2014 ISSI (Bern) call for international teams
Research domain: Earth sciences using space data

Scenarios of future solar activity for climate modelling

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Summary

Model simulations of 21st century climate undertaken by the IPCC suggest that the recently observed decline in solar activity may affect projected antropogenic warming scenarios. Although the solar impact is likely to be small, large uncertainties remain in projected levels of solar forcing because of the lack of realistic scenarios. The latest assessment report of the IPCC has highlighted a need for having better projections of future climate change up to 2100, including more realistic forecasts of solar activity on multi-decadal time scales.

The level of solar activity on multi-decadal time-scales cannot be predicted in a strict sense. However, assessments of possible future scenarios are possible, though challenging. Reconstructions over the last millennia can be used to constrain future variations. Our present understanding of the solar dynamo may bring in additional constraints. Finally, various statistical tools are now at our disposal for building scenarios.

This multidisciplinary team precisely aims at answering this need for meaningful scenarios that are of direct use to climate modellers. The team will bring together 10 experts (including two young scientists) in solar activity reconstructions, in solar dynamo models, in climate modelling with the use of solar radiative and particle inputs (with a particular focus on the middle atmosphere), and in statistical analysis. Three 3-day meetings are foreseen.

Our prime output will be a data set with a series of realistic scenarios of the level of solar activity 500 years ahead, with a special emphasis on the 2100 horizon for the SPARC-CCMI (Chemistry-Climate Model Intercomparison) and CMIP6 (Coupled Model Intercomparison Project) climate model experiments. This team will consider multi-decadal and centennial time-scales, not the actual solar cycle. A review paper will accompany this data set.

1 Rationale

This proposal addresses a challenging and multidisciplinary problem that has recently come under the spotlight: what is the contribution of solar variability to future climate change? This problem requires: 1) a good understanding of past solar activity for making scenarios of future solar forcing, 2) a strong interaction with the climate modelling community in order to determine whether and how realistic scenarios of solar forcing can be included in present modelling efforts, and 3) good expertise in statistical methods for building such scenarios. Here, our definition of a scenario[1] will be that of the IPCC, namely *a plausible description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships* [Nakicenovic and Swart, 2000].

During the 20th century, solar activity has increased in magnitude to a so-called grand maximum [Usoskin, 2013]. This high level of solar activity now seems to be followed by a state of low activity that is exceptional since the first satellite observations became available. The special state of the Sun is by itself a topic of major interest. Also interesting is whether solar activity is likely to reduce further and whether this could have a significant impact on climate. The latest assessment report of working group 1 of the IPCC [Stocker and Qin, 2014] has precisely highlighted the need for improving climate reconstructions for the 21st century by including more realistic contributions from natural forcings.

Although the contribution of solar forcing to recent global warming is most likely small (as to compared to anthropogenic contributions), large uncertainties in the magnitude of the former contribute to the uncertainty of the global picture. Present model simulations run under the CMIP5 (Coupled Model Intercomparison Project - Phase 5, `http://cmip-pcmdi.llnl.gov/cmip5/`) project predict global temperature increases of the order of 1-3.5 K for 2100, but do not include uncertainties in future levels of natural forcings. Nor do they include realistic scenarios of solar activity, since in most runs the levels essentially reproduce those observed during the last solar cycles.

This growing interest for better scenarios of solar forcing has recently lead to a series of studies [Lockwood, 2011, Anet et al., 2013, Hind and Moberg, 2013, Steinhilber and Beer, 2013] wherein changes in temperature and in solar radiation on centennial timescales are used to constrain the Sun's impact on climate, and make climate projections with different levels of solar activity. These activities have been fueled by the recent low level of solar activity, which has considerably broadened the range of possible levels of solar activity [Jones et al., 2012, Meehl et al., 2013]. Present simulations suggest that a Sun in a quiet Maunder-like state of low activity would most likely offset global temperature projections for 2100 by -0.1 K. However, because of uncertainties in future solar irradiance variations, and in the description of solar forcing in climate models, much larger excursions cannot totally be ruled out (possibly mediated by regional effects).

