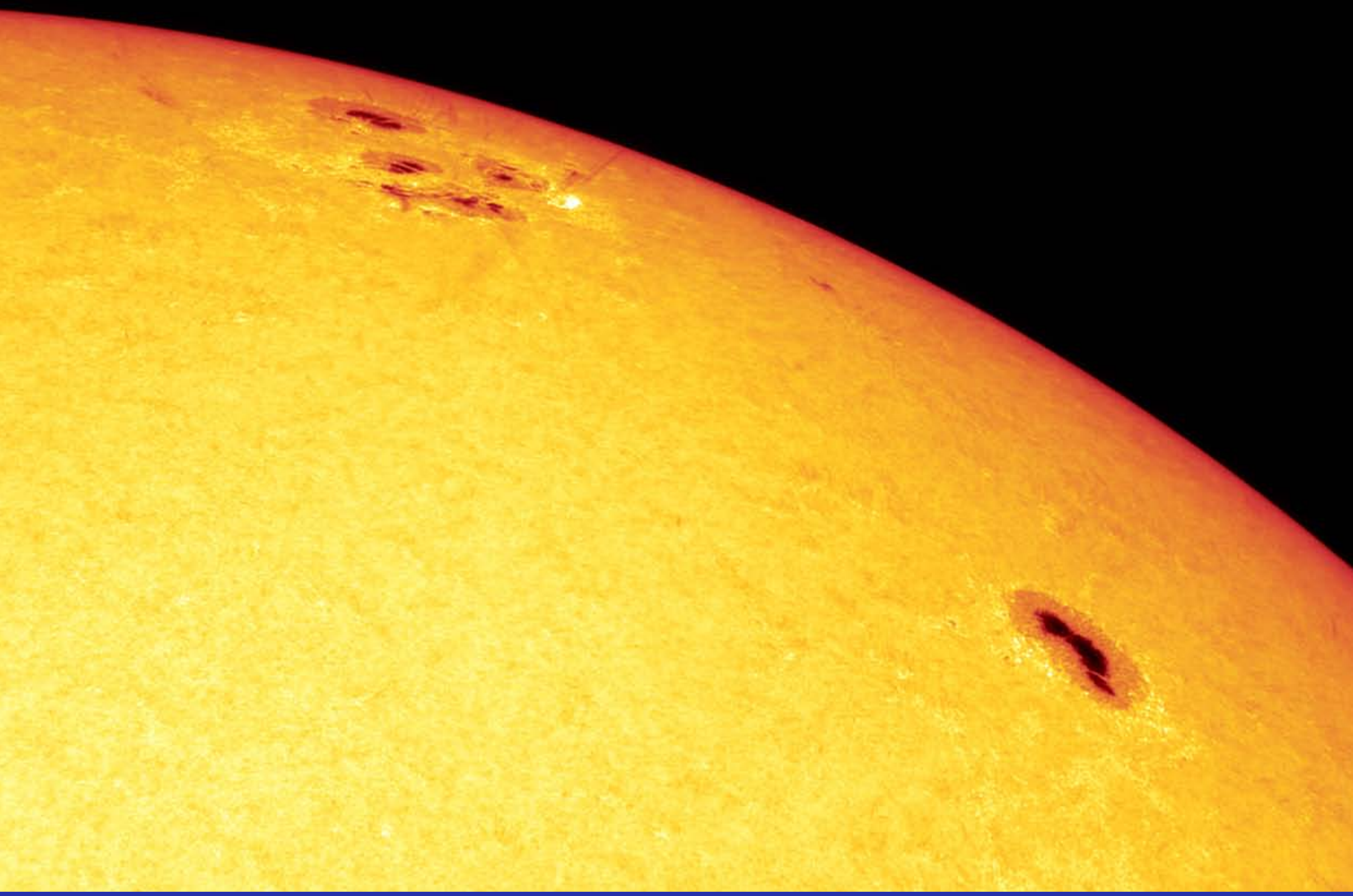
FORCE MAJEURE

The Sun's Role in Climate Change

Henrik Svensmark



The Global Warming Policy Foundation

GWPF Report 33

FORCE MAJEURE
The Sun's Role in Climate Change

Henrik Svensmark

ISBN 978-0-9931190-9-5

Contents

About the author

Henrik Svensmark (born 1958) is a physicist and a senior researcher in the Astrophysics and Atmospheric Physics Division of the National Space Institute (DTU Space) in Lyngby, Denmark. In 1987, he obtained a PhD from the Technical University of Denmark and has held postdoctoral positions in physics at three other organizations: the University of California, Berkeley, the Nordic Institute for Theoretical Physics, and the Niels Bohr Institute. Henrik Svensmark presently leads the Sun–Climate Research group at DTU Space.

Acknowledgement

I thank Lars Oxfeldt Mortensen, Nir Shaviv and Jacob Svensmark and two reviewers for contributing helpful comments to this manuscript.

Executive summary

Over the last twenty years there has been good progress in understanding the solar influence on climate. In particular, many scientific studies have shown that changes in solar activity have impacted climate over the whole Holocene period (approximately the last 10,000 years). A well-known example is the existence of high solar activity during the Medieval Warm Period, around the year 1000 AD, and the subsequent low levels of solar activity during the cold period, now called The Little Ice Age (1300–1850 AD). An important scientific task has been to quantify the solar impact on climate, and it has been found that over the eleven-year solar cycle the energy that enters the Earth's system is of the order of 1.0–1.5 W/m^2. This is nearly an order of magnitude larger than what would be expected from solar irradiance alone, and suggests that solar activity is getting amplified by some atmospheric process.

Three main theories have been put forward to explain the solar–climate link, which are:

- solar ultraviolet changes
- the atmospheric-electric-field effect on cloud cover
- cloud changes produced by solar-modulated galactic cosmic rays (energetic particles originating from inter stellar space and ending in our atmosphere).

Significant efforts has gone into understanding possible mechanisms, and at the moment cosmic ray modulation of Earth's cloud cover seems rather promising in explaining the size of solar impact. This theory suggests that solar activity has had a significant impact on climate during the Holocene period. This understanding is in contrast to the official consensus from the Intergovernmental Panel on Climate Change, where it is estimated that the change in solar radiative forcing between 1750 and 2011 was around 0.05 W/m^2, a value which is entirely negligible relative to the effect of greenhouse gases, estimated at around 2.3 W/m^2. However, the existence of an atmospheric solar-amplification mechanism would have implications for the estimated climate sensitivity to carbon dioxide, suggesting that it is much lower than currently thought.

In summary, the impact of solar activity on climate is much larger than the official consensus suggests. This is therefore an important scientific question that needs to be addressed by the scientific community.

