Mem. S.A.It. Vol. 76, 913

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Closing remarks on the Sun influence on climate changes

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Abstract. Numerous attempts have been made over the years to link various aspects of solar variability to changes in the Earth's climate. Since the Sun's output of electromagnetic radiation and energetic particles varies, and since the Sun is the ultimate driver for the climate system, it seems natural to link the two together and look for the source of climate variability in the Sun itself. In recent years there has been a growing concern about the possible anthropogenic forcing of climate change through the increasing atmospheric content of greenhouse gases. This has made the connection between solar variability and global climate change a very controversial research area. This conference brings together the solar and climate community to present the most recent results gained on the knowledge of solar variability and the effects on the Earth's climate system. From the presentations it appears that the understanding have come a long way, with the Sun driving global warming in the early part of the last century and anthropogenic effects taking over in the second half. However, it is also evident that we need to improve our knowledge about historic solar and temperature proxy data. Furthermore we need to better understand the atmospheric response to variations in the ultraviolet and extreme ultraviolet radiation and the physics of cloud formation.

1. Introduction

The Earths atmosphere is responding to several internal and external stimuli. The past 150 years the Earth has experienced a warming of about 0.6 degrees. In the same period both the amount of greenhouse gasses in the atmosphere and the solar activity have increased. Thus, it is not trivial to detangle the two effects. Furthermore, there are other important forcing factors that need to be accounted for such as aerosols, land use changes (deforestation, irrigation etc.), urbanization, and volcanoes. The specific challenge is to better understand the variability of the Sun on all time scales and the complex physics of the terrestrial response,

We have heard reviews on the structure of the Sun, helioseismology and comparison with other stars. Several reviews on advances in the history of terrestrial climate and proxy estimates of past solar variability were presented. An up to date status on the solar irradiance measurements from satellites were given and it was stressed that better knowledge about the spectral distribution of solar variability is very important. Reviews of current climate models and how they include solar variability were presented.

This paper will not repeat what we all heard from the speakers and what we have read in the posters during the conference. That I leave to the authors contributing to this book. I will rather focus on a few topics where I think there are still room for improved understanding. I apologize to the many authors whose individual, and very interesting, contributions I will not mention explicitly.

2. Historical review

Apparent references to sunspots were made by first millennium AD Chinese astronomers, who probably could see the largest spot groups when the sun's glare was filtered by wind-borne dust from the various central Asian deserts. Early observations of this sort exist, but not much was remembered of them, and when around 1610 they were seen more clearly with the help of the telescope, the discovery came as a great surprise. Three observers claimed the discovery–Galileo, who risked blindness by looking at the Sun through a telescope, the priest Christopher Scheiner in Germany, who invented the safe observing method of projecting the Sun's image onto a screen, and Johann Fabricius in Holland.

The sunspot number was introduced by Wolf in 1850 and in 1859 Heinrich Schwabe announced the discovery of the 11 years sunspot cycle. There is also a relationship between solar surface activity and the occurrence of aurora, which could also be seen in the short-term fluctuations in the Earth's magnetic field, called geomagnetic activity, which was systematically observed at magnetic observatories from around 1870. Radio astronomers found that the intensity of the 10.7 cm radio signal from the Sun was well correlated with the sunspot number.

In the 1950's Forbush discovered that the intensity of the cosmic ray flux was noticeably reduced during high solar activity. This latter finding pointed at a completely new aspect of solar activity. The solar wind is a consisting stream of plasma blowing out from the solar atmosphere and carrying with it a magnetic field from the Sun. This varying modulation of cosmic ray flux by the solar wind is also the reason for the important discovery of the modulation of 14C production due to changing geomagnetic field and the varying solar activity. The 14C content in organic material and the radioactive isotope 10Be in precipitated snow comprise a major source of knowledge regarding past variations in solar activity.

The debate over a solar contribution to climatic change is by no means of recent vintage. As early as the late eighteenth century, widespread concern for the deterioration of the earth's climate led to speculation on the sun's role in climate change. The astronomer William Herschel suggested in 1801 that greater sunspot activity would result in warmer earth climates. Herschel supported his hypothesis by reference to price series for wheat. Later, correlations with different weather patterns were suggested and Leonardo DaVinci pointed out a correlation between the climate and distance between tree-rings.

In the mid seventies Eddy (1976) pointed out the rough coincident between the cold period of the so-called Little Ice Age in the late 17th and the early 18th centuries and the Maunder Minimum of sunspot activity, when no sunspots were detected for a period of about 45 years. Eddy also used radiocarbon records to show that there was also a rough coincidence between earlier periods of warmth and cold in the northern hemisphere and periods of unusually high and low solar activity respectively. He suggested that the cause might be in the variations in the Sun's total radiative output (the solar "constant").

The paper by Eddy appeared in the time when the global temperatures were decreasing and before global warming was a topic of concern. However, in the 1990s a comparison with the Northern Hemisphere land temperature during the last 130 years did show a remarkably good correlation with the smoothed curve of the varying solar cycle length indicating that this parameter was possibly a better indicator of a solar activity variations that could affect the Earth's climate compared to sunspot numbers. One already knew that the estimated change in total solar irradiance (TSI) the last century could not alone explain the warming in this period. If the correlations were not just by coincidence, there must be other forcing mechanisms where the Sun can influence the global temperatures. Thus, this result did not proof anything but it was an inspiration to search for other forcing mechanisms.

3. Solar variability and climate forcing mechanisms

Meteorological records show that the global average surface air temperature has increased about 0.6 C in the last 150 years. Longer-term climatic variations, on the other hand, have been inferred from a variety of proxy climate indicators including growth rings in trees. Because tree growth depends partly on temperature, the width of an individual tree ring can be used to identify paleotemperature trends. Many reconstructions of the past climate have been published the last 15 years. Some of them seem show very little past climate variability while other more recent show larger variability. The latter suggests that earlier reconstructions underestimated the past variability somewhat. Uncertainties and generating such records were discussed in detail during the meeting and we still have some way to god before we have a consistent picture of how the climate have changed in the past and also the spatial distribution of these changes. Obviously the climate changes have been spatially uneven and different forcing mechanisms, both anthropogenic and natural, will have different spatial signatures.

The uncertainties in producing reliable data of past solar activity were also pointed out. Are sunspots the best tool to derive past solar forcing mechanisms or should we look to other features of solar activity (cycle length, solar wind speeds, geomagnetic activity etc.). Whatever solar proxy one use it still looks like the Sun has been unusual active the last century.

There are several ways the Sun may impact the climate trends on the Earth:

- A change in the solar total (wavelength-integrated) irradiance, which directly produces a terrestrial temperature response on time scales of years to century
- A change in ultraviolet irradiance, which modulates the stratospheric ozone abundance, thereby impacting atmospheric circulation, and in turn and indirectly, terrestrial temperatures on time scales of years to century
- Direct and indirect influence by solar and cosmic ray particles modulated by the solar wind and the Sun's magnetic field. These particles interact with the Earth's atmosphere through nuclear collisions producing secondary particles which can penetrate deeper into the atmosphere.

3.1. Variations in Total Irradiance

The most obvious candidate for climate forcing is the direct effect of the varying total solar irradiance (TSI) with solar activity. A big break came with a launching of the first absolute radiometer into space in 1978. Many were sceptical to such a vast of effort and money since the Sun is obviously constant. Luckily NASA went ahead with these plans and for the last two decades it has been possible to make high-precision measurements of the total solar irradiance outside the Earth's atmosphere. The difficulties in combining the different time series from several satellites were stressed at the meeting. Some data indicates that there has been a slight increase in the minimum level of TSI - that the Sun still shows increasing activity. However, the consensus on this topic leans toward a Sun where there has been no increase of the minimum values the last two solar cycles. Clearly we need to continue monitoring the Sun for several future cycles.

Despite the lack of direct observations, several attempts have been made to estimate the long term variation in the Sun's radiative output since the Maunder Minimum. The general conclusion of these estimates is that the Sun's total irradiance has varied by somewhere between 0.2 and 0.6

3.2. Variations in UV Spectral Irradiance

The solar cycle variation at ultraviolet wavelengths is much larger than the 0.1

Since certain UV wavelengths are responsible for production and loss of ozone in the stratosphere and troposphere any variation in the UV emission from the Sun will produce changes in chemistry and dynamics of the atmosphere. These changes can propagate downward and cause climate changes. In the lower stratosphere, one has found a very clear variation of the height of the 30 hPa pressure level in phase with the solar activity variation. This correlation has been constant during the last 4 solar cycles.

One of the unanswered questions is how these profound changes in the stratosphere may propagate down to the troposphere. Using both observational data and GCM simulations it has been shown that when the Sun is more active, there is a pattern of response in meteorological fields in the lower atmosphere. Changes in the sub-tropical jets and tropospheric Hadley cells are observed. One important result from these studies is that the heating of the atmosphere is not uniform. However, most of these model simulations are looking at the 11year cycle variation only. At least one study suggests that lower solar activity changed the atmospheric circulation from 1400-1700 and triggered the Little Ice Age. This dimmer Sun reduced the westerly winds, cooling the continents during wintertime.

Proxy data has been used to derive long term changes in the ultraviolet. At wavelengths just below 30 nm an increase of 3

3.3. Variations in the Solar Wind

Although the energy in the solar wind is negligible compared to the energy in the ultraviolet and visible spectral bands, the relative variations are much larger. From records of the radio-isotopes 14C and 10Be we know there is a clear signal in the troposphere and ground. But how can these small energy fluctuations possible affect the climate? The cosmic ray flux is the main cause of ionization of the upper atmosphere and this ionization changes significantly with solar activity. There has been suggested that cosmic rays may play a role in cloud formation. One possible mechanism includes the effects of ionization or electric fields associated with solar activity on the freezing of supercooled water droplets in high clouds. Another mechanism that has been proposed involves aerosols and formation of low clouds. A striking correlations correlation with global cloud cover measured by satellites during a considerable part of a solar cycle was highly correlated with the cosmic ray flux. Using an improved released data set from International Cloud Climate Project (ISCCP) covering a period from 1983 to 1994 it was demonstrated that only the low clouds are responsible for the found correlation.

It was mentioned during the conference that the correlations between cosmic rays and low clouds broke down after 1994 where new and updated cloud data have been provided by the ISCCP project. In that respect it should be mentioned that there is an ongoing scientific discussion around the calibration of this new data set. Comparison with independent cloud data from SSMI on the DMSP satellite suggests a sudden drift in the ISCCP data after 1994. If there really is a calibration problem with the latest ISCCP data and the adjustment of these data, based on the SSMI data set, is correct, then the correlations with GCR and clouds still holds.

A change in cloud cover would indeed be a very effective amplifying mechanism for climate forcing. But it is still a very controversial idea and it is still not clear whether there is a real effect on clouds. Are there any possible mechanisms where GCR could affect cloud condensation nuclei? The actual experimental knowledge about these mechanisms is very poor. Thus, the ongoing CLOUD experiment in Copenhagen is therefore of great interest. It is designed to test the coupling between high energy particles and cloud seeding.

3.4. High energetic particles from the Sun

Solar storms are most known for creating space weather effects in the Earths environment causing problems for a number of systems our society depends on. However, such transient events can also influence the chemistry of our atmosphere and, thus, possibly also the climate.

Solar storms consist of coronal mass ejections and solar flares. Coronal mass ejections are huge bubbles of gas ejected from the Sun and are often associated with these flares. Solar flares are explosions on the Sun that happen when energy stored in twisted magnetic fields (usually above sunspots) is suddenly released. Some solar storms can accelerate particles to speed approaching the speed of light and they can penetrate spacecrafts and be a hazard to humans in space.

When these particles hit the atmosphere they break up molecules of nitrogen gas and water vapor. When nitrogen gas molecules split apart, they can create molecules, called nitrogen oxides, which can last several weeks to months depending on where they end up in the atmosphere. Once formed, the nitrogen oxides react quickly with ozone and reduce its amounts. When atmospheric winds blow them down into the middle stratosphere, they can stay there for months, and continue to keep ozone at a reduced level. The strong proton showers in the fall 2003 let to significant depletion of the ozone levels between 42 and 55 km and this solar induced ozone "hole" stayed for 8 months before it recovered. Thus, solar activity on shorter time scales also need to be accounted for when studying climate effects from the Sun.

