The Grand Maximum was not a unique event

The "best" TSI reconstruction

Unfortunately, there is no known imprint of Total Solar Irradiance (TSI) in the past. Here I mean that we have no terrestrial record which would be influenced by TSI so that its variability would be primarily defined by TSI. For example, the width of tree rings in a tree at mid-latitudes is an imprint of the local climate (the warmer is the summer, the more tree grows, and the wider is the ring), sunspot number is an imprint of solar activity, etc. If we could find something (e.g. a substance in the Earth's environment) that would respond to changes in TSI without being essentially affected by other factors, we could use it as an imprint for TSI. However, such a proxy is missing.

Sometimes, indices of solar activity, such as the sunspot number, are called TSI proxies, but that's not correct. They are used as input parameters to calculate TSI in some models but cannot serve as a real proxy, simply because we don't know how they are related. Most of the models use a linear regression between solar indices and TSI, based on an empirical correlation. This is very risky, as correlations never give a real relation for the periods outside when it was established. An example is a correlation between cloudiness and the temperature somewhere. It looks obvious than cloudy days are colder, but not for the high-latitude winter days, where cloudy days are warmer than sunny days. Thus, an extension of a correlation outside the range of its validity may easily lead to spurious results (is we used temperature as a proxy for cloudiness, we would get wrong for winters).

Since all the TSI reconstructions in the past are based on extrapolations and cannot be directly verified via imprints or proxy records. Thus, no OBJECTIVELY "best" reconstructions can be defined. Most of the TSI models use a simple regression between TSI and other indices (e.g. the modulation potential, which is a measure of cosmic ray variability; or sunspot numbers) extrapolated backwards in time. Only a few models (e.g. the one developed by a group at the Max-Planck Institute for Solar System Research in Göttingen, which pioneered a physical way to model TSI, see Vieira et al. 2011) use a physics-based numerical model rather than a regression. In this model they try to use a physical model to account for all known physical processes that lead to changes in solar irradiation – dark sunspots, bright structures, background radiation. This makes an "absolute" basis for TSI reconstructions.

On the other hand, the regression-based approaches are crucially dependent on the choice of the reference period and dataset and need to be ad-hoc "calibrated" without any guarantee that it works in the past. E.g. the model by Shapiro et al. uses the quite sun model which leads to a very large variability of TSI at centennial scale. But this cannot be checked. To conclude I would slightly favour the model of the Max-Planck Institute MPS (VSK in Figure 1 below), for the reason that it is based on a physics-based approach which, supposed the physics behind it is correct, should catch the non-linearity of the relations.

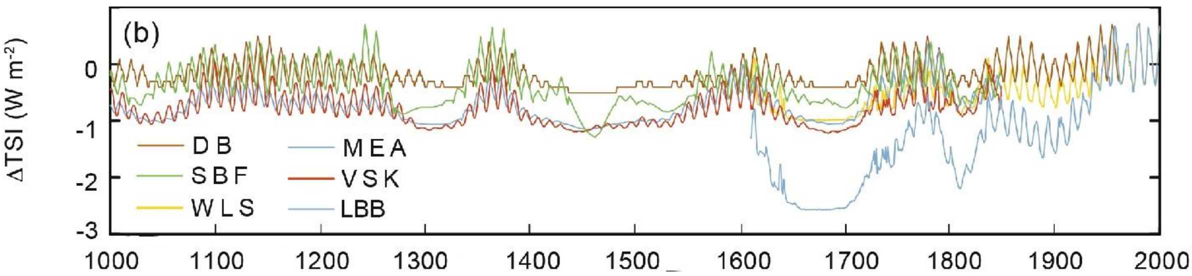

Figure 1: changes in TSI during the last millennium. Replication of figure 5.1b in IPCC's AR5 report. The blue reconstruction is one published by Lean et al. 1995. Since the 90-ies reconstructions of the TSI have become considerably flatter suggesting that the influence of the sun through time is relatively small. See AR5 for all the references.