1 Introduction

The Sun provides nearly all the energy responsible for the dynamics of the atmosphere and oceans, and ultimately for life on Earth. However, when it comes to the observed changes in our terrestrial climate, the role of the Sun is not uniformly agreed upon. Nonetheless, in climate science an official consensus has formed suggesting that the effect of solar activity is limited to small variations in total solar irradiance (TSI), with insignificant consequences for climate. This is exemplified in the reports of Working Group I of the Intergovernmental Panel on Climate Change (IPCC), who estimate the radiative forcing on climate from solar activity between 1750 and 2011 at around 0.05 W/m^2. This value is entirely negligible compared to changes in anthropogenic greenhouse gases, whose forcing is estimated at around 2.3 W/m^2.[1]

The aim of this report is to give a review of research related to the impact of solar activity on climate. Contrary to the consensus described above, there is abundant empirical evidence that the Sun has had a large influence on climate over the Holocene period, with temperature changes between periods of low and high solar activity of the order of 1–2 K. Such large temperature variations are inconsistent with the consensus and herald a real and solid connection between solar activity and Earth's climate. The question is: what is the mechanism that is responsible for the solar–climate link? A telling result is given by the energy that enters the oceans over the 11-year solar cycle, which is almost an order of magnitude larger ($\sim$1–1.5 W/m^2) than the corresponding TSI variation ($\sim$0.2 W/m^2). Solar activity is somehow being amplified relative to the TSI variations by a mechanism other than TSI.

There are other possible drivers of these changes: solar activity also manifests itself in components other than TSI. These include large relative changes in its magnetic field, the strength of the solar wind (the stream of charged particles that carries the magnetic field), modulation of cosmic ray ionisation in the Earth's atmosphere, and the amount of ultraviolet (UV) radiation, to name a few. All of these are part of what is referred to as 'solar activity', and all have been suggested to influence climate as well. In particular, it will be shown that a mechanism has been identified that can explain the observed changes in climate, and which is supported by theory, experiment and observation.

This report is not meant to be an exhaustive representation of all the published papers related to a solar influence on Earth's climate, but aims to give a clear presentation of the current knowledge on the link between solar activity and climate. A comprehensive review of the Sun's impact on climate was published previously,[2] but is now eight years old; important progress on the mechanism linking solar activity and climate has been made since. Technical material will not be included in the report, but rather reference will be made to the literature in the field so that the interested reader can find further information.

2 The sun in time

Solar activity

One of the lessons from scientific studies of the Sun is that it is highly dynamical, exhibiting changes on timescales from seconds to millennia. Solar activity is caused by magnetic fields that are generated by the Sun's differential rotation and by convection of the solar plasma. The solar equator rotates faster than the poles: the equator has a period of around 25 days, compared to around 38 days at the poles. This difference causes the magnetic dipole field to wind up. Due to the repulsion and lower density of the field lines, they eventually pene-

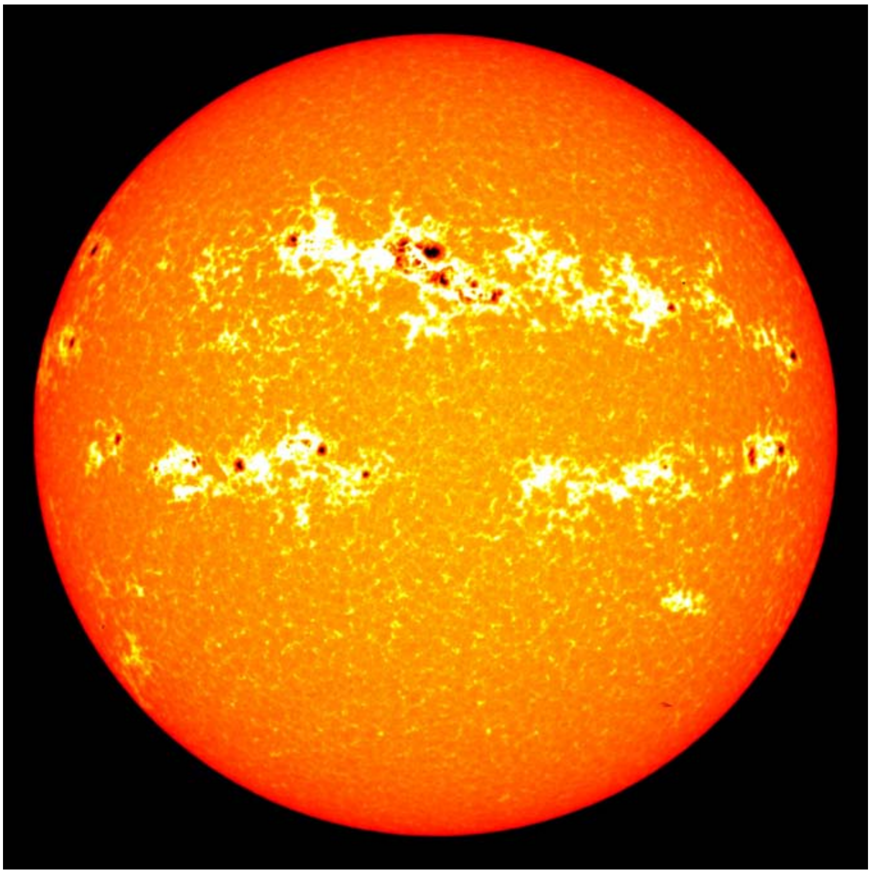


Figure 1: The Sun during a period of high solar activity.
The colours have been altered to enhance the appearance of the faculae (white regions) which are hotter than the sunspots (red–black regions). The dark regions associated with sunspots tend to lower, whereas the brighter regions tend to increase, the solar flux reaching the Earth. Source: NASA/Goddard Space Flight Center Scientific Visualization Studio.

trate the surface of the Sun – the Photosphere – as what are called 'sunspots'. These regions appear dark because the magnetic fields inhibit convection and so they are colder than the surrounding regions. In addition to sunspots, there are bright regions called 'faculae', which are granular structures on the Sun's surface that are slightly hotter than the surrounding photosphere (see Figure 1). The basic variation in sunspots is an activity cycle of about 11 years, which arises from quasi-periodic reversals of the solar magnetic dipole field. Every solar cycle, the number of sunspots increases to a peak, which is known as a 'solar maximum'. Then, after a few years of high activity, the Sun will display low activity for a period known as a 'solar minimum'.

On longer timescales (from decades to millennia), there are irregular variations in solar activity that modulate the 11-year sunspot 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 they were low or almost absent during the Maunder Minimum (1645–1715) and the Dalton Minimum (1796–1820), as shown in Figure 2. Here the record of activity is based on observations of sunspots using a telescope. The record was initiated by Galileo Galilei in 1610 and since that time observations have been performed by numerous observers, resulting in a continuous record more than 400 years long.

