# The Climatic role of the Sun – How, How Much and What does it Mean?

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## Abstract

The extent of the solar variability's climatic role is a topic of intense debate. The main reason is that if the sun is important, it can explain part of the 20th century warming, and it would imply that the climate sensitivity is on the low side, such that 21st century temperature increase due to human activity will be moderate. Here I summarize the evidence for how the sun affects the climate (primarily through modulation of the cosmic ray flux), how large the solar forcing is, and its implications to the understanding of current climate issues.

## 1. Introduction

Different empirical pieces of evidence suggest that the sun affects the climate. But the size of the effect and its implications are still part of a highly contentious debate. On one side stand those who claim that the sun does not affect the climate by mechanisms other than the relatively small changes in the solar irradiance. In such a scenario, the sun could not have played an important role in the 20th century warming. On the other side, there are those who argue that the sun is affecting the climate more than one could expect from changes in the solar irradiance. This in turn implies that the increased solar activity over the 20th century should have played a role in the 20th century global warming. I will argue here that the evidence suggests the latter.

We begin in §2 by summarizing the evidence that the sun has a large effect on climate. We will then continue in §3 by showing that the large effect appears to arise from the climate's sensitivity to the amount of atmospheric ionization, which is governed by the flux of cosmic rays. In §4 we will show that the effect can be quantified by several means, in particular, by looking at the 11-year solar cycle in the ocean heat content. In §5 we will show that the amplified solar effect helps us understand 20th century warming and also predict the possible range of global warming over the 21st century.

## 2. Does the sun affect the climate?

It is already more than 200 years since Sir William Herschel [1] claimed that variations in solar activity affect climate on Earth. Since he did not have any reliable temperature measurements, Herschel looked for indirect proxies. He compared the price of wheat in the London wheat exchange to the solar activity as mirrored in the sunspot number, and found a correlation between them.

In the 1970's, Eddy [2] pushed the idea that solar activity may be affecting the terrestrial climate. He found a correlation between long-term variations in solar activity and different climate indicators. For example, he found that the nadir of the period called "the little ice age" in Europe during the latter half of the 17th century took place in a period during which solar activity was very low. This low activity culminated in a several decade period during which there were almost no apparent sunspots, which was called the "Maunder minimum". On the other hand, there were other periods, such as the end of the middle ages, during which solar activity was as high as the latter half of the 20th century, and the temperatures were roughly as warm as today. During the "medieval optimum", Vikings could settle in Greenland (and call it a "green land") and catholic monks adopted sandals suitable for warm climates.

Presently, there is a large number of different empirical indicators showing that changes in solar activity have a non-negligible climatic effect. Changes in solar activity manifest themselves as changes in the strength of the solar magnetic field, changes in the sunspot number, in the strength of the solar wind (which is responsible for the impressive tails of comet) and other phenomena. These changes can be divided into three time scales.

The basic variation is an activity cycle of about 11 years, which arises from quasi-periodic reversals of the solar magnetic dipole filed. 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, solar eruptions may appear on the time scale of days. Today there is evidence linking solar activity to the terrestrial climate on all these scales (e.g., ref. [3-11]).

Since the work of Eddy, many empirical results show a correlation between different climatic reconstructions and different solar activity proxies [5-7]. In particular, one of the most beautiful results is of a correlation between an Indian Ocean temperature proxy and solar activity [5].

It is much harder to see climate variations over the 11-year solar cycle. 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 oceanic 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 1°C after several centuries, as is observed [10], then the same radiative forcing varying over the 11-year solar cycle is expected to give rise to temperature variations of only 0.1°C or so [11]. 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 [3,4,11].

Clearly then, there is ample evidence to suggest that solar variability has a large effect on climate. The question is therefore how does this link arise and whether it can be quantified.