There are two important challenges here. One is to improve the description of the solar forcing in climate models through the proper inclusion of ozone feedback in atmospheric chemistry, the ocean-atmosphere (bottom-up) coupling, but also the role of energetic particles [Gray et al., 2010]. Most of the research on these issues is today coordinated by various international initiatives, in which several of the team members are actively involved. We do not aim here at addressing them here.

The second important challenge is the making of scenarios of future solar activity, which is at the heart of this proposal. Realistic scenarios that go beyond simple *what-if* analyses can be built only by looking into the past, hence the attention paid to reconstructions of past activity based on solar proxies. The main proxies of interest are the sunspot number (going back by about 400 years), and the cosmogenic isotopes ^{14}C (about 14'000 years) and ^{10}Be (about 100'000 years). The making of these proxies, however, is still a topic of ongoing research, which requires careful elimination of other natural contributions [Steinhilber et al., 2012].

Let us stress that we shall focus on multi-decadal and centennial time-scales, avoiding the solar 11-year Schwabe cycle. The latter is of great interest for space weather applications [Pesnell, 2012] but its prediction horizon is limited to about 2 cycles because of the properties of the solar dynamo [Charbonneau, 2010]. The making of long-term projections is a completely different problem, which

[1] Notice the difference between *scenario* and *prediction*: the latter is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future.

has not received wide attention until very recently. Indeed, a fierce debate around the existence of periodicities in an otherwise randomly fluctuating solar signal has recently cast a sharp spotlight on it [Charbonneau, 2013]. A critical assessment of the origin of such deterministic behaviour, if significant, is clearly beyond the scope of this proposal. Such an apparent lack of understanding, however, does not preclude the making of scenarios by using advanced time series analysis techniques. This is where proper solar proxies become crucial.

All solar proxies by definition provide a reductionist view of solar variability, and cannot properly describe the multiple facets of solar radiative and particular impacts on the various atmospheric layers. The climate impact of sporadic solar protons events is likely to be small [Jackman et al., 2009]. However, although their timing is unpredictable, their occurrence rate is modulated by the level of solar activity, and hence their accumulated fluence may eventually be expressed in terms of solar proxies. Other energetic particles, such as auroral and radiation belt electrons, however, do have a lasting impact [Verronen et al., 2013]. These particle fluxes are essentially driven by the conditions of the solar wind and are usually specified by means of geomagnetic proxies (such as the Ap index) they are strongly correlated with. Likewise, the impact of UV variability is known play a significant role in the so-called top-down mechanism [Ermolli et al., 2013] but is still ignored in many models.

Today, the state of the art in multi-decadal projections with solar inputs is represented by the CMIP5 project, whose results show important inter model differences. Two outstanding questions are the proper description of the top-down forcing via the impact of solar UV variability on the stratosphere, and the description of NOx and HOx production by charged particle fluxes, which are parameterized by geomagnetic proxies. In the context of scenario making, the important issue is the design of proxies that properly describe the solar input, while also allowing for meaningful reconstructions in the past, so that at least some forecast to be made. The Total Solar Irradiance (TSI) is a prime choice because of its historical importance for climate models, and its convenient correlation with cosmogenic proxies. Much more challenging is the UV forcing because large uncertainties in present observations [Lean and DeLand, 2012, Ermolli et al., 2013] cast doubts on the levels that may arise during Maunder-like periods of low activity. Likewise, there are important uncertainties in the long-term evolution of energetic particle fluxes.

At this stage, perspectives for making meaningful scenarios may look dull, but they are not. Indeed, there is room left for improvement along the following directions:

- Reconstructions of past solar activity are continuously improving, which gives a strong incentive for considering the most recent data. In particular, a new reconstruction of the ^{10}Be proxy is about to be issued by Jürg Beer (a team member). ISSI team 233 on "Long-term Reconstruction of Solar and Solar Wind Parameters" (lead by L. Svalgaard) will release improved reconstructions of solar wind parameters, which are important for specifying energetic particle fluxes.
- Most studies of the impacts of solar variability on future climate tend to concentrate on one type of solar forcing only, whereas all forcings are strongly correlated. This affects the quality of the climate projections because the uncertainty on the combined effect of all forcings is lower than what the sum of independent forcings would give.
- The question of whether solar variability on multi-decadal time scales is truly stochastic or partly deterministic is unsettled. Clearly, the answer to that question will strongly impact our capacity of forecasting future levels.
- Likewise, there are many possible strategies for building scenarios of future variability: probabilistic, non-probabilistic, etc. There remains a big issue in building scenarios that properly incorporates our present understanding of solar variability while being meaningful for climate models.