Of course, the record contains observational bias due to changes in instrumentation and

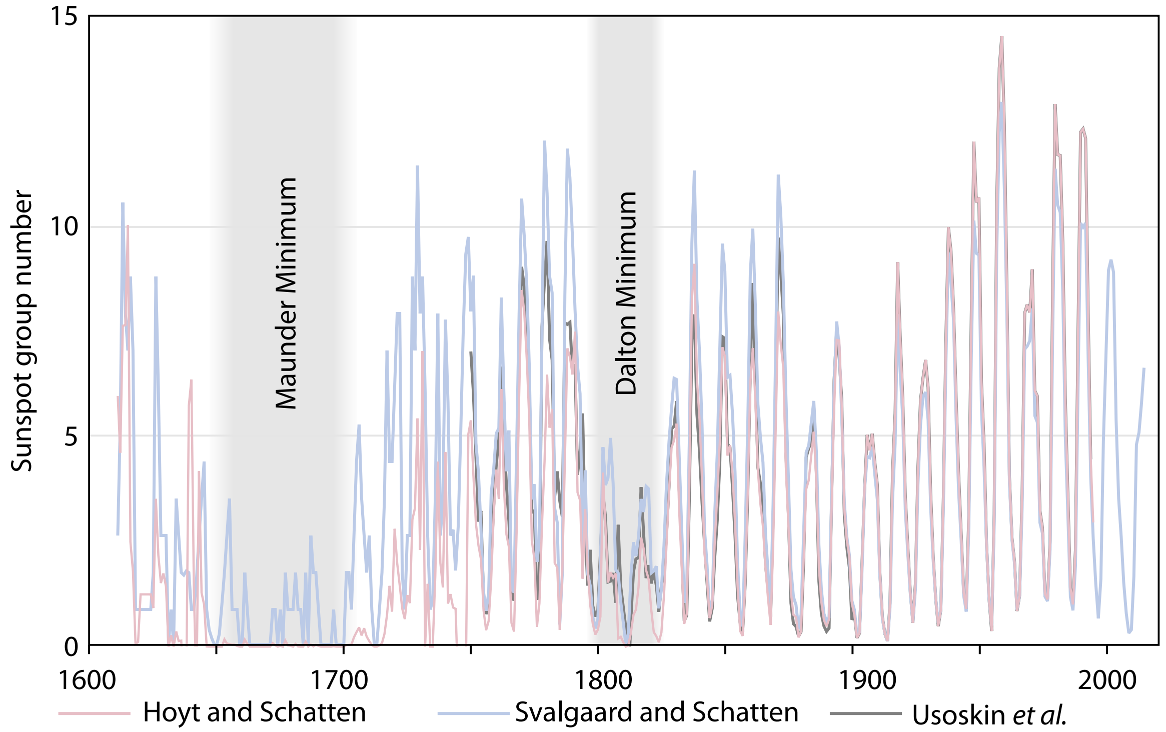


Figure 2: Three reconstructions of the sunspot group record.
The sunspot group number is the number of groups of sunspots. Sunspot groups have been easier to observe in the past since it is not necessary to resolve individual sunspots. Notice that the quasi-period of 11 years is modulated on longer timescales. Two of the three reconstructions indicate a secular increase in solar activity since the Maunder Minimum. Sources: Hoyt and Schatten, covering 1610–1995,[3] Svalgaard and Schatten, covering 1610–2015,[4] and Usoskin *et al.*, 1749–1995.[5]

changes in the method of counting sunspots, leading to uncertainty, particularly in the early part of the record. Figure 2 illustrates this problem. The three reconstructions of the sunspot group number are shown. It is seen that two of the reconstructions (pink and grey curves) support the idea of a secular increase in solar activity towards the end of the 20th century.[3,5,6] However, the third reconstruction (blue curve) deviates from the other two by being significantly and systematically higher in the 18th and 19th centuries.[4] This discrepancy has not been resolved but, as we shall see, records of changes in cosmogenic isotopes support the idea of increasing magnetic solar activity up to end of the 20th century.

Solar modulation of cosmic rays

Solar activity modulates cosmic rays, also referred to as galactic cosmic rays. These are very energetic particles originating from the interstellar medium; in other words, from outside the solar system. They obtain their energy when they are accelerated by the shock-fronts from supernovae (stars that ends their lives in violent explosions). When cosmic rays enter the solar system they have to penetrate the Heliosphere, the region of space that is dominated by the Sun's magnetic field, carried by the solar wind. Here the cosmic ray particles get scattered by magnetic fluctuations, a process which screens the inner part of the Heliosphere from a large proportion of the particles.

Cosmic rays consist mainly of protons (90%) and of alpha-particles (9%), plus a smaller proportion of heavier components. Their energies range between a few million electron volts (eV) and 10^{20} eV; as the energy of the particles increases, they become rarer. Cosmic rays can be recorded through ground-based neutron monitors, which can detect variations in the low-energy part of the primary cosmic ray spectrum. The lowest energy that can be detected at the top of the atmosphere depends on the geomagnetic latitude, and ranges from 0.01 GeV (1 GeV = 10^9 eV) at stations near the geomagnetic poles to about 15 GeV near the geomagnetic equator.

Systematic instrumental monitoring of cosmic rays started after 1950 with the use of neutron monitors. Figure 3 shows normalised cosmic ray variations for 1951–2006, and the variation in sunspots over the same period.[7] The cosmic ray intensity exhibits an inverse relationship to the sunspot cycle. This is caused by the magnetic structure of the solar wind in the interplanetary medium, which has a larger shielding effect on cosmic rays during periods of high solar activity.

It is, however, possible to obtain information about variations in cosmic rays in the years before neutron monitors became available. When energetic cosmic rays collide with the atoms of the atmosphere, new elements are produced. These elements are referred to as 'cosmogenic isotopes'. Examples are beryllium-10, carbon-14 and chlorine-36. When the cosmic ray flux is high, the production of cosmogenic isotopes is also high, and vice versa when the flux is low. Variations in the quantity of cosmogenic isotopes therefore provide information on the variations in the cosmic-ray flux. For example, beryllium-10 (^{10}Be) is produced high in the Earth's atmosphere by cosmic rays. The ^{10}Be atoms can then stick to small aerosols (molecular clusters floating in the air), and sometimes they become incorporated into snowflakes. If these fall somewhere where they will not melt, for example the Greenland icesheet, then by taking ice-cores and measuring the content of ^{10}Be atoms in each dated layer of ice, a record of ^{10}Be production, and thereby an indirect measure of past cosmic ray flux, is obtained.

Figure 4 shows such a record: a reconstruction of cosmic rays back to 1391; after 1951 the instrumental record is used.[8] The figure also shows the sunspot group number starting in 1610. Notice there is a clear inverse correlation between solar activity and cosmic rays in the period of overlap. However, there are subtle differences. For example, the Maunder Minimum (1645–1715) had very few sunspots, but the end of the Maunder Minimum (1690-1715) has the highest cosmic ray flux compared to the rest of the period.