The Grand Maximum in the 20th century

Before discussing further, I would like to correct the statement in the Introduction article for this Climate Dialogue after Fig. 8 that "Several papers in the last decade have claimed that solar activity in the second

half of the 20th century was higher than [at] any time in the past 10000 years". The fact is that the recent Grand Maximum is rare but not unique on the time scale of the Holocene. Several similar Grand Maxima (about 20) took place over the last 11 millennia (Usoskin et al. 2007), thus one per about 500 years. Therefore, the Grand Maximum in the 20th century is not a unique event but a rare event.
The very existence of the Grand Maximum is not questioned by others I think. As e.g. stated by Clette et al. (Space Sci. Rev., 2014 in press): "The recalibrated series may thus indicate that a Grand Maximum needs to be redefined as a tight repetition/clustering of strong cycles over several decades, without requiring exceptionally high amplitudes for those cycles compared to other periods." This indicates that even in the "corrected" sunspot series the Grand Maximum is observed as a period of clustering of several consecutive high cycles, even though the height of the cycles is not unique.
A special word can be said about the "corrected" sunspot number series shown in Fig. 9 of the Introduction. It is not a result of the scientific consensus, not even mainstream yet, as still many uncertainties remain, and the proposed series is yet a working hypothesis based on unpublished work. Other corrections and justifications (e.g. Leussu et al., 2013; Lockwood et al., 2014) also exist and are being discussed in the community. Anyway, Fig. 9 is picked up from a popular article rather than from a scientific paper and represents the personal view of an author (B. Owens who presented it in the New Scientist magazine) rather than a scientific paradigm.

The preferred temperature reconstruction.
I don't have any preferred reconstruction as it is beyond my field of expertise.

The correlation between global temperature and solar activity
There are many indirect results suggesting such a relation on long-term scale (centuries to millennia). Just a few examples can be the correlation between solar activity and the extent of icebergs in the North Atlantic (Bond et al., 2001) or a coincidence between solar activity minima and cold/wet spells in Europe (Usoskin & Kovaltsov, 2008), both at millennial time scales. Each of those is weak and not very convincing along, since it is based on a statistical correlation which can be disputed. However, in the aggregate they imply that there is a link between paleoclimatic and solar activity reconstructions.

Attribution of warming to the sun
Although the present knowledge remains poor, in particular since most of the climate models consider only the direct TSI effect which is indeed quite small, I would intuitively and subjectively say that the solar influence was an important player until mid-20th century, but presently other factors play the dominant role. However, such time-delaying processes as e.g. ocean heating, are not straightforwardly considered.

Amplification processes
The most famous mechanism for an indirect influence of the Sun on climate is the cosmic-ray-cloud connection, aka Svensmark's mechanism, which suggests induced/mediated nucleation of cloud condensation nuclei by atmospheric ionization caused by cosmic rays. This mechanism, called also the clear-sky mechanism, has been extensively studied recently, in vitro, in the dedicated laboratory experiments CLOUD and SKY. It was shown that the effect does exist but is too small to play a notable role in the climate. Thus, this mechanism is hardly a strong player.
On the other hand, another mechanism, related to the global electric circuit, may operate in already existing clouds (see e.g. Tinsley, 2008; Harrison et al., 2011). This may operate via the electro-scavenging or electro-freezing of condensation nuclei in the presence of electric field, which is induced by the global electric current between the ground and the ionosphere. Cosmic rays, which control the conductivity of air via ionization, and geomagnetic activity, which affects the ionospheric potential, both affect this current and thus may slightly modulate the properties of clouds. However, quantitative models are still missing.
Other possible positive feedback (amplification) mechanisms include top-down and bottom-up ones involving atmospheric chemistry and large scale air-mass and ocean dynamics. In a very simplified way the "top-down" mechanism may be related to the ozone depletion in the stratosphere by charged energetic particles of solar or magnetospheric origin, that leads to enhanced UV irradiation of the ground, and also

changes the wind pattern in the stratosphere, affecting the heat redistribution. It can be completed by the "bottom-up" mechanism related to the large-scale atmosphere-ocean interaction, which provides a positive feed-back (see a review by Gray et al., 2010).

The predictability of solar variability.

Although there are different long-term "predictions" of solar activity, they are not predictions in a strict sense. It is more correct to call them "possible scenarios". Such scenarios are based typically on multi-harmonic (or neural network or other) mathematical extrapolations of the existing series. This would work if the time series were stationary (in the sense that a sufficiently long subset of data contains the main statistical features of the entire series). However, the solar activity data sets have been shown to be essentially non-stationary thus making true predictions hardly possible because of an essential stochastic/chaotic component. E.g. with an equal success one can predict the behaviour of the financial market and become rich.

The issue is that no one knows when the new Grand Minimum occurs and no one really knows what would happen then. I call such extended minima of suppressed solar activity Grand Minima, since the Maunder Minimum (lasting from 1645 till about 1700 or 1712) is only one of those. Later minima, such as the Dalton Minimum (ca. 1800 AD) and modern (ca. 1900 AD) ones were not really Grand Minima, in neither depth or duration.