2 Objectives and tasks for building future scenarios

The rationale above sets the scene: producing a set of plausible scenaria of the impact of natural forcings on future climate change is a timely and highly important issue, but also a challenging one. Many aspects are already being investigated by initiatives such as CMIP, SOLARIS-HEPPA (Solar Influences for SPARC - High Energy Particle Precipitation in the Atmosphere, http://solarisheppa.geomar.de/solarisheppa/), PAGES (Past Global Changes, http://www.pages-igbp.org, CCMI (Chemistry-Climate Model Initiative, http://http://www.met.reading.ac.uk/ccmi/), and COST action TOSCA (Towards a more complete assessment of the impact of solar variability on the Earth's climate, http://www.tosca-cost.eu). Members of our team play a leading role in all of these. Our team, by relying on this large body of expertise, aims at addressing one particular aspect that requires multidisciplinary interactions for making solid progress, namely the definition of solar forcing scenarios for the next 500 years.

The three tasks to be addressed by this team are

1. **Collect and analyse proxies of past solar activity** in order characterize their variability, and in particular constrain future variations. The main proxies of interest are the Ap and aa geomagnetic indices, the sunspot number, and the ^{14}C and ^{10}Be cosmogenic isotopes. All but the Ap/aa indices are about to witness a new release and so the team will rely on the latest data available. Long-term reconstructions of the Ap and aa indices will make use of their correlation with the solar proxies. Periodicities and their significance will be identified by time series analysis. Non-linear techniques will be used to test the impact of bimodal activity in the Sun, i.e. phases of regular activity with the occasional occurrence of Maunder-like periods of exceptionally low activity. The time-scales of interest will be multi-decadal, i.e. excluding the solar Schwabe cycle. A detailed physical explanation of possible deterministic variations in the solar proxies (e. g. planetary influences, or else) is clearly beyond the scope of this team, but the existence and role of periodicities will be duly investigated.
2. **Define a set of solar forcings** that are based on the proxies from Task 1. and rely on our present understanding of recent solar activity (and in particular the low solar minimum between cycles 23 and 24) to constrain past variations of the TSI, the UV flux and the Ap/aa indices. This task really is about the physical understanding of the climate impact of solar variability. Our prime objective is to narrow down the range of possible scenarios and reduce their uncertainties.
3. **Build plausible scenarios of solar radiative and particle forcing** based on a coherent and internally consistent set of assumptions that are derived from Task 1. Our target horizon is 500 years, with one century as a minimal requirement for the next assessment report of the IPCC. These scenarios should fully comply with the requirements of chemistry-climate models. This task will require considerable interaction between the team members and it is not clear yet what the exact set of solutions will be. Different options include probabilistic forecasts with their probability density function, and "best guess"-type of projections with an assessment of the likelihood. Some model runs may be done, but CMIP6 is the proper framework we are targeting for that.

3 Schedule to accomplish goals

This team heavily relies on interactions between participants, who are then supposed to do most of the work offline. For that reason, we plan to have three 3-day meetings that are 6-7 months apart rather than two longer ones. The project should run from autumn 2014 till the end of 2015, and certainly not later than spring 2016 in order to be ready for CMIP6. Between team meetings, email exchanges and a few telecoms will enable continued collaborations.

1. The first meeting is planned in Sept-Nov 2014, will be attended by all 9 team members, and will address:
   - Review recent solar activity records (sunspots, ^{14}C, ^{10}Be).
   - Review the description of solar forcings in CCMI and CMIP
   - Identify what constraints can be put on future solar forcing scenarios (probabilistic and non-probabilistic).

- Determine how such scenarios can best match model requirements (key variables, type of forecast, etc.)
- Identify actions to be completed before the next meeting.