Cosmogenic isotopes can be used to reconstruct the cosmic ray variation for up to 10,000 years back in time, and such indirect reconstructions are called 'proxies' of cosmic rays or solar activity. On longer timescales it may be necessary to correct for changes in Earth's magnetic field.[8]

Reconstructed solar irradiance

Total solar irradiance (TSI) describes the integrated radiant energy arriving from the Sun at the top of Earth's atmosphere, and represents nearly all the energy that the Earth receives. It is therefore an important parameter in Earth's climate. Since 1978, direct observations of TSI have been obtained from Earth-orbiting satellites. However, these wear out and have to be replaced from time to time, so the records from each have to be inter-calibrated to provide a continuous time series.[9] Due to data gaps and instrument degradation, the precise calibration needed is not universally agreed upon.[9–11]

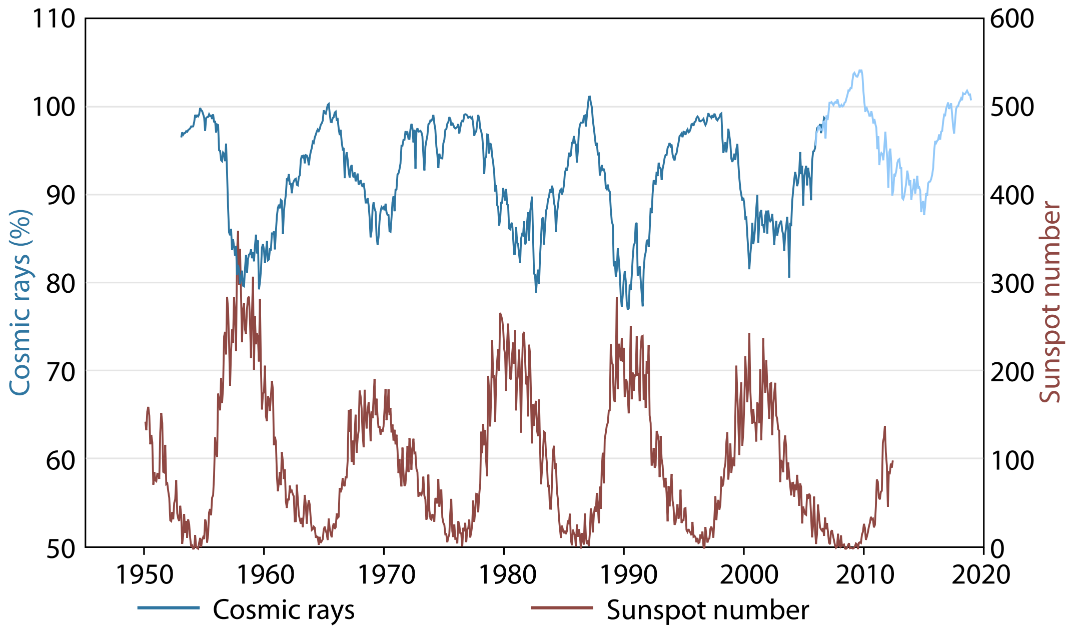


Figure 3: Cosmic ray and sunspot variations over the instrumental period (1951–2018).

Sources: Cosmic rays per McCracken and Beer,[8] sunspots per Climax neutron monitor,[7] extended after 2006 by the author using data from the Oulo monitor.

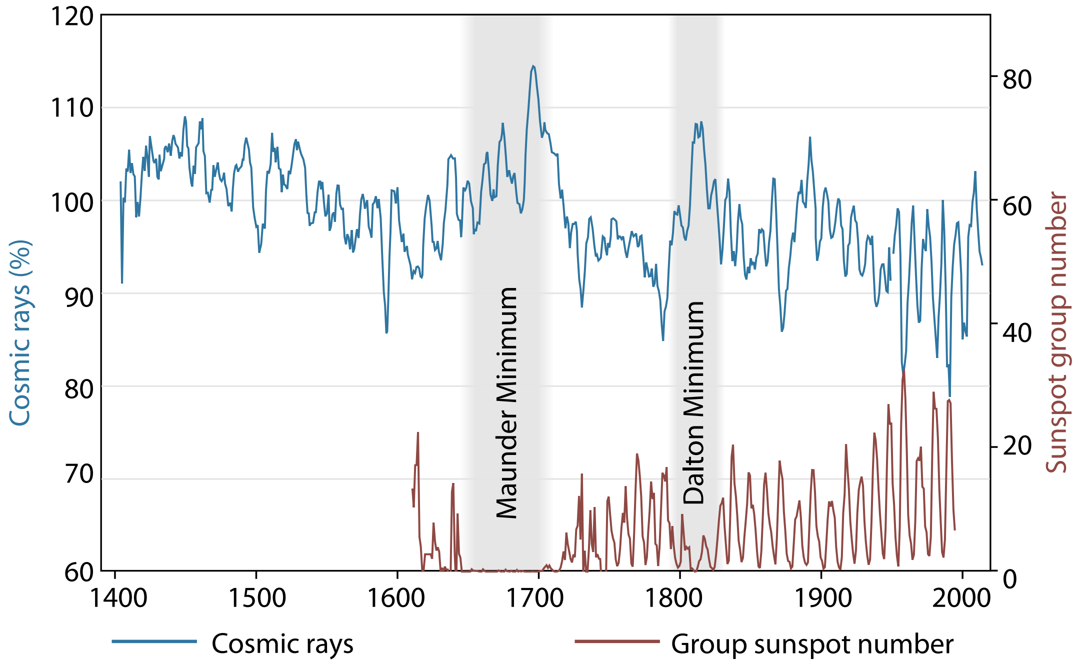


Figure 4: ^{10}Be reconstruction of cosmic ray variation since 1391.

There has been a steady decrease in the cosmic rays on long timescales, indicating that the part of solar magnetic activity responsible for modulating cosmic rays has increased over this period. Sources: Cosmic rays: McCracken and Beer;[8] sunspot group record, Hoyt *et al.*[3,6]

An important question concerns if there is a trend in the TSI data beyond the 11-year cycle: this could have implications for estimates of TSI changes on long timescales and thereby on climate. Satellite data demonstrate that TSI varies by as much as 0.05–0.07% over a solar cycle.[9–11] At the top of the atmosphere this variation amounts to around 1 W/m^2 out of a solar constant of around 1365 W/m^2. At the surface it is only 0.2 W/m^2, after taking geometry and albedo into account.

On longer timescales there has been interest in reconstructing TSI beyond the satellite period by using a number of solar proxies. Typically, the TSI is represented as the sum of the radiances from three distinct regions of the sun: the bright faculae, the dark sunspots, and the other areas, known as the 'quiet Sun'. Past observations of faculae and sunspots can drive estimates of the first two components, but there is no way to estimate past activity of the quiet Sun, so it is common to assume a constant level of irradiance. A majority of reconstructions find only small changes in overall secular solar radiative output: since the Maunder Minimum, TSI is believed to have increased by around 1 W/m^2, which corresponds to 0.18 W/m^2 at the Earth's surface. This is too small to have had an impact on climate.[12,13]

In contrast, a few TSI reconstructions suggest a much larger TSI increase since the Maunder Minimum (0.4%, or around 6 W/m^2).[14,15] These reconstructions are based upon the hypothesis that the quiet solar irradiance *has* varied significantly over time. The assumption is that the irradiance from the quiet regions can be parametrised by the solar magnetic field that modulates the cosmic rays, resulting in large variations in TSI. However, the suggestion of large variations in the irradiance from the quiet Sun has been severely questioned.[16,17] For example, a test of TSI variations over the 20th century was performed using CaK spectroheliograms of the solar disk covering the period 1914–1996. The heliograms showed very little variation in the magnetic network over the period, an observation which is inconsistent with large TSI variations.[18,19]

If solar activity continues declining over the next few decades it may be possible to better constrain TSI variations.

