Solar Forcing and 20th century climate change

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A long list of empirical results strongly suggests that solar variations play an important role in climate change. We will 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, i.e., the amount of warming expected for a certain increase in anthropogenic greenhouse gases. The climate sensitivity is of course necessary if we are to predict future climate change.

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. Indeed, when one considers the observed increase in temperature and the increase in anthropogenic greenhouse gases, 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. Loosely speaking, the temperature change over the 20th century is the product of the changed energy balance, presumably mostly anthropogenic greenhouse gases, and the climate sensitivity:

Temperature Change (ΔT) = Radiative Forcing Changes (ΔF) x Climate Sensitivity (S)

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 don't know the net radiative forcing because human activity increased the amount of atmospheric aerosols which "seed" clouds and cool.[1] 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 changes when the global temperature changes, is not really known. It was shown in 1989 by Robert Cess of the State University of New York and colleagues, that it is by far the dominant source of uncertainty.2 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. In chapter (xxTemperatur) we have seen that this argument holds no water. Second, climate modelers cannot explain the warming without including the anthropogenic contributions to the net radiative forcing, in particular that of the greenhouse gases.

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.[3] For example, the Little Ice Age in Europe took place while the sun was particularly inactive, during the Maunder 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.[4] These results by the Heidelberg cosmogenic isotope group of Prof. Mangini are portrayed in figure x10x.

Another impressive result over the same time scale is that of the late Prof. Bond and his group, where the solar activity was compared with the Northern Atlantic climate, as recorded on the ocean floor through ice rafted debris[5] (Figure x9x). 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.[6] 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.[7] 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.[7]

Moreover, as we shall demonstrate 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 chapter, it should be mentioned that the leading contender is through solar modulation of the cosmic ray flux reaching the Earth.[8] This is now supported by a range of both empirical and experimental results. More about it in chapter (xxVerstärker).

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 20th 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. The tide gauge record can be seen in figure 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.[9] In absolute terms, it is a variation 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 (see chapter xxVerstärker), 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 the order of 1W/m^2—the amount of heat going into the oceans. Within the radiative forcing uncertainties of clouds, this is indeed the observed variations.[7]

Second, because the forcing variation 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 its 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 minimum and solar maximum, over the 11-year cycle, we can expect the radiative forcing to be similar, i.e., around 1 W/m^2. For comparison, the IPCC in its

2007 report estimates the net anthropogenic forcing to have been 0.6 to 2.4 W/m^2, 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/m^2.

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 ranges for the different climate variables, including the 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 figure 2.

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 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 predictions fit the observations 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 to CO_2. 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".

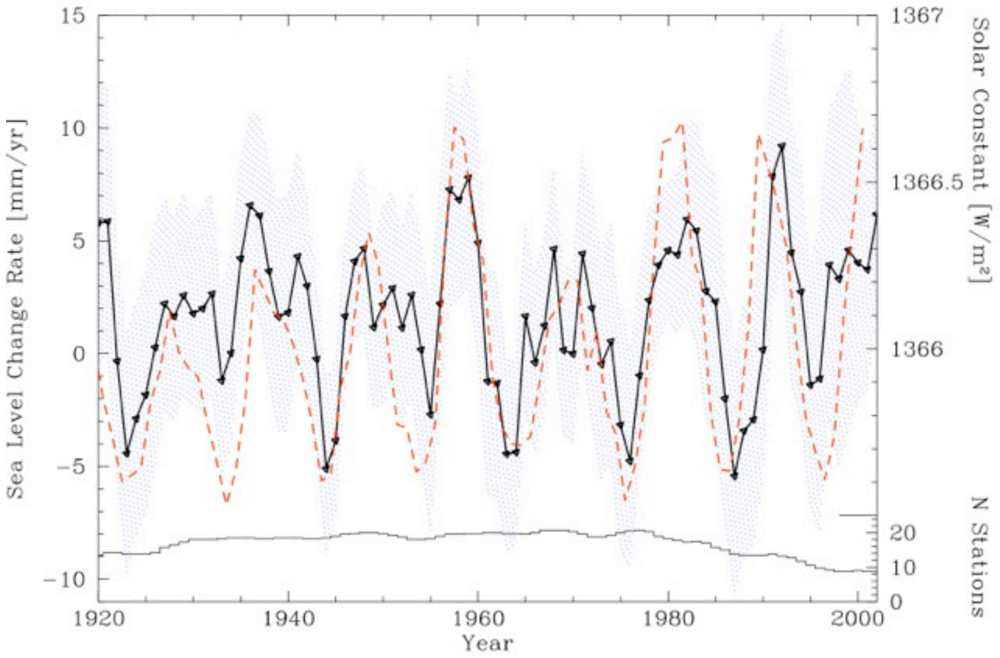

Figure sh1sh: *The sea level change rate (black, with a hatched 1σ error) and solar constant (dashed red line). On short time scales, it originates predominantly from changes in the oceanic heat content. Using this data, the derived changes in the energy budget over the solar cycle correspond to 1 W/m^2, almost an order of magnitude more than can be expected from changes in the solar irradiance (modified after*9*).*