2. The second team meeting is planned for summer 2015, will be attended by all 9 team members + one additional expert (if there is a need for it), and will address:
   - Review recent progress.
   - Assess the level of predictability of solar variability.
   - Agree on solar forcing scenarios and identify a small set of model runs that be used to test them.
   - Identify actions to be completed before the next meeting.
3. The last team meeting is intended for the end of 2015, will be attended by all 9 team members + one additional expert (if there is a need for it), and will address:
   - Analyse the model runs and correct scenarios accordingly.
   - Finalise the forcing scenarios and prepare their distribution to the community.
   - Prepare joint publication.

   This additional expert will not necessarily be the same one as in the second team meeting.

4 Team organisation

The areas of expertise of the 10 team members committed to participating in this project are listed below. Two of them are young scientists, and are marked with an *. All team members have already been involved in multi-disciplinary projects or initiatives, and several have participated in ISSI teams before.

	NAME	AREA OF EXPERTISE	AFFILIATION
1	*Luke BARNARD	solar activity scenarios, heliospheric activity reconstructions	University of Reading, UK
2	Jürg BEER	cosmogenic isotope data	EAWAG, Dübendorf, Switzerland
3	Paul CHARBONNEAU	solar dynamo models	University of Montreal, Canada
4	Thierry DUDOK DE WIT	solar activity scenarios (team leader)	University of Orléans, France
5	Bernd FUNKE	energetic particle impacts	Inst. de Astrofísica de Andalucía, Spain
6	Katja MATTHES	climate modelling, solar influence on climate	GEOMAR, Kiel, Germany
7	*Amanda MAYCOCK	climate modelling	University of Cambridge, UK
8	Adam SCAIFE	climate modelling, decadal scale predictions	MetOffice, Exeter, UK
9	Ilya USOSKIN	solar and heliospheric activity reconstructions	University of Oulu, Finland
10	TBD	one additional expert	

Our experience with past ISSI teams is that small teams allow for more active interactions, hence the relatively small size.

The problems we will address will be very diverse. This team may not have all the necessary expertise, nor is it able to identify now some of the more technical issues that may arise in the making of scenarios. For that reason we propose to leave some flexibility in the team composition and make room for a potential 10th team member. This additional person, if needed, will be invited to attend the second team meeting. A different one may be invited at the third meeting. Their names will be proposed first to ISSI.

5 Timing, requirements and added value to ISSI

5.1 Timing

The project is timely, for several reasons. First, the present state of low solar activity has recently led to a renewed interest in solar activity studies on time scales beyond the Schwabe cycle. New records of past solar activity (based on sunspot numbers, and on cosmogenic isotopes) have just been published, or are about to be released, thus providing new and better material for investigating long-term solar variability. In addition, the latest assessment report of the IPCC has highlighted the need for predicting natural forcings on multi-decadal time scales; answering this need is precisely one of our motivations. Finally, we plan to deliver our results by the end of 2015, which is right in time for starting phase 6 of the CMIP project.

5.2 Deliverables

This team will produce two deliverables:

- a public data set with a series of scenarios for future solar activity up to 500 years ahead, with different contributions for the radiative and particle forcings. The exact format (with confidence intervals, best guess scenarios only, ...) is still to be decided. Our objective is to make these scenarios the reference for CMIP6.
- a review article, co-written by all team members, which describes these scenarios and the underlying assumptions.

5.3 Requirements

No specific facilities are required except for the use of a meeting room, ISSI standard facilities, and ISSI's web site for exchanging data.

Per the guidelines of the call for proposals, the requested financial support will cover the per diem and accommodation of the team members, in addition to the travel expenses of the coordinator. Publication expenses will be covered by the institution of the coordinator.

5.4 Added value to/from ISSI

The format of ISSI's stimulating and multidisciplinary working meetings is ideally suited for this small team, whose members belong to different communities, and thus hardly get a chance of interacting or working together. Another advantage of ISSI is its location, which reduces work distractions.

The main added value to ISSI is the international visibility it will gain from the publication of scenarios of future solar forcing (and its data set), which we would like to become a reference in the field.

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