3 Correlation between solar activity and climate on Earth

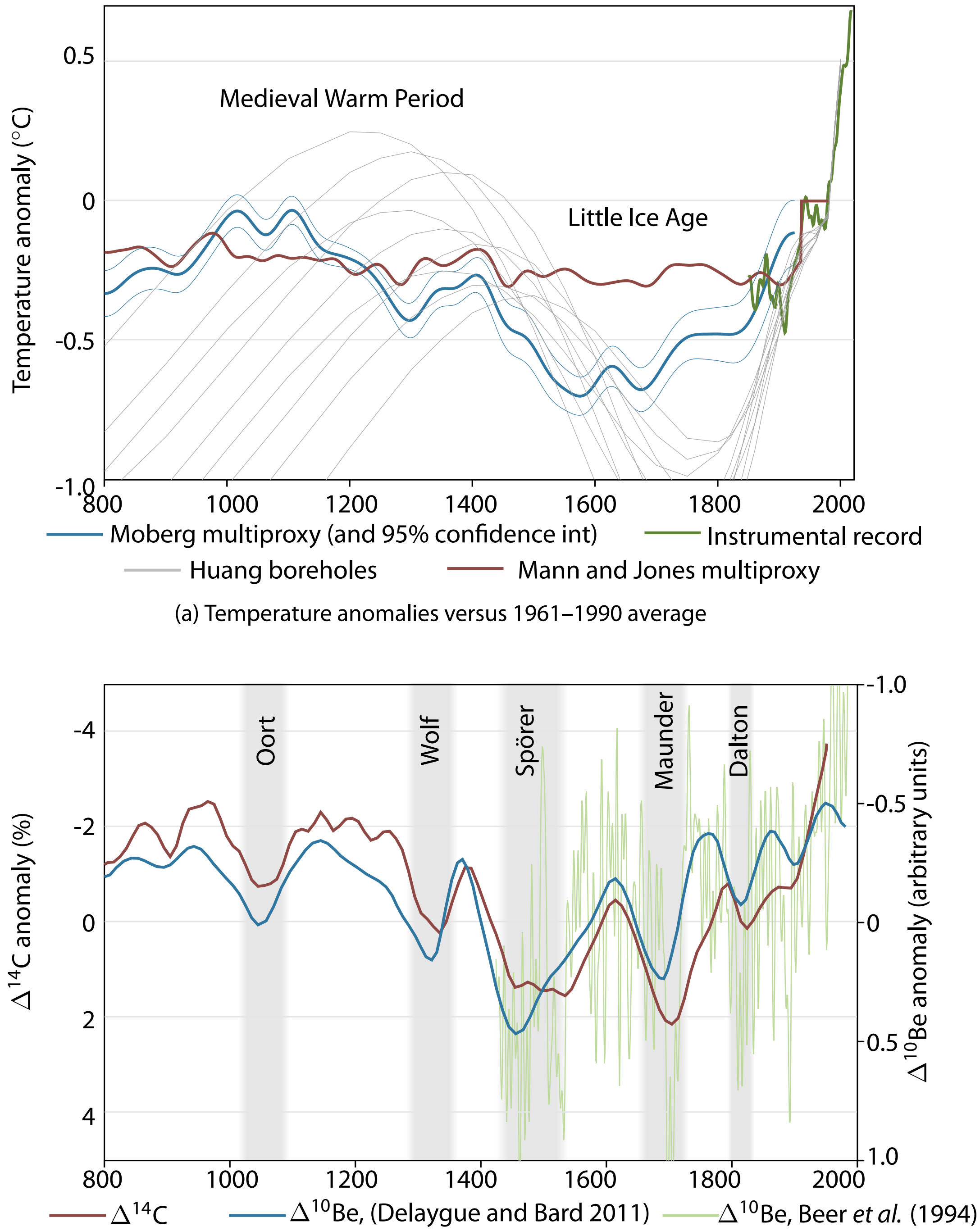
Many empirical studies have shown a clear correlation between proxy measurements of climate and of solar activity on timescales of decades or longer. In the 1970s, John Eddy noticed a correlation between solar activity and the European climate over the previous millennium.[20] For example, the Little Ice Age (1300–1850 AD), was a cold period that took place while the Sun was particularly inactive. The Medieval Warm Period (1000–1200 AD), on the other hand, occurred while the Sun was active.

Figure 5a shows recent reconstructions of temperature variation over the last 1000 years. A number of temperature records are compared (with respect to the 1961–1990 average temperature):

- two multiproxy reconstructions of Northern Hemisphere temperatures[21,22]
- a global temperature reconstruction based on borehole temperatures[23]
- the instrumental record over the last 150 years.[24]

Figure 5b displays cosmic ray reconstructions based on:

- ^{14}C measurements in tree rings[1]
- ^{10}Be concentrations from



(a) Temperature anomalies versus 1961–1990 average

(b) Galactic cosmic rays (inverted scale; solar minima are shown in grey)

Figure 5: Temperature and cosmic ray variations over the last millennium.
Note the inverted scale in the lower chart; high cosmic ray fluxes are associated with cold temperatures. See main text for sources.

– ice cores from Antarctica.[25]

– an ice core from Greenland.[26]

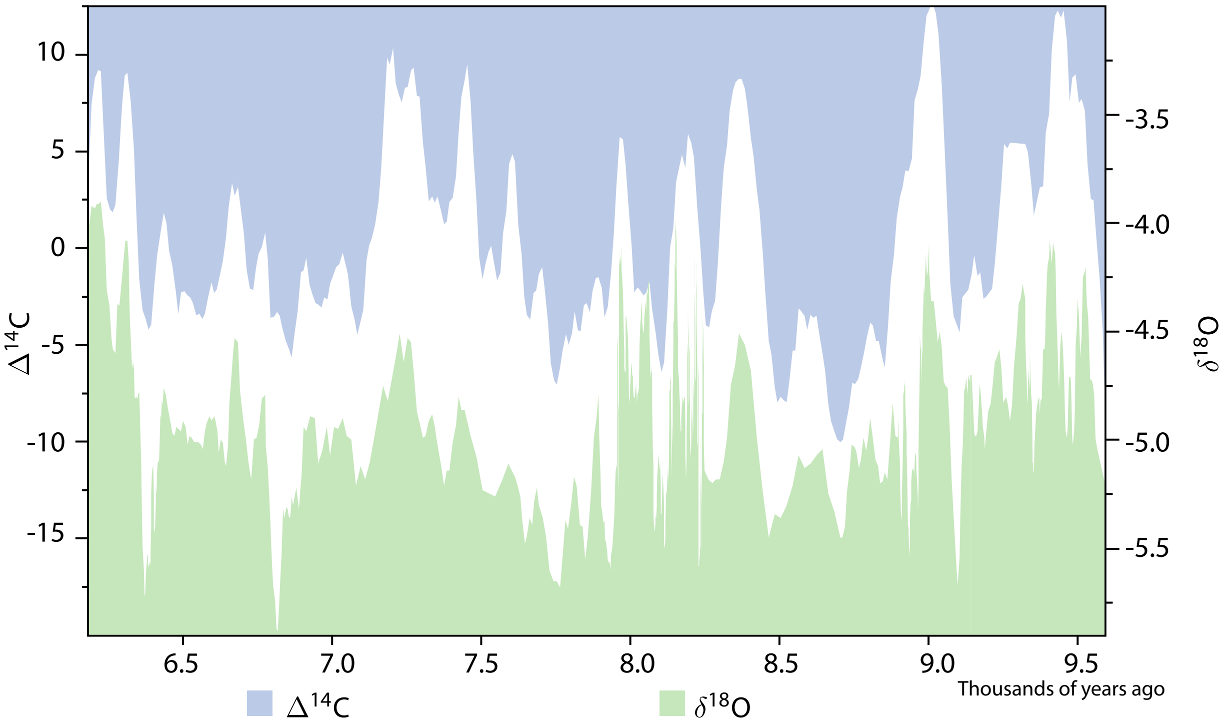


Figure 6: Remarkable correlation between a temperature proxy and a solar activity proxy.
Temperatures based on $\delta^{18}O$ in stalagmites in a cave in Oman, reflecting monsoon rainfall.
Solar activity based on $\delta^{14}C$. Source: Neff *et al.*[27]