## 3. How does the sun affect the climate?

Grossly speaking, there are two types of mechanisms that can amplify solar activity. The first type is hypersensitivity to one of the non-thermal solar components. One such mechanism was proposed by Joanna Haigh from the UK, and it is hypersensitivity to variations in the UV [12]. This kind of sensitivity can arise because UV is almost entirely absorbed in the stratosphere and although it only includes about 1% of the solar output, the stratospheric structure (and thus the tropospheric-stratospheric interface) is determined by this 1%. Numerical simulations have shown that by including the variations in the UV and their effects on the stratosphere, one can amplify the surface climate variations by as much as a factor of two [13], namely, it can be a large effect. But as we shall see below, it still cannot explain for example the large amounts of heat seen entering the oceans every solar cycle.

The second type of mechanisms is indirect, through the solar modulation of the cosmic ray flux and the effect that the latter may have on the climate. Cosmic rays are high energy particles (primarily protons) which appear to originate from supernova remnants (the leftovers from the explosive death of massive stars). A possible climatic link through cosmic rays was first suggested by Ney already in 1959 [14]. It was well known that the solar wind decreases the flux of these high energy particles and that these particles are the primary source of ionization in the troposphere (which is the lower part of the atmosphere). Ney proposed that the changing levels of ionization can play some climatic role.

In the 1970's, Dickinson proposed the possibility that the atmospheric ion density could play a role in the formation of cloud condensation nuclei [15]. When air reaches saturation, that is, 100% humidity, the preferred equilibrium state is that of liquid water. However, if the water vapor has nothing to condense upon, it will not do so. In fact, under very clean environments, it is possible to reach 400% humidity before the vapor condenses spontaneously. In order to get clouds at 100%, as we see in nature, we need cloud condensation nuclei (CCNs). Over land, there are many natural sources for CCNs, however, this is not the case over the oceans, were the CCNs must be grown out of something. Dickenson suggested that this growth process of CCNs could be affected by the amount of atmospheric charge.

In the 1990's, Svensmark and his colleagues found empirically that clouds, and in particular low altitude clouds, appear to vary in sync with the solar activity [16-19]. Since Svensmark's work, more evidence was found to support this link, the full picture of which is the following. When the sun is more active, it has a stronger solar wind. The stronger wind slows the cosmic rays as they propagate into the inner solar system. As a consequence, the amount of atmospheric ionization is reduced. Less ions reduce the efficiency with which new cloud condensation nuclei can grow, especially over the oceans, such that the clouds that later form have fewer but larger droplets. These clouds are less white, they reflect sunlight less efficiently and therefore cause more warming.

The evidence to this particular link comes from experimental results and from correlations between independent cosmic ray flux variations and climate changes on different time scale. Just by itself, a cosmic ray climate correlation over the 11-year solar cycle does not necessarily imply a causal link. One could imagine that the solar activity affects both the cosmic ray flux and the climate, making it appear that there is a causal relation between the latter two. Nevertheless, there are indications that it is not just an apparent link. For example, the dependence of the relative cloud cover variations with the magnetic latitude is the same as the latitudinal dependence of the relative change in the atmospheric ionization, over the solar cycle. Another important fact is that the full solar cycle is not that of 11-years, but 22-years instead. It takes 11-years for the magnetic field to flip, but 22-years for it to return to the original state. However, all the solar activity proxies are "blind" to the polarity of the magnetic field, all except the cosmic ray flux which exhibits a clear asymmetry between odd and even solar cycles. This asymmetry is seen in the change of the low altitude cloud cover [19], implying that the cloud cover variations originate from cosmic ray flux variations.

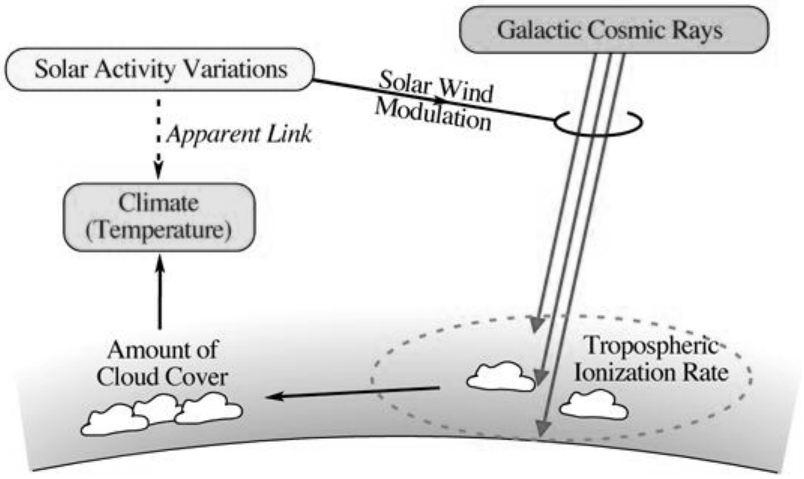

Figure 1: The cosmic ray link between solar activity and the terrestrial climate. The changing solar activity is responsible for a varying solar wind strength. A stronger wind will reduce the flux of cosmic ray reaching Earth, since a larger amount of energy is lost as they propagate up the solar wind. The cosmic rays themselves come from outside the solar system (cosmic rays with energies below the "knee" at $10^{15}$eV, are most likely accelerated by supernova remnants). Since cosmic rays dominate the tropospheric ionization, an increased solar activity will translate into a reduced ionization, and empirically (as shown below), also to a reduced low altitude cloud cover. Since low altitude clouds have a net cooling effect (their "whiteness" is more important than their "blanket" effect), increased solar activity implies a warmer climate. Intrinsic cosmic ray flux variations will have a similar effect, one however, which is unrelated to solar activity variations.

On short time scales, 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, a recent study of Forbush decreases has shown the cosmic ray mechanism at work. Not only was a cloud signal observed, the intermediate step of affecting the aerosol size distributed was detected as well [9].

Over longer time scales, of decades to millennia, there are the aforementioned solar climate links, however, even though they demonstrate a clear causal link between solar activity and climate change, it is hard to prove with them that this link is specifically due to solar modulation of the cosmic ray flux. If we however go to longer time scale still, there is evidence from cosmic ray flux variations, which are not associated with solar activity.

On the time scale of tens of thousands of years, Earth's magnetic field varies and with it the flux of cosmic rays which can penetrate the atmosphere. However, because the magnetic field can only prevent the penetration of cosmic rays which are anyway severely attenuated by the atmosphere, changing the magnetic field, and even altogether switching it off is not expected to give rise to significant climate effects. A rough estimate gives that switching the magnetic field will only cool the Earth by typically 1°C. However, over the time scale that the magnetic field changes, Earth witnesses variations that are 5 times larger from other natural causes. In other words, it is not easy to detect the terrestrial field effects, but it was claimed to be detected nonetheless [20].

Over geological time scale, the cosmic ray flux changes because of our motion around the Milky Way and the changing solar neighborhood. Because the cosmic ray flux originates from the death of the short living massive stars, in events called supernovae, passage through regions with a higher star formation rate is associated with an elevated cosmic ray flux level. The largest variations actually originate from the solar system's passage through the milky way spiral arms [21-22].

As it turns out, it is possible to reconstruct the changes in the cosmic ray flux originating from these passages, using iron meteorites. This reconstructed flux shows variations by as much as a factor of 3 between the flux between the spiral arms and the flux in them. And indeed, when the global climate is studied over this time scale, it is possible to see all the past seven passages of the solar system through the arms of the galaxy over the past billion years. Every spiral arm passage, the increased cosmic ray flux manifested itself as a cold epoch during which Earth's poles were glaciated. When the solar system was in between the arms, it was much warmer than the present climate [21-23].

In addition to the empirical evidence, an experiment was carried out by Svensmark's group. This experiment was carried out to simulate marine air conditions and study how the changed atmospheric ionization affects the growth of condensation nuclei under controlled laboratory conditions. The experiment demonstrated that elevated ionization rates give rise to a more efficient formation of condensation nuclei [24]. Today, this experiment is carried out in a mine in the UK to see how the total removal of ions affect the formation of condensation nuclei, and also at CERN, to corroborate the effects of ionization.

