheric composition (e.g. ozone, water vapour) to solar activity changes. The chemistry module can also be turned off to use prescribed idealised composition fields. EMAC can be run in different model configurations. In SOMOSA we plan specific simulations with a high-top (e.g. L39, model upper lid at 0.01 hPa, ~80 km) and a low-top (L19, model upper lid at 10 hPa, ~30 km) to examine the role of the stratospheric model resolution and vertical extension on the tropospheric results. EMAC is available as atmosphere-ocean CCM (coupled to the MPI-OM ocean module, Jungclaus et al., 2006), hence allowing for studying the feedback of the ocean to solar activity changes, which is essential on the long-term time scale.

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