The two parts of the figure show that there is a remarkable correlation between the changes in temperature and changes in cosmic rays (caused by solar activity). In fact, it is possible to see all the solar activity minima manifested in the temperature curve. Notice that the axis for the cosmic ray plot is inverted so that a high cosmic-ray flux corresponds to colder temperatures and a low cosmic-ray flux to higher temperatures.

One way to show that the solar–climate link is seen globally is to look at the temperature reconstructions based on worldwide borehole data (Figure 5a, grey curves). Due to the slow diffusion of heat into the ground, the measured temperature profile down the depth of a borehole contains information about past surface temperatures.[23] From these data, it can be seen that the temperature maximum of the Medieval Warm Period was as warm or slightly below the 1960–1990 reference level, and the minimum of the Little Ice Age was about 1 K below it.

A close correlation between changes in cosmic rays and climate is not just limited to the last 1000 years: it can be seen in multi-millennial records too. Figure 6 shows records covering the period between 6200 and 9600 years before the present:

- changes in ^{18}O levels in stalagmites from a cave in Oman, a proxy for variations in the tropical circulation and monsoon rainfall
- changes in cosmogenic ^{14}C, a proxy for solar activity.[27]

The correlation of the two series is remarkable. Studies of other stalagmites from caves in Oman and China have shown that the Asian monsoon correlates with solar activity over the whole Holocene period.[28–30]

It should also be recognised that the impact of solar activity on climate influences society too. An example of this can be seen in a 1810-year record of monsoons, derived from a cave in China. This correlates closely with ^{14}C records of solar activity,[31] showing that periods when the monsoon was weak – during the Little Ice Age and during the final decades of the Tang, Yuan, and Ming dynasties – were characterised by popular unrest. In contrast, when the monsoon was strong, food production and populations increased. The collapse of the Maya civilisation in South America is believed to have been triggered by drought resulting from changes in solar activity.[32,33] In Europe, the Medieval Warm Period and Little Ice Age also had severe impacts on the population.[34,35]

Another impressive result regarding the Holocene climate of the Northern Atlantic comes from Bond *et al.*,[36] who compared solar activity with climate, as recorded through so-called 'ice rafted debris'. As ice moves over the North Atlantic, it melts, and small grains of debris sink to the bottom. Cores drilled from the ocean floor can then give a measure of the number of such grains as a function of time, and these measurements reflect changes in ice-drift and thereby climate. Figure 7 shows the variation in ice-rafted debris over the last 12,000 years and the change in cosmogenic ^{14}C, a proxy for the variation of solar modulation of cosmic rays. Again, a close correlation is seen.

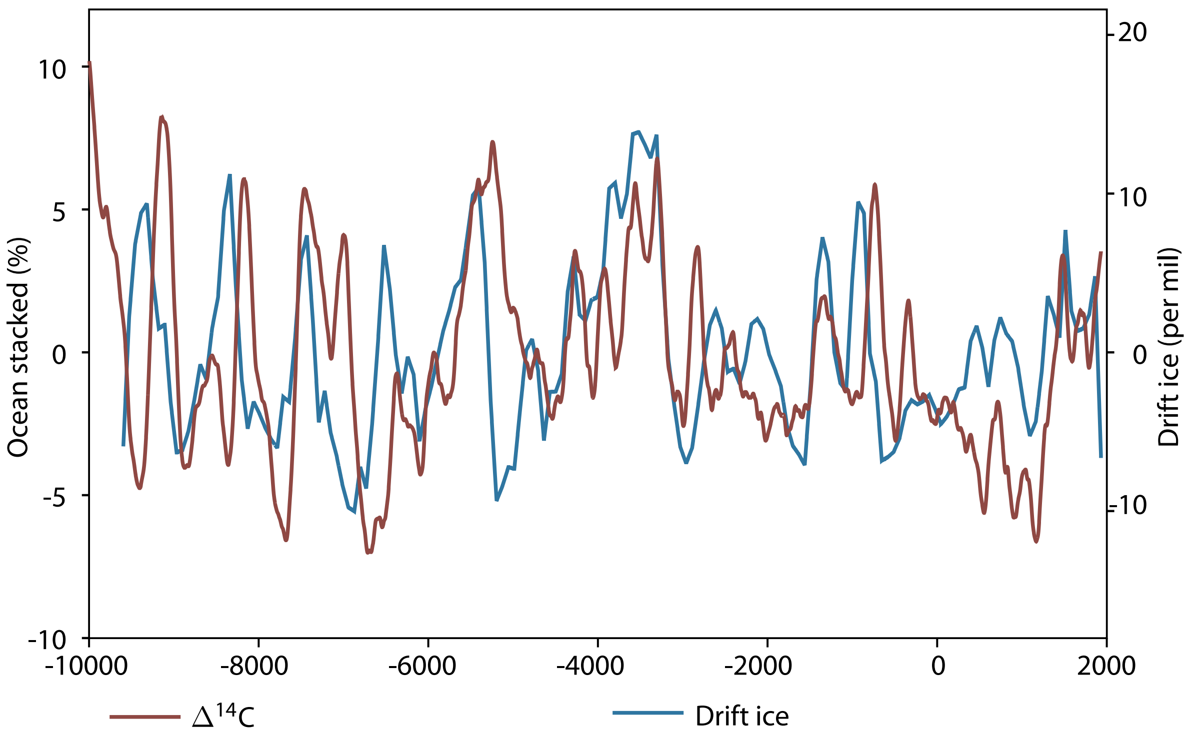


Figure 7: Variation in North Atlantic climate (10000 BC to 2000 AD).
Ice-rafted debris expressed as percentages of lithic grains in the 63- to 150-mm size range. ^{14}C from tree-rings. Adapted from *Bond et al.*[36]

Many other studies support the above findings of a close correlation between solar activity and climate. It is therefore near certain that solar activity during the Holocene period