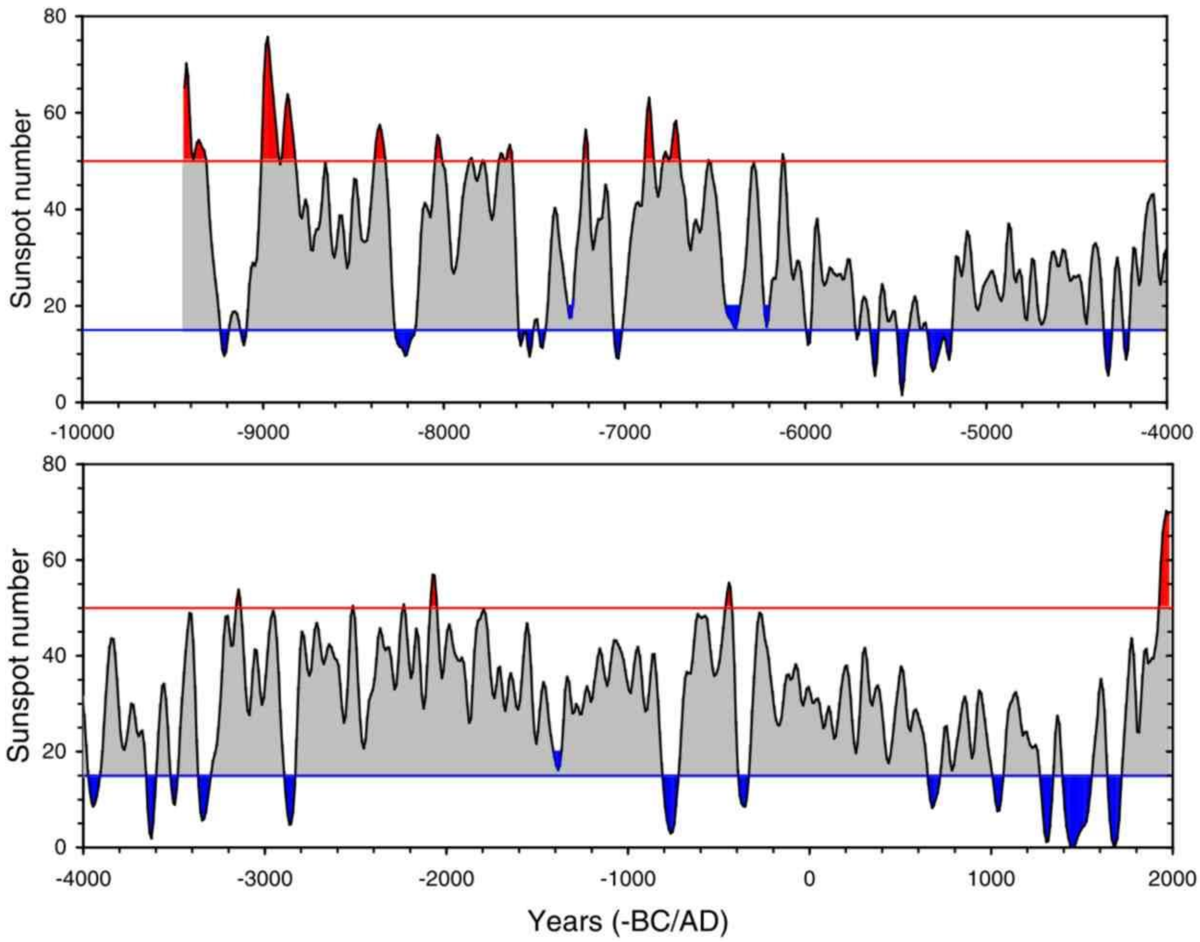

Fig. 2: Solar activity (sunspot number) reconstructed from ^{14}C data for the last 11 millennia (Usoskin et al., 2007). Blue/red color indicate the Grand Minima/Maxima of solar activity.

Indeed, we are certain that there will be a Grand Minimum sooner or later (there were 27 ones during the last 11 millennia, see Fig. 2) but their occurrence is unpredictable. The 27 minima during 11 millennia imply that Grand Minima appear roughly every 400 years, but they are spread very unevenly, with intervals

between them being from a hundred years to a few thousand years. No regularity was found in their occurrence (except for the ~200-yr repetition appearing sporadically), but rigorous statistical studies suggest that they occur randomly. Thus, no definite prediction of a future Grand Minimum is possible, but a probabilistic forecast can be made, e.g. Barnard et al., (2011) said: “There is an 8% chance of the Sun falling into a grand minimum during the next 40 years”. This is not a prediction but a probabilistic forecast or also called a possible scenario.
Concerning the influence on climate, I think we are unable at the moment to make a realistic assessment to what will be the consequence, since many processes are still poorly understood and modelled.

Biosketch

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