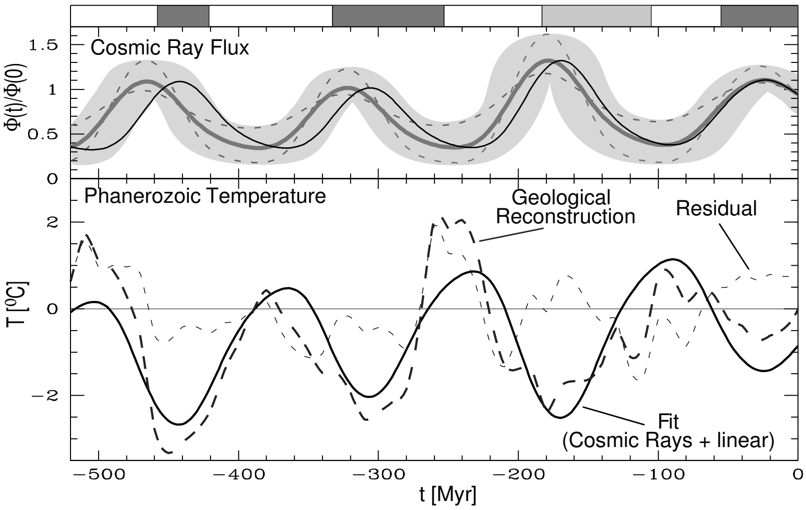

Figure 2: The cosmic ray flux (Φ) and tropical temperature anomaly (ΔT) variations over the Phanerozoic. The upper curves describe the reconstructed CRF using iron meteorite exposure age data. The heavy gray line depicts the nominal CRF, while the shading delineates the allowed error range. The two dashed curves are additional CRF reconstructions that fit within the measurement errors. The solid black curve describes the nominal CRF reconstruction after its period was fine-tuned, *within the measurement error*, to best fit the low-latitude temperature anomaly. The bottom dashed curve depicts the temperature reconstruction, measured with a 10 Myr bin and smoothed with a 5-bin top hat averaged. The solid line is the predicted ΔT based on the nominal CRF model above while also taking into account a secular long-term linear contribution. The light dashed line is the residual. More details can be found in ref. [23].

## 4. How large is the solar/climate effect?

After demonstrating that cosmic ray modulation amplifies solar activity, the next step is to quantify the size of the effect. Here we will concentrate on three methods (out of more which exist). In the first two, we will consider at the changes in the cloud cover and the changes in the heat going into the oceans, both over the solar cycle. In the third method, we will consider the 20th century warming. Since the latter is relevant to the understanding of 20th century warming, will address it in the next section.

Cloud cover variations: If one works under the assumption that the cloud cover variations which are observed to be in sync with the 11-yr solar cycle are the mechanism through which solar variability is amplified, then satellite observations can be used to estimate the forcing associated with solar variability.

It was shown using the ERBE satellite data that the observed 1.6±0.4% low altitude cloud cover variations correspond to a radiative forcing of 1.0±0.35 $W/m^2$ [17,4]. Note that this implicitly assumes several assumptions. For example, it assumes that the radiative forcing changes associated with the total 27% low altitude cloud cover is the same, per 1% change, as the 1.6% change associated with the solar cycle. This is not necessarily the case because we should expect cloud cover of the oceans to be more susceptible to change in the atmospheric ionization than cloud cover land (where cloud condensation nuclei are naturally abundant).

<u>Ocean Heat Content:</u> Another method for determining the radiative forcing variations associated with the solar cycle is by studying the total ocean heat content. This is because the total ocean heat capacity is by far larger than that of any other component in the climate system. As a consequence, changes in the total amount of heat can be used to derive the changes in the radiative budget of Earth.

Such an analysis reveals that the amount of heat going into the oceans is 1.05±0.25 $W/m^2$, of which only 0.17 $W/m^2$ can be explained by changes in the solar irradiance [11]. This large flux can be seen in three independent data sets – direct measurements of the ocean heat content, the sea surface temperature, and the thermal expansion derived from tide gauges. Although this analysis cannot point to the actual mechanism amplifying the solar climate, it is interesting to note that it is consistent with the changes in the energy budget associated with the cloud cover variations. The tide gauge based data is depicted in fig. 3.