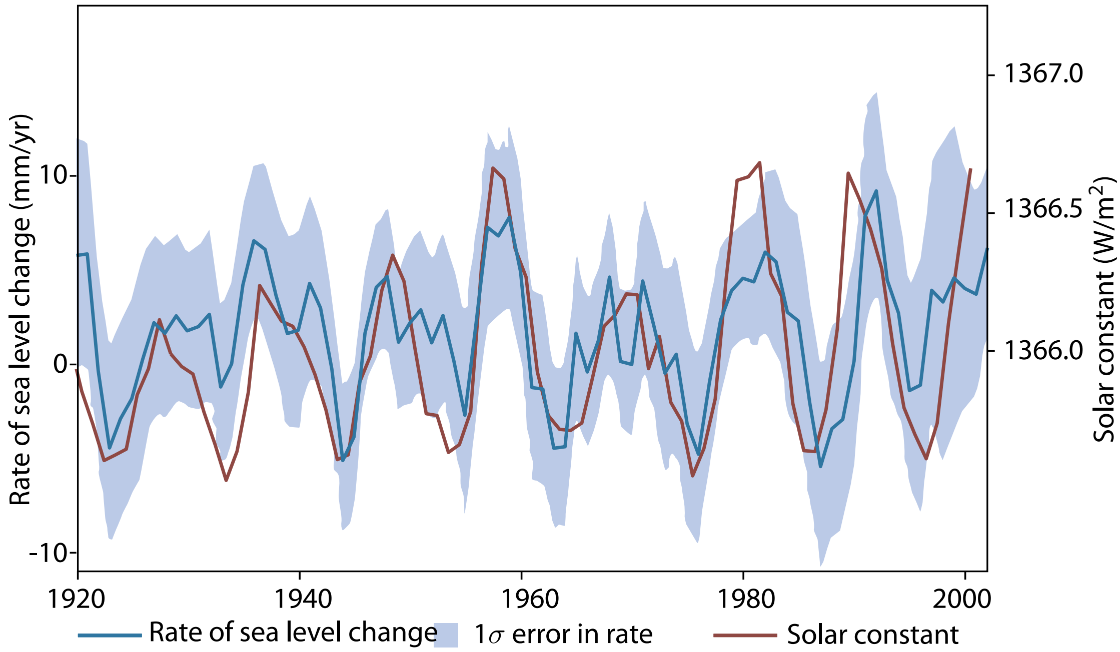


Figure 8: Sea level and solar activity.
Sea levels from tide gauge data. On short timescales, the sea level change rate reflects changes in the ocean heat content (through thermal expansion). Thus, one can conclude that there is a large change in the oceanic heat content over the solar cycle. This calorimetric measurement can be used to quantify the solar radiative forcing.[38]

(approximately, the last 10,000 years) has had a significant impact on the climate.

Finally, it is not only during the Holocene period that correlations between solar activity and climate have been observed. Extending the time frame through the last glacial maximum (20,000 years ago) reveals another clear correlation.[37] There is therefore good reason to infer that correlations are present on all timescales.

4 Quantifying the link between solar activity and climate

So far, it has been shown that there are strong correlations between solar activity and climate over long timescales (centuries to millennia). However, this says nothing about how the effect comes about or how large it is. Fortunately, it is possible to quantify the effect of solar variations by estimating energy input into the oceans over the 11-year solar cycle. This energy produces small temperature changes in the water, causing it to expand. So tide-gauge records of sea level can give us a record of solar variation.[38]

Figure 8 displays the rate of change in sea level and a reconstruction of solar irradiance over the period 1920–2000. A close correlation is seen between the two curves, suggesting that energy enters the ocean approximately in phase with the 11-year solar cycle. The observed expansion of the ocean corresponds to a peak forcing of approximately 1.5 W/m^2 entering the ocean over the solar-cycle.

There are other independent data sets supporting this result:[39]

- ocean heat content measurements
- sea-surface temperature measurements

- satellite observed variations in sea level.

These datasets are shown in Figure 9. Over the 11-year cycle, the solar forcing they imply is also of the order of 1.0–1.5 W/m^2. This forcing might be explained by solar irradiance changes over the solar cycle but, as can be seen from Figure 9, the TSI change is only around 0.2 W/m^2 – almost an order of magnitude too small to explain the observations. Therefore, an amplifying mechanism must be in operation.[38] A simple derivation of the need for an amplification is given in the Appendix.

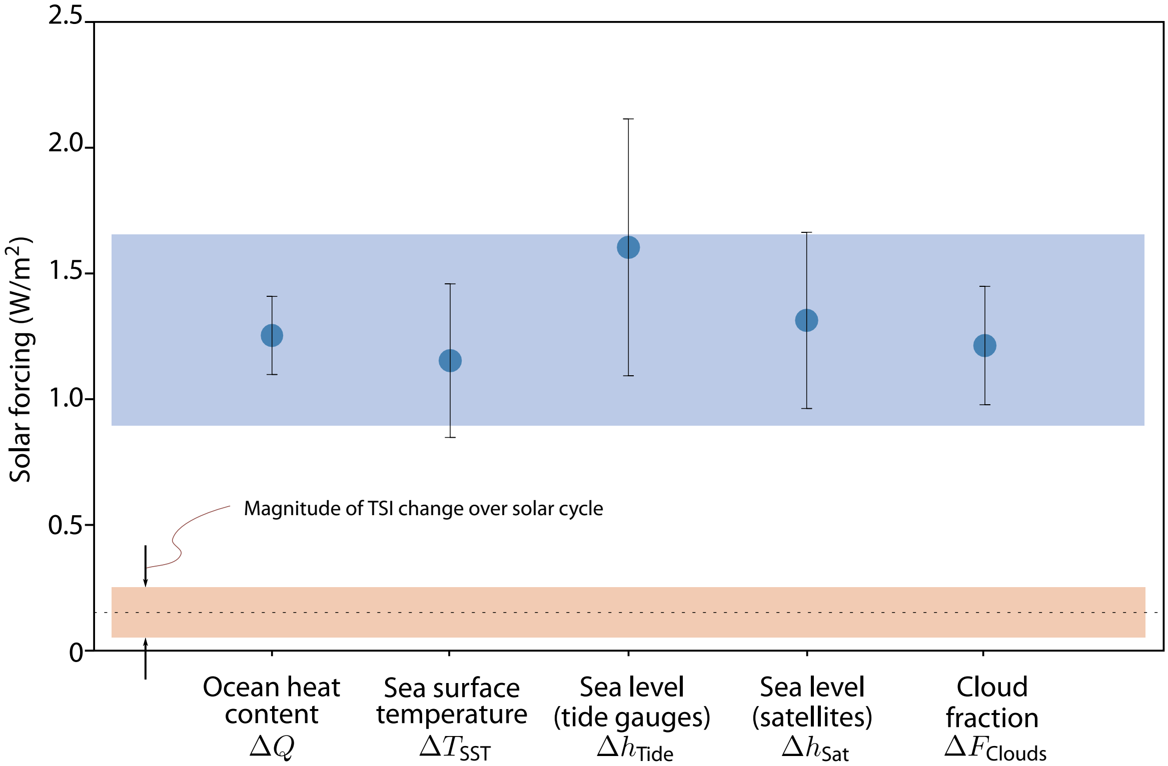


Figure 9: Estimates of energy entering the ocean over a solar cycle.
TSI is almost an order of magnitude to small to explain the observed forcing. Sources: Δh_{Sat} from Howard *et al.*[39], clouds from Svensmark (1998).[40] Figure adapted from Shaviv (2008).[38]

We therefore conclude that the Sun has a large effect over the solar cycle. In fact, it is about 5–7 times larger than can be expected from changes in solar irradiance alone.

5 Possible mechanism linking solar activity with climate

There have been a number of suggestions to explain the size of the Sun–climate link. Here we will focus on the most important of these.

Total solar irradiance and temperature

The simplest explanation would be if variations in TSI were large enough to explain the climate variations. However, as shown in the last section, the changes in TSI are too small to explain the energy that enters the Earth's system over a solar cycle.

Of course, there could still be larger TSI variations on longer timescales. For a global change in forcing since the Maunder Minimum of 1 W/m^2, and adjusting for geometry and albedo, the change in global temperature should be of the order of 0.1 K.[2] The best estimate of the actual changes in temperature over this period are from the borehole measurements[23] (see Figure 5). These suggest a change of the order of 1 K. This suggestion is also supported by a Greenland temperature reconstruction (not shown).[41] However, if a large variation in TSI is assumed ($\sim$0.4%) then the change in temperature will be $4 \times \frac{0.7}{0.4}$ W/m^2 = 0.7 K. However as discussed in Section 2.3, such large TSI variations seem unlikely.

Returning to the observed 1.0–1.5 W/m^2 forcing over the solar cycle (see Section 4), it is clear there must be an indirect mechanism amplifying solar activity.

UV changes and temperature

Although the variation in TSI over a solar cycle is small – of the order 0.1% – there can be large relative variations in the UV spectrum. For example,

- in the wavelength range 120–121 nm, the changes are approximately 40%
- in the wavelength range 250–300 nm , the changes are approximately 1%
- in the wavelength range 600–700 nm , the changes are approximately 0.1%.[42]

This variable UV energy is absorbed in the stratosphere, resulting in heating, and it has been suggested that this might lead to a change in the atmospheric circulation, which would subsequently propagate down, through the troposphere, to the Earth's surface.[43] However, global circulation models suggest the net effect on the surface temperature is actually less than the effect due to changes in TSI,[44,45] and the tropospheric response appears in many cases to be insignificant.[46] It is therefore unlikely this mechanism alone can explain the observations showing a change of 1 W/m^2 entering the oceans over a solar cycle (see Section 4).

Cosmic rays, clouds and climate

Another possible mechanism involves solar modulation of cosmic rays and the effect this has on cloud cover.[40,50–52] Since clouds have a large effect on the energy budget of Earth (the net effect of clouds is to cool the Earth by about 20–30 W/m^2), any systematic change in clouds will have a significant effect on the energy budget of Earth and hence the climate.

In 1996, it was announced that the intensity of galactic cosmic rays incident on Earth's atmosphere correlates closely with variations of global cloud cover. It was suggested that this connection could be responsible for the observed correlations between variations in solar activity and climate. Figure 10 shows a correlation between cosmic rays and low clouds, as measured by satellites. The changes in the energy budget associated with the 11-year cloud-cover variations have been estimated[53] to be 1.1 ± 0.3 W/m^2, which is an order of magnitude larger than the corresponding TSI variations.[38]

If the proposed link between cosmic rays and clouds is real, there must be a microphysical mechanism linking cosmic ray ionisation in the Earth's atmosphere and cloud formation. The idea that has been put forward relates to the formation of aerosols.[3] A large fraction of aerosols is formed directly in the atmosphere from trace gases. These aerosols grow by continued gas condensation and collisions until they reach sizes of 50–100 nm, when they are referred to as 'cloud condensation nuclei' (CCN). CCN-sized aerosols are im-

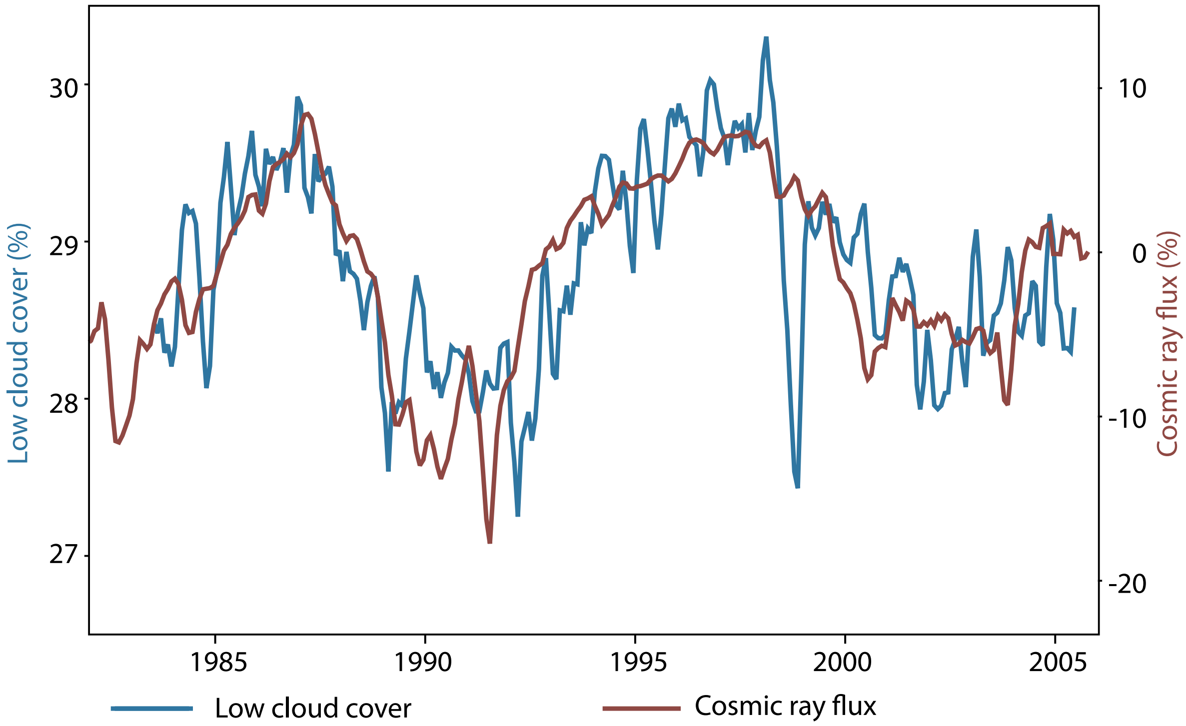


Figure 10: The correlation between low altitude cloud cover and cosmic ray flux reaching Earth.[47] It is difficult to measure clouds over multiyear periods due to inherent calibration problems. The data used in this figure has already been recalibrated due to a problem in 1994,[48] but continued difficulties with this dataset suggest that long-term trends are no longer trustworthy.[49]

portant in cloud formation because, in order to form a cloud droplet in Earth's atmosphere, water vapour needs a surface to condense on. Suitable surfaces are provided by CCN.

Figure 11 is a satellite view of the northern Pacific Ocean, showing a scene with low clouds. The white stripes are ships' tracks, caused by the exhaust from their engines, which adds additional CCN into the air. The extra CCN change the microphysics of the clouds, with result that the cloud droplet number density increases (the cloud becomes whiter) and more sunlight is reflected back to space. Although these ships' tracks are not caused by cosmic rays, the image illustrates that any systematