Mem. S.A.It. Vol. 76, 751

Memorie della

Solar variability and climate change

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Abstract. Understanding past and predicting future climate changes requires a good knowledge of the various forcing factors and the corresponding response of the climate system over long periods of time. Ice and sediment cores turned out to be useful natural archives which provide a wealth of information about many aspects of climate forcing and climate change. Ice cores in particular offer the unique opportunity to reconstruct the solar variability over at least 10000 years. However, it is not easy to extract and decipher the information stored by nature.

1. Introduction

Everybody agrees that the Sun drives the climate system. Every second, the Sun looses some 4 million tons of weight which are irradiated into space mainly in the form of visible light. One billionth of this power (10^{17} W) arrives at the top of the atmosphere an amount which corresponds to about 10000 times mankinds present global consumption. This solar power arriving at the top of the atmosphere is called the solar constant (1365 Wm^{-2}).

Until recently almost nobody believed that the Sun has anything to do with climate change. Only very few scientists tried to test whether the solar constant really is constant. As they were only able to observe the Sun from the Earths surface they failed because absorption of the sunlight crossing the atmosphere fluctuates.

It was only in the satellite era that it became possible to continuously monitor the solar constant from outside the atmosphere. A compilation of several instrumental records clearly shows that the solar constant is indeed not a constant (Fig. 1) (Frohlich and Lean 2004). It follows the solar activity as represented by the sunspot number. However, the observed change over an 11-y cycle is only about 0.1% which is quite small. From these results many people conclude that solar forcing does exist but is negligible. Beside these direct measurements of the solar constant, more appropriately called total solar irradiance (TSI) there are several indirect pieces of evidence proving that the sun is a variable star and may well have an influence on climate change.

In the following we address some aspects related to different mechanisms and the amplitude of solar variability and the corresponding sensitivity of the climate system. In contrast to the TSI, changes in the UV part of the solar spectrum are large and affect the ozone content in the stratosphere. Model calculations show that these changes can ultimately affect the circulation of the lower atmosphere (Haigh 1999).

While these changes in the total and the spectral irradiance are caused by processes on the solar surface, models describing the lifetime of the Sun (approx. 10 billion years) tell us that 4.5 billion years ago when the solar system was created, the TSI was lower by

some 30%. Since then it is steadily increasing and will continue to do so for about another 4 billion years. A very interesting issue is how the Earth system managed not to become an "ice house" known as the "faint young sun paradox".
On much shorter - but still quite long - time scales we have some unique information. The amount of solar radiation arriving at the top of the atmosphere is not only related to the emission from the Sun but also to the position of the Earth relative to the Sun. As a consequence of the gravitational forces of the other planets (mainly Jupiter and Saturn) acting on the Earth the orbital parameters of the Earths change with periodicities ranging from 400000 and 100000 years (eccentricity) over approximately 40000 years (tilt angle) to periodicities around 20000 years (precession of the Earths axis). The theory of orbital forcing which was developed to a large extent by Milutin Milancovic is unique in the sense that it is the only forcing which can be calculated precisely not only for the past several million years but also for the future (Berger et al. 2003). Fig. 2 shows the measured $\delta^{18}O$ record of the GRIP ice core from Greenland reflecting the temperature changes during the past 100000 years together with the calculated solar insolation at 72N (latitude of the GRIP ice core) during the months July and August. Although the $\delta^{18}O$ record is mainly characterized by the so-called Dansgaard Oeschger events the general longterm trend agrees quite well with the insolation with the exception of the past 10000 years.

The biggest effect of the orbital forcing is the cyclic change between glacials and interglacials over the past 700000 years with a periodicity of 100000 years. This is surprising because the corresponding mean annual change in forcing is very small ($\approx 0.2Wm^{-2}$). This raises questions regarding the sensitivity of the climate system which is the next issue to be discussed.

A fundamental problem in assessing the effect of any forcing change is the fact that the climate system consists of many components which interact in non-linear ways on very different spatial and temporal scales. Due to positive feedback mechanisms even very weak but persistent forcing signals can be amplified and lead to strong effects. The sensitivity of the climate system is investigated by means of climate models which are designed to simulate the reality (Rind 2002). Unfortunately, the closer the climate models approach the complexity of the climate system, the less they are able to simulate orbital forcing effects on time scales of 20000−100000 years.

The final issue is the question whether in view of the uncertainty in the forcing and the sensitivity there is any evidence for solar forcing in the paleoclimate records. We have already seen that on multi-millennial time scales, solar forcing is active (Fig. 2).
Fig. 1 suggests a weak relationship between TSI and solar activity. If true this offers the possibility to estimate solar irradiance in the past. The sunspot record, which goes back to 1610 when the telescope was invented, clearly shows that the satellite era is characterized by a comparatively high solar activity. Periods like the Maunder minimum (1645−1715) were quite different with almost no sunspots. This points to a TSI considerably lower than during the past 30 years. However, we do not yet know how much lower. Anything between 0.1 % and 1 % is possible. But what did the sun do before 1600 ?
Using cosmogenic radionuclides such as ^{14}C, ^{10}Be, and ^{36}Cl which are produced by the interaction of cosmic rays with the atmosphere it is possible to reconstruct the solar activity over the past 10000 years which gives a first order estimate of solar forcing based on the suggested relationship between solar activity and solar irradiance (Beer et al. 2000).
A growing number of high resolution and well-constrained reconstructions of the paleoclimate during the Holocene reveals considerable climate changes which point to external forcing. Prior to the industrial era the anthropogenic influence on the climate was probably negligible, so we are basically left with solar and volcanic forcing. The fact that many of the paleorecords show a relatively

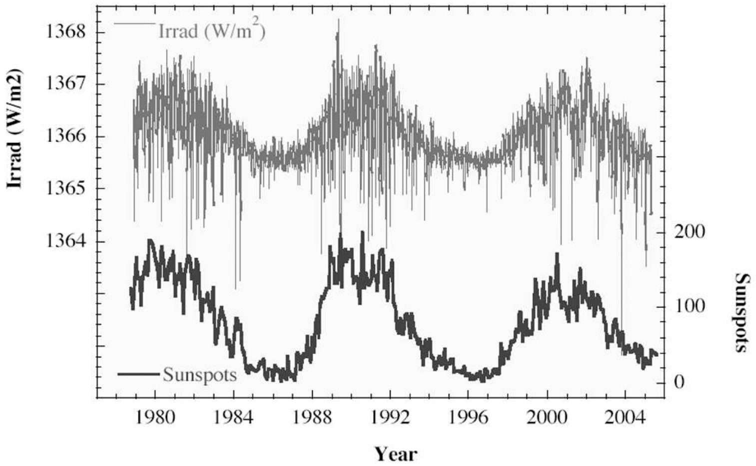

Fig. 1. Total solar irradiance (TSI) measured from satellite based radiometers (daily values) compared with the corresponding sunspot numbers (monthly values). Note the positive correlation between solar activity and TSI. TSI from http://www.pmodwrc.ch/, sunspots from: http://sidc.oma.be/index.php3.

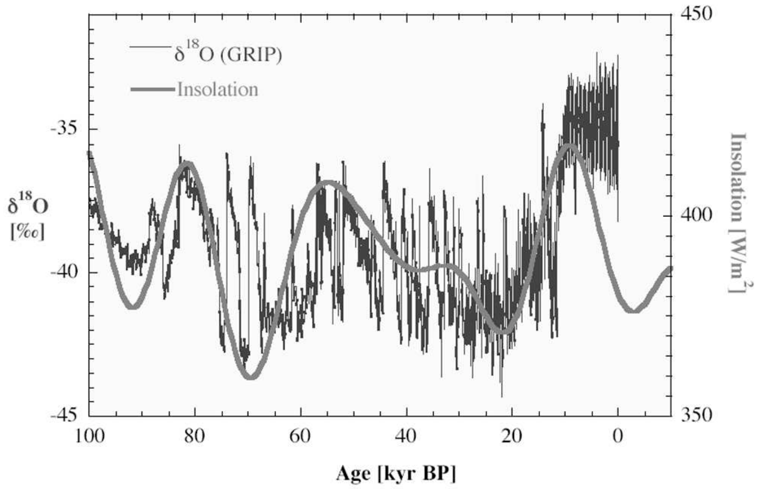

Fig. 2. Comparison of the $\delta^{18}O$ record from GRIP (central Greenland) reflecting climate change since 100000 years ago with the corresponding summer insolation at this site. The long-term trend of $\delta^{18}O$ follows pretty well the insolation curve. The abrupt large changes (Dansgaard-oeschger events) can are attributed to changes in the deep-water formation of the North Atlantic. $\delta^{18}O$ from: http://www.ncdc.noaa.gov/paleo/icecore/greenland/summit/document/gripisot.htm insolation calculated with AnalySeries http://www.ncdc.noaa.gov/paleo/softlib/softlib.html).

high correlation with the reconstructed solar activity indicates that solar forcing does indeed play an important role.

As an example for such good correlation Fig. 3 shows a comparison of the ice rafted debris in the North Atlantic with the solar activity record derived from ^{10}Be in the GRIP ice core from Greenland (Bond et al. 2001). Ice rafted debris consist of characteristic particles which

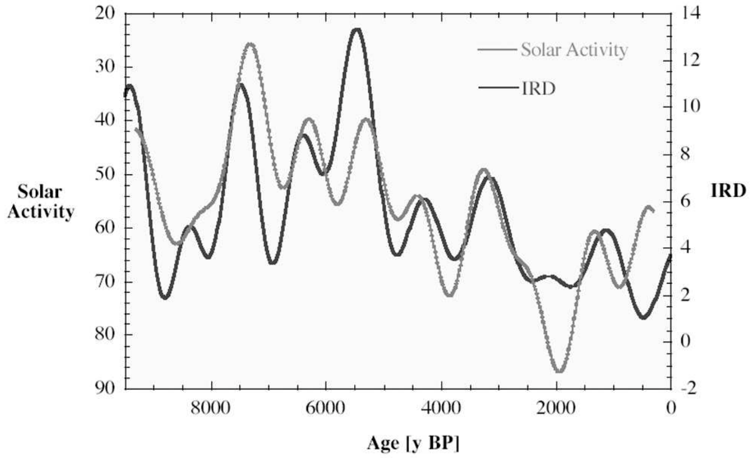

Fig. 3. Comparison of ice rafted debris in North Atlantic sediments (Bond, personal communication) with the solar activity derived from ^{10}Be (arbitrary units) (Vonmoos, personal communication). Both records are low pass filtered with a cut-off frequency of 1/900 y.

are picked up by the glaciers moving towards the sea where they break up into icebergs. The origin of some particles is well known: hematite stained grains can be traced back to an area in Greenland and glass particles originate from volcanic eruptions in Iceland. As the icebergs drift southwards they melt slowly and release the particles which finally find their way into the sediment. If the climate is generally cold, the icebergs drift further south than during warm periods as Titanic experienced in 1912.

Fig. 3 shows that on longer time scales cold periods with large numbers of ice rafted debris coincide quite well with periods of low solar activity (high ^{10}Be concentration), as suggested by the direct measurements of the total and spectral solar irradiance.

Differences arise due to uncertainties in the time scales of the sediment and the ice core, other forcing factors, and the non-linear response of the climate system.

Solar forcing is just one forcing factor. Understanding climate change requires taking all the different forcing factors into account. A better knowledge of the natural forcing factors during the industrial era will lead to a better quantification of the anthropogenic forcing and ultimately to better predictions of the future climate change.

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