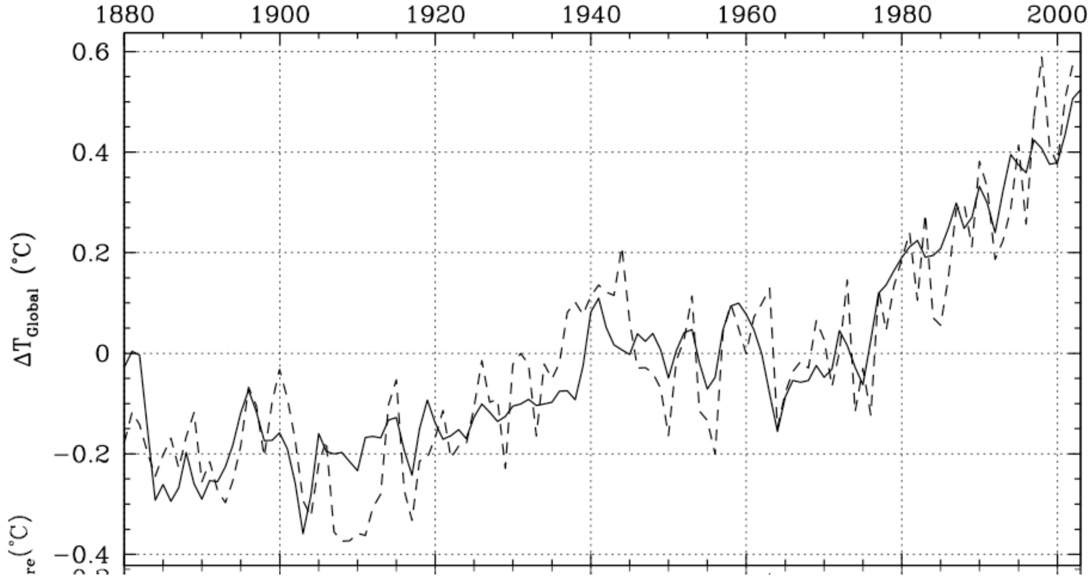

Figure sh2sh: *A comparison between the observed global temperatures (dashed line) and the temperatures modeled using an energy balance model with a diffusive ocean (solid line). The small residual, which is twice smaller than obtained in typical global circulation models, can be obtained if we allow the sun to have large effect on the climate, and that the climate to have a low climate sensitivity. (Source of figure:*10*).*

1. IPCC (2007): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).
2. Cess, R. D., G. L. Potter, J. P. Blanchet, G. J. Boer, S. J. Ghan, J. T. Kiehl, H. Le Treut, Z.-X. Li, X.-Z. Liang, J. F. B. Mitchell, J.-J. Morcrette, D. A. Randall, M. R. Riches, E. Roeckner, U. Schlese, A. Slingo, K. E. Taylor, W. M. Washington, R. T. Wetherald and I. Yagai (1989): Interpretation of Cloud-Climate Feedback as Produced by 14 Atmospheric General Circulation Models. Science **245**, 513-516.
3. Eddy, J. A. (1976): The Maunder Minimum. Science **192**, 1189-1202.
4. Neff, U., S. J. Burns, A. Mangini, M. Mudelsee, D. Fleitmann and A. Matter (2001): Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. Nature **411**, 290-293.
5. Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas and G. Bonani (2001): Persistent Solar Infuence on North Atlantic Climate During the Holocene. Science **294**, 2130-2136.
6. Huang, S., H. N. Pollack and P. Y. Shen (1997): Late Quaternary temperature changes seen in world-wide continental heat flow measurements. Geophysical Research Letters **24**, 1947-1950.
7. Shaviv, N. J. (2005): On climate response to changes in the cosmic ray flux and radiative budget. Journal of Geophysical Research **110**, 1-15.
8. Svensmark, H. (1998): Influence of Cosmic Rays on Earth’s Climate. Physical Review Letters **81**, 5027-5030.
9. Shaviv, N. J. (2008): Using the oceans as a calorimeter to quantify the solar radiative forcing. Journal of Geophysical Research **113**, 1-13.
10. Ziskin, S. and N. J. Shaviv (in press): Quantifying the role of solar radiative forcing over the 20th century. Astrophysics and Space Science.