4. Concluding remarks

The topic Sun-climate is gaining more and more respect and it was almost unthinkable to organize an entire international conference like this 15 years ago. Now one sees a genuine interest among a larger group of climate scientists. Our understanding on this topic has increased dramatically during the recent years. At the same time we have realized that the Sun affects the Earth's environment in a much more complicated way than we have imagined. We still don't understand all processes and the climate change encompasses more than surface temperatures. Drought and rainfall are just two examples of other possible solar influences.

During this conference solar and climate researches came together to present the current understanding on this important topic and to discuss still unsolved problems. Climate models that include both the direct effects from the Sun, volcanoes and anthropogenic forcing reproduces the temperature trend the last 100 years quite good. But do this mean we understand the climate system? It is important to stress that this may well be due to the selection of the forcing mechanisms and that some of these may have been over- or underestimated. Many other open questions still remain and I will just mention a few here.

Is sunspots really the best proxy to use for deriving past changes in TSI? The geomagnetic activity indices have clearly a different trend and cycle shape compared to sunspot numbers, often staying high well after the peak of the solar cycle. Will different solar forcing mechanisms produce different spatial climate response? And were should we look for such signals? Are there mechanisms that magnify the forcing from the Sun? And what are they? What are the underlying causes for changes in the solar activity? If these are known would we be able to predict future solar activity? Can climate models overestimate or underestimate solar forcing? Can climate variations amplify the solar signal in the 10Be records? How can we improve our knowledge about feedbacks from clouds?

We still have a long way to go before we understand the complexity of the Earth's atmosphere and how it interacts with both natural and anthropogenic forcing mechanism. And we have an even longer way to go before the climate models can include in full detail the indirect effects from solar variability and other atmospheric parameters, such as clouds. We need to monitor the total irradiance, as well as the spectral irradiance, from the Sun over a long time period. It is equally important to improve the monitoring of surface and atmospheric temperatures as well as atmospheric parameters such as clouds, ozone, and circulation patters etc. Satellites will play an important role in the future and several planned missions will focus on these topics the next decades.

The indirect effects, e.g. cloud cover, UV heating of the stratosphere as well as possible effects not yet identified, must be investigated, quantified, and included or discarded. The ultimate goal must be a compressive understanding of all processes, which can then be combined into an ultimate comprehensive dynamical global climate model.

A new international cooperative program in solar-terrestrial physics, the International Living With a Star program (ILWS), has been established to stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity. ILWS follows the highly successful International Solar Terrestrial Physics (ISTP) program, which has involved partners from Europe, Japan, Russia, and the United States. ISTP, with its steady flow of discoveries and new knowledge in solar-terrestrial physics, has laid the foundation for the coordinated study of the Sun-Earth system as a connected stellar-planetary system, the system that is humanity's home.

The scientific goal of the ILWS program is to increase our understanding of how solar variability affects the environment on Earth and other planets, both in the short and long term. Of particular interest of the ILWS program are those aspects of the Sun-Earth system that have consequences for life and society. Over the next decade, the ILWS program will assemble the largest fleet of spacecraft ever focused on a single scientific goal. Together with Earth observing satellites these could greatly improve our knowledge about the topic of this conference.

Finally I will end this summary paper with a few bullets of thoughts:

- Whatever mechanism caused past changes in the climate could perhaps be at work today and in the future.
- None of the natural or anthropogenic effects can alone explain the temperature variations the last 150 years
- The complexity of our atmosphere is a huge barrier. For instance - long term trends in cloud cover represents a huge challenge to present and future global circulation models
- Whether the global warming trend recently (last 30 years) measured is dominated by greenhouse gases or has a significant solar component or other anthropogenic effects, like land use changes urbanization etc., is not yet fully understood.
- If anthropogenic effects are dominating the climate signal the last few decades, this does not rule out that natural variations can be more significant in the future. The climate of the future will be the sum of natural and anthropogenic effects
- Maybe there are other mechanisms that contribute and that we have not even thought of!
- We need a combined effort on monitoring the Sun and climate parameters from ground and space to improve our knowledge of all forms of climate change.
- We need an improved understanding of historic proxy data (solar and climate)
- We need to improve our knowledge about how indirect solar forcing may propagate down to our climate system

I would like to thank the LOC and SOC that made this conference to such a great event. Thanks to all the participants for their excellent presentations and interesting discussions and I look forward to continued progress within this field.