<u>Effect on the global temperature</u>. If we wish to translate the changes in the radiative forcing into changes in the temperature, we require the Earth's climate sensitivity, namely, how large is the temperature change expected from a given change in the energy budget.

The canonical IPCC range, obtained primarily from global circulation models is a temperature increase of 1.5 to 4.5°C per $CO_2$ doubling, i.e., 0.4 to 1.2°C/(W $m^{-2}$). The reason for the large uncertainty is the very limited understanding of different climate feedbacks, with cloud cover being the primary one. Several different analyses have shown empirically that the climate sensitivity is low [e.g., ref. 25]. In particular, Shaviv [4] has shown that once one includes the CRF/climate link, different empirical estimates become more consistent with each other, and give a sensitivity of 0.35±0.09°C/(W $m^{-2}$).

If we use the latter value and assume that the long term solar activity variations are similar in amplitude to the variability over the 11-year cycle, then about 0.4±0.2°C of the 20th century warming should be attributed to the increased solar activity.

On shorter time scales, the expected variations are smaller. This is because of the large heat capacity of the oceans, which forces the terrestrial climate system to behave as a low pass filter for variations in the radiative budget. In particular, the 1 W m$^{-2}$ variations over the 11-yr solar cycle translate into ~0.1°C variations, as is indeed observed.

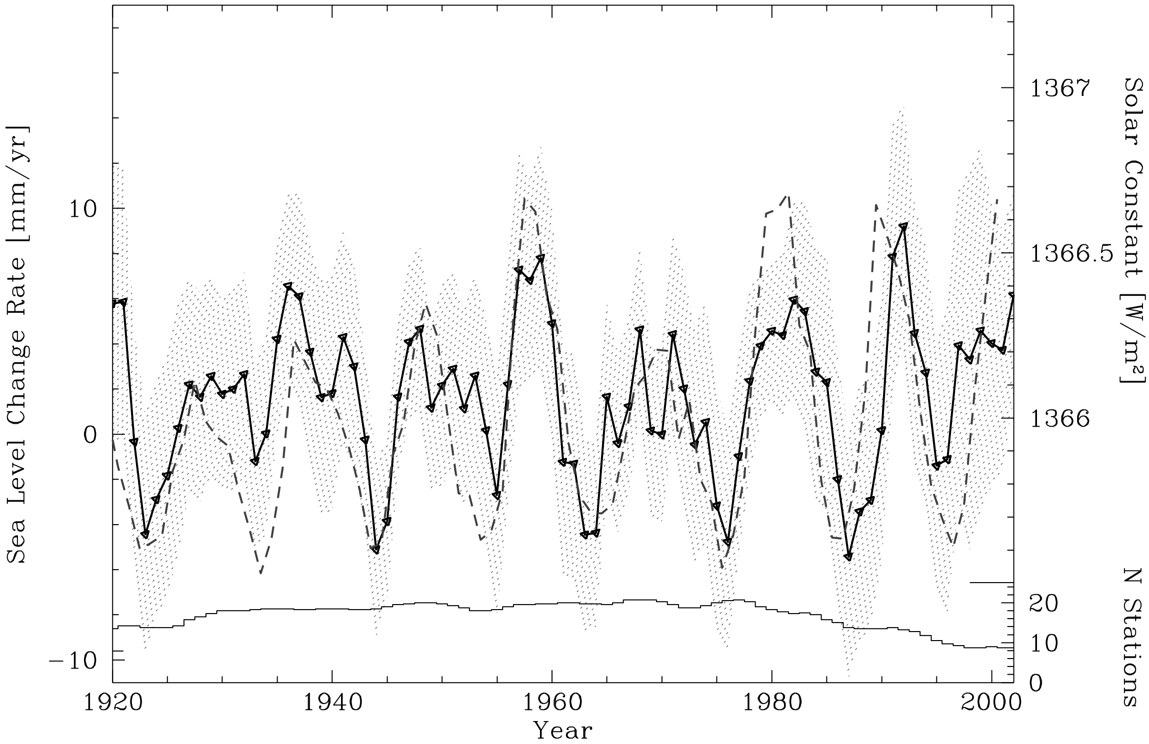

Figure 3: Sea Level vs. Solar Activity. Sea level change rate is based on 24 tide gauges for the stringent criteria they satisfy (solid line, with 1-σ statistical error range denoted with the shaded region). The rates are compared with the total solar irradiance variations (dashed line, with the secular trends removed). More details in ref. [11].

## 5. What does it mean?

Understanding the 20th century warming. The fact that the sun has a large effect on the climate implies that the increased solar activity over the 20th century should have played a role in the 20th century warming, one which cannot be neglected. As shown above, the solar forcing associated with the 11-year solar cycle can be used to estimate this contribution to be 0.4±0.2°C. Since the total temperature increase is about 0.8°C, the contribution from other forcings, in particular that of anthropogenic greenhouse gases, is comparable.

This conclusion can be obtained more directly by studying the actual 20th century temperature increase. Ziskin [26] modeled the 20th century climate using a multi-box diffusion model with various free parameters. The most important were the climate sensitivity, the size of the indirect solar forcing and the size of the indirect aerosol effect. By systematically searching for the region in parameter space for which the model gave temperature and ocean heat content variations which best fit the observed data over the past century, it was possible to obtain probability distribution functions for the different climate model parameters.

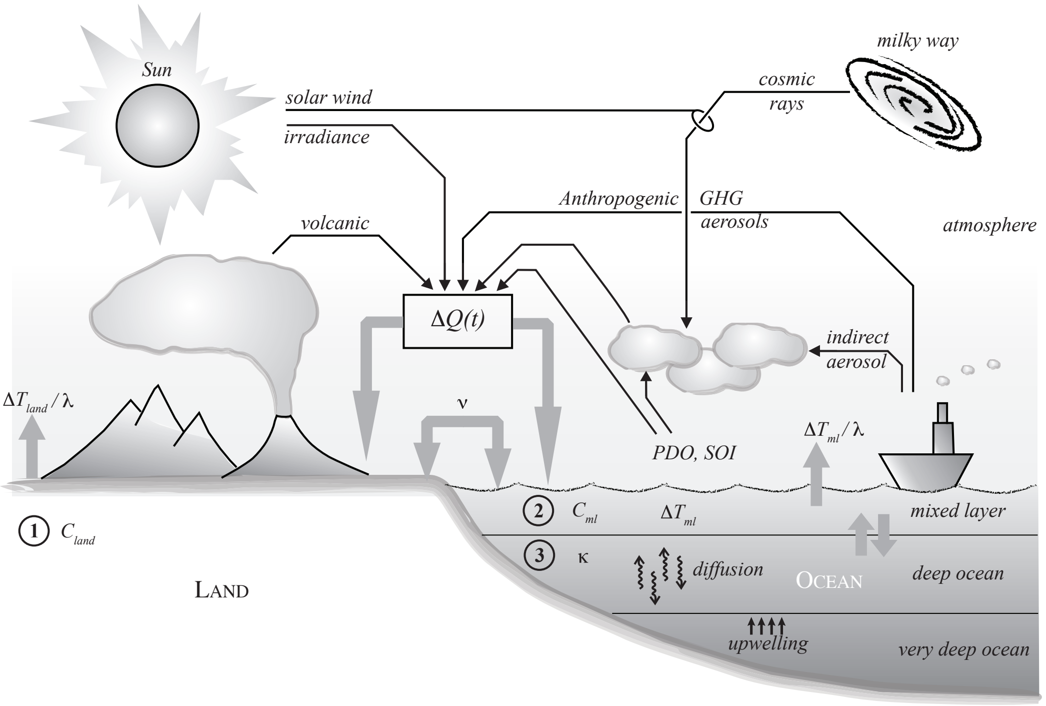

Figure 4: A heuristic description of the energy model employed. The black lines with arrows denote the different forcings, which are either known or described with the different model parameters. The heavy gray arrows denote interaction between the different components in the systems: Land, Ocean Mixed Layer and Ocean Deep Layer. The set of equations in described in detail, in ref. [26].

It was found that by allowing the sun to have a climatic effect that is larger than just the changes in the solar irradiance one obtains that the r.m.s of the residual between the predicted temperature and the observed temperature is typically 0.1°C. In addition, one finds that the increased solar forcing explains 0.3±0.1°C of the warming, while the anthropogenic caused increase is 0.4±0.1°C. Last, the most important result, is that the best fit requires a climate sensitivity of 0.25±0.09°C/W $m^{-2}$. The fit and the residual are depicted in fig. 5.

These results should be compared with fits obtained using the same climate model or with full GCMs that do not include additional solar forcing, where the r.m.s. residuals are typically 0.2°C. The reason for the degraded fit is that in order to explain the observed warming without the extra solar forcing, the climate sensitivity has to be higher. But the higher sensitivity forces the climate to overreact to different radiative forcings, more than the real climate does, for example, following volcanic eruptions (e.g., see ref. [25]).

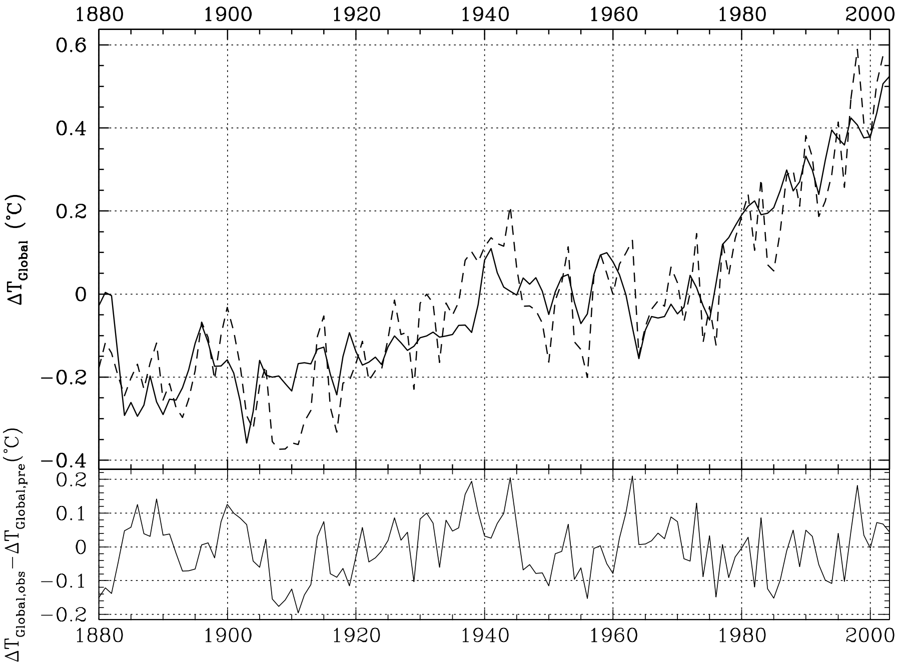

Figure 5: Top: The predicted (solid) and observed (dashed) global temperature [26]. Bottom: The residual temperature.

Predictions for the 21st century temperature increase. As demonstrated above, the climate sensitivity obtained by different empirical methods is typically comparable to that expected for a feedback-less black body Earth, when allowing the sun to have a large effect on climate. This sensitivity can be used to estimate the temperature increase over the 21st century, based on the chosen emission scenario.

Business as usual scenarios typically give that the amount of tropospheric $CO_2$ will roughly double over the 21st century. This corresponds to a radiative forcing of about 4W/m$^2$, or, an equilibrium warming of about 1°C. This is significantly less than the much larger predictions of the GCM based IPCC predictions.

## References:

1. W. Herschel. Some remarks on the stability of the light of our sun. Royal Society of London Philosophical Transactions Series I, 86:166–226, 1796.
2. J. A. Eddy. The Maunder Minimum. Science, 192:1189–1202, 1976.
3. W. B. White, J. Lean, D. R. Cayan, and M. D. Dettinger. Response of global upper ocean temperature to changing solar irradiance. J. Geophys. Res., 102:3255–3266, 1997.
4. N. J. Shaviv. On climate response to changes in the cosmic ray flux and radiative budget. J. Geophys. Res., 110:8105, 2005.
5. U. Neff, S. J. Burns, A. Mangini, M. Mudelsee, D. Fleitmann, and A. Matter. Strong coherence between solar variability and the monsoon in Oman between 9 and 6kyr ago. Nature, 411:290–293, 2001.
6. G. Bond, B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, and G. Bonani. Persistent Solar Influence on North Atlantic Climate During the Holocene. Science, 294:2130–2136, 2001.
7. D. A. Hodell, M. Brenner, J. H. Curtis, and T. Guilderson. Solar forcing of drought frequency in the Maya lowlands. Science, 292:1367–1370, 2001.
8. B. A. Tinsley. Correlations of atmospheric dynamics with solar wind-induced changes of air-earth current density into cloud tops. J. Geophys. Res., 101:29701–29714, 1996.
9. H. Svensmark, T. Bondo, and J. Svensmark. Cosmic ray decreases affect atmospheric aerosols and clouds. Geophys. Res. Lett., 36:15101, August 2009.
10. S. P. Huang, H. N. Pollack, and P.-Y. Shen. A late Quaternary climate reconstruction based on borehole heat flux data, borehole temperature data, and the instrumental record. Geophys. Res. Lett., 35:13703, July 2008.
11. N. J. Shaviv. Using the oceans as a calorimeter to quantify the solar radiative forcing. J. Geophys. Res., 113(A11), 2008.
12. J. D. Haigh. The Role of Stratospheric Ozone in Modulating the Solar Radiative Forcing of Climate. Nature, 370:544, 1994.
13. A. Larkin, J. D. Haigh, and S. Djavidnia. The Effect of Solar UV Irradiance Variations on the Earth's Atmosphere. Sp. Sci. Res., 94:199–214, November 2000.
14. E. P. Ney. Cosmic radiation and weather. Nature, 183:451, 1959.
15. R. E. Dickinson. Solar Variability and the Lower Atmosphere. Bull. Am. Met. Soc., 56:1240–1248, 1975.
16. H. Svensmark. Influence of Cosmic Rays on Earth's Climate. Phys. Rev. Lett., 81:5027–5030, 1998.
17. N. Marsh and H. Svensmark. Cosmic Rays, Clouds, and Climate. Sp. Sci. Rev., 94:215–230, 2000.
18. E. Palle Bago and J. Butler. The influence of cosmic terrestrial clouds and global warming. Astron. Geophys., 41:18–22, 2000.
19. H. Svensmark. Cosmoclimatology: a new theory emerges. Astronomy & Geophysics, 48(1):1–18, 2007.
20. M. Christl, A. Mangini, S. Holzkämper, and C. Spötl. Evidence for a link between the flux of galactic cosmic rays and Earth's climate during the past 200,000 years. Journal of Atmospheric and Terrestrial Physics, 66:313–322, 2004.
21. N. J. Shaviv. The spiral structure of the Milky Way, cosmic rays, and ice age epochs on Earth. New Astron., 8:39–77, 2003.
22. N. J. Shaviv. Cosmic Ray Diffusion from the Galactic Spiral Arms, Iron Meteorites, and a Possible Climatic Connection. Phys. Rev. Lett., 89(5):051102, 2002.
23. N. J. Shaviv and J. Veizer. A celestial driver of phanerozoic climate? GSA Today, pages 4–11, July 2003.
24. H. Svensmark, J. O. P. Pedersen, N. D. Marsh, M. B. Enghoff, and U. I. Uggerhøj. Experimental evidence for the role of ions in particle nucleation under atmospheric conditions. Royal Society of London Proceedings Series A, 463:385–396, 2007.
25. R.S. Lindzen and C. Giannitsis. On the climatic implications of volcanic cooling. Journal of Geophysical Research. D. Atmospheres, 103:5929–5941, 1998.
26. S. Ziskin and N. J. Shaviv. Quantifying the role of solar radiative forcing over the 20th century. submitted to J. Atmos. Sol. Terr. Phys.