The Role of the Solar Forcing in the 20th century climate change

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Abstract

A long list of empirical results strongly suggests that solar variations play an important role in climate change. We begin by trying to understand why such variations are crucial if we are to understand 20th century climate change, and how it is related to the value of the climate sensitivity. The latter is of course necessary if we are to predict future climate change. We then review some of the aforementioned evidence, and in particular, the data which can be used to quantify the size of the solar climate link. We will end by building a more consistent picture for 20th century global warming, while mentioning a few words on the expected 21st century climate change.

Introduction: why do we need to understand the climate role of the sun?

In the standard picture advocated by the IPCC, most of the global warming observed over the 20th century is attributed to the increase in anthropogenic greenhouse gasses (AGHG). Indeed, when one considers the observed increase in temperature and the increase in AGHG, it is very tempting to do so. However, we have to remember that there are many uncertainties—primarily the unknown radiative forcing changes and unknown climate sensitivity—which imply that most of the warming is not necessarily human.

When the Earth's energy budget changes, that is, when the net radiative forcing changes, so does the climate equilibrium. Climate sensitivity is simply the ratio between the temperature change needed to reach the new equilibrium and the changed radiative forcing. Thus, loosely speaking, the temperature change over the 20th century is the product of the changed energy balance, presumably mostly anthropogenic GHG, and the climate sensitivity. It is somewhat more complicated because it takes many decades for the climate system to adjust.

Here comes the problem, we very poorly know the net radiation forcing imposed by humans over the 20th century and we very poorly know the climate sensitivity. It turns out that the Achilles heel for both is clouds. We do not know the net radiative forcing because human activity increased the amount of atmospheric aerosols which "seed" clouds and cool (e.g., IPCC AR4 WG1, 2007). Unfortunately there is a very large uncertainty on size of the effect. Clouds are also very important to the determination of climate sensitivity. The reason is that the climate feedback through clouds, namely, by how much does the cloud cover change when the global temperature changes, is not really known. It was shown by Cess et al. (1989), that is it by far the dominant source of uncertainly. Twenty-odd years later, the situation is virtually the same.

For these reasons, there is no unique prediction for how large should the anthropogenic warming have been over the 20th century—multiplying two very uncertain numbers gives an even more uncertain temperature change.

Because theory cannot uniquely predict the 20th century warming, it can be attributed to human activity only because of *indirect* lines of argument. First, 20th century warming is unprecedented. This was based on the famous "hockey stick". However, it was shown by McIntyre and McKitrick (2003) to be false, as was later corroborated by the climategate e-mails. The second argument is that climate modelers cannot explain the warming without including the anthropogenic contributions to the net radiative forcing, in particular that of the GHGs.

Now we see why the climate role of the sun is so important. Because solar activity increased over the 20th century, if it has an effect on the climate it should have contributed a net positive forcing and it may have been responsible for some of the 20th century warming. This would then diminish the role of anthropogenic activity.

More quantitatively, if the sun has contributed a positive radiative forcing, then the total radiative forcing change over the 20th century is necessarily larger as well. As we shall see below, the sun does have a large effect on the climate, and it is roughly twice as large as the anthropogenic forcing alone. This implies that in order to explain the same observed 20th century warming, we require a climate sensitivity which is only half as large. In fact, the range of sensitivities required to explain 20th century warming is just below the often quoted IPCC range of 1.5 to 4.5°C increase per CO_2 doubling.

Needless to say, a lower climate sensitivity is very important if we are to predict 21st century temperature increase. For a given emissions scenario, such as a "business as usual" one, the warming should be correspondingly smaller.

Evidence for a solar/climate link.

One of the most interesting aspects of our sun is that it is not entirely constant. The variations that it exhibits appear in the total irradiance of the sun, i.e., primarily in the visible and infrared bands (by as much as 0.1%). But they also appear in components other than the total emitted flux. These include very large *relative* changes in the magnetic field, the sunspot numbers, the strength of the solar wind, and the amount of UV, to name a few.

The basic variation is an activity cycle of about 11 years, which arises from quasi-periodic reversals of the solar magnetic dipole field. On longer time scales (of decades to millennia) there are irregular variations which modulate the 11-year cycle. For example, during the middle ages and during the latter half of the 20th century, the peaks in the 11-year cycles were notably strong, while these peaks were almost absent during the Maunder minimum. On the other hand, eruptions may appear on the time scale of days. Today there is evidence linking solar activity to the terrestrial climate on all of these time scales.

Since the work of Jack Eddy in the 1970's, many empirical results show a clear correlation between different climatic reconstructions and different solar activity proxies on the time scale of decades or longer. Eddy realized that there is a correlation between solar activity and the European climate over the past millennium (Eddy 1976). For example, the little ice age in

Europe took place while the sun was particularly inactive, during the Mounder minimum. The medieval warm period, on the other hand, occurred while the sun was as active as it was in the late 20th century. Since then, many empirical results show a correlation between different climatic reconstructions and different solar activity proxies.

One of the most beautiful results is that of a multi-millennial correlation between the temperature of the Indian Ocean as mirrored in the ratio between different Oxygen isotopes in stalagmites in a cave in Oman, and solar activity, as reflected in the cosmogenic carbon 14 isotope (Neff et al. 2001).

Another impressive result over the same time scale is that of Bond et al. (2001), where the solar activity was compared with the Northern Atlantic climate, as recorded on the ocean floor through ice rafted debris. Many other correlations exist at other locations in the world.

One way to see that this solar-climate link is global and it affects the global temperature is to look at *borehole* data (Huang et al. 1997). This reveals that the solar variations give rise to changes which are as large a 1°C between low and active states of the sun.

Over the 11-year solar cycle, it is much harder to see climate variations. There are two reasons for that. First, if we study the climate on short time scales, we find that there are large annual variations (for example, due to the el-Ñino oscillation) which introduce cluttering "noise", hindering the observation of solar related signals. Second, because of the large ocean heat capacity, it takes decades until it is possible to see the full effects of given changes in the radiative budget, including those associated with solar variability. It is for this reason that climates of continental regions are typically much more extreme than their marine counterparts.

If, for example, a given change in solar forcing is expected to give rise to a temperature change of ½°C after several centuries, then the same radiative forcing varying over the 11-year solar cycle is expected to give rise to temperature variations of only 0.05-0.1°C or so (e.g., Shaviv 2005 and references therein). This is because on short time scales, most of the energy goes into heating the oceans, but because of their very large heat capacity, large changes in the ocean heat content do not translate into large temperature variations.

Nevertheless, if the global temperature is carefully analyzed (for example, by folding the global temperature of the past 120 years over the 11-year solar cycle), it is possible to see variations of about 0.1°C in the land temperature, and slightly less in the ocean surface temperature (e.g., Shaviv 2005 and references therein).

Moreover, as we shall see in the next section, it is in fact possible to see the large amount of heat going into the oceans every solar cycle.

We therefore conclude that the sun has a large effect on the climate. Although the link itself is not the topic of this article, it should be mentioned that the leading contender is through solar modulation of the cosmic ray flux reaching the Earth (Svensmark, 1998). This is now supported by a range of both empirical and experimental results.

For example, on the time scale of days, the sun can undergo flaring activity which is caused from the reconnection of magnetic loops. These flares are accompanied by a strong solar wind "gust" which later causes a decrease in the cosmic ray flux for several days. If the cosmic ray flux has an effect on clouds, then cloud properties should change following these events, known also as Forbush decreases. Several results indicate that clouds are affected during Forbush decreases. In particular, Svensmark et al. (2009) have shown the cosmic ray mechanism at work during these decreases. Not only was a cloud decrease signal clearly observed, the intermediate step of affecting the aerosol size distributed was detected as well.

Quantifying the solar climate link.

Having established that the sun has a large effect on the climate, we can proceed to quantify the size of the link. In particular, we are interested in the radiative forcing associated with solar variability. This is important if we are to assess its role in 20 th century climate change.

As mentioned above, looking for the temperature response over the 11-year solar cycle is tricky because of the large heat capacity of the oceans and the climate variability on short time scales. Nevertheless, we can use the large ocean heat capacity to our advantage, since it implies that short term variations in the energy balance will translate into heat content variations in the Oceans without affecting other components, that is, without any internal feedbacks operating. This implies that the 11-year cycle variations in the heat content in the oceans can be straightforwardly used to calculate the radiative forcing imposed by the sun.

Presently, the ocean heat content can be derived from three independent data sets. First, there is the direct measurement of the heat content, as measured by small temperature changes down to depths of 700m since 1955, over the whole ocean. The second data set is the surface sea temperature, while the third is that of tide gauge records of the sea level. Each of the three data sets has its advantages and disadvantages. For example, the data over the ocean volume are the most direct measurements of the heat content, however, because the oceanic volume was only poorly covered (at different locations and different times), there are problems of incompleteness. The sea surface data is of higher quality, but one requires some modeling in order to translate the small sea surface temperature variations to changes in the heat content. The third record, of tide gauges, is of relatively high quality. It suffers however from contamination. Although the dominant contribution to sea level change rate over the several year time scale is that of thermal expansion, some contribution is due to changes in the total land ice volume. The tide gauge record can be seen in fig. 1.

Nevertheless, all the three records consistently reveal that the amount of heat going into the oceans every solar cycle is about 6 to 7 times larger than the changes expected from just the variations in the total irradiance (Shaviv 2008). In absolute terms, it is a variations of about 1 W/m^2.

The number we obtain this way is very interesting. First, the leading contender to explain the solar/climate link is through cosmic ray flux modulation of the atmospheric ionization, which in turn affects the cloud cover. This implies that the radiative forcing change associated with the cloud cover variations over the 11-year solar cycle should too be of order $1W/m^2$—the amount of heat going into the oceans. Within the radiative forcing uncertainties of clouds, this is indeed the observed variations (Shaviv, 2005). The different estimates for the forcings are summarized in fig. 2.

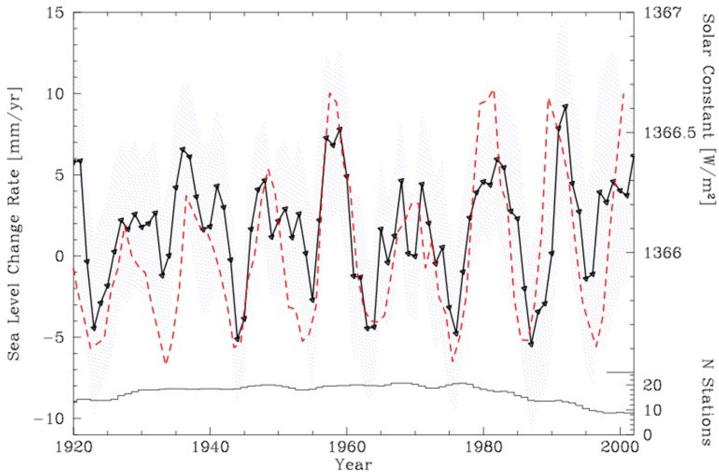

Figure 1: The sea level change rate. On short time scales, it originates predominantly from changes in the oceanic heat content. Using this data, the derived changes in the energy budget over the solar cycle correspond to 1 W/m², almost an order of magnitude more than can be expected from changes in the solar irradiance (see Shaviv, 2008).

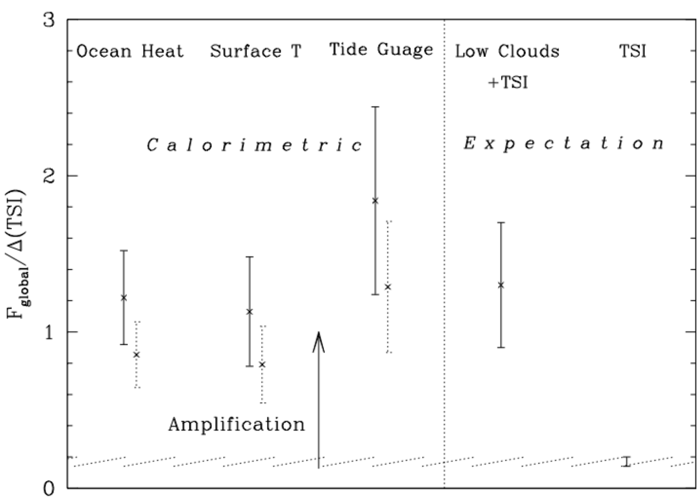

Figure 2: Summary of the "calorimetric" measurements and expectations for the average global radiative forcing (Shaviv, 2008). The solid error bars are the global radiative forcing obtained while assuming that similar forcing variations occur over oceans and land. The dotted error bars assume that the radiative forcing variations are only over the oceans. These measurements should be compared with two different expectations. The TSI is the expected flux if solar variability manifests itself only as a variable solar constant. The "Low Clouds+TSI" point is the expected oceanic flux based on the observed low altitude cloud cover variations, which appear to vary in sync with the solar cycle. Since the TSI cannot explain the observed flux going into the ocean, an amplification mechanism is required.

Second, because the forcing variations is large, it is comparable to the net anthropogenic changes in the radiative forcing over the 20th century. This implies that one has to consider solar variability when trying to understand 20th century global warming.

20th Century climate change – the full picture

Now that we have quantified the size of the link, we can proceed to estimate the effect that the sun had over the 20th century. Since the increased solar activity between the first half and second half of the 20th century is comparable to the variations between solar minim and solar maximum, over the 11-year cycle, we can expect the radiative forcing to be similar, i.e., around 1 W/m². For comparison, the IPCC estimates the net anthropogenic forcing to have been 0.6 to 2.4 W/m² (IPCC AR4 WG1, 2007), but the solar forcing that modelers typically include is only the changes in the solar irradiance, which are of order 0.1 to 0.2 W/m².

To better understand the climate change, we can employ a simple "box" climate model, one which includes temperatures for the land, ocean mixed layer, and diffusion into the deep ocean. We can then ask the question, what are the allowed climate variables, including the different couplings, sensitivity, radiative forcings, and so forth which can consistently explain the 20th century global warming. The answer is that if we allow the sun to have contributed more than changes in the solar irradiance, we find that 20th century warming can be much better explained than present global circulation models which exclude a large solar effect. In fact, the residual in the fit between model and observations is twice smaller! This can be seen in fig. 3.

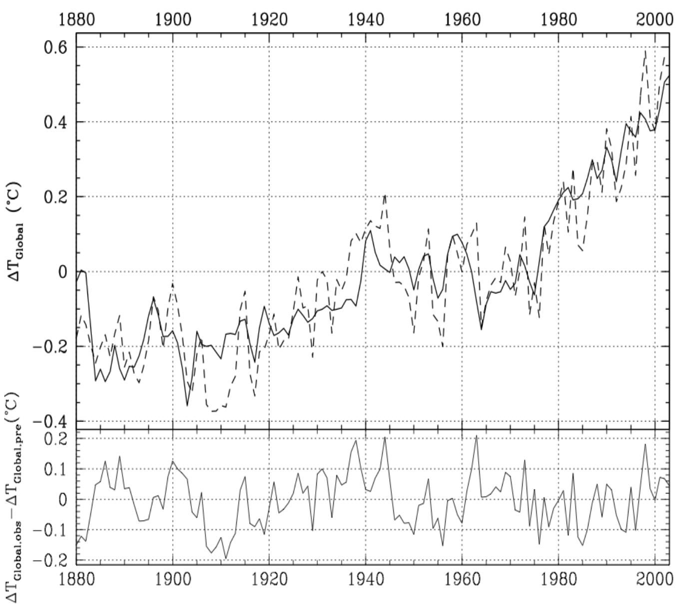

Figure 3: A comparison between the observed global temperatures and the temperatures modeled using an energy balance model with a diffusive ocean. The small residual, which is twice smaller than obtained in typical global circulation models, can be obtained if we allow the sun to have large effect on the climate, and that the climate to have a low climate sensitivity. (From Ziskin & Shaviv 2011).

The numbers that this fit gives is a net solar contribution of 0.8±0.4 W/m^2, and a climate sensitivity of 0.95±0.35°C increase per CO_2 doubling. These values are consistent with previous empirical determinations of the solar effect and of the climate sensitivity.

Summary

We have seen that there is ample evidence to prove that the sun has a large effect on the climate. This is important because it allows us to present a much more consistent picture to explain the observed 20th century global warming—one in which model fit the predictions much better. In this picture, the sun has contributed a net radiative forcing which is comparable to the anthropogenic contribution. As a consequence, the same 20th century warming can be explained with a smaller climate sensitivity. It also implies that for a given emissions scenario the predicted 21st century warming should be correspondingly smaller, typically around 1 to 1.5°C, for a "business as usual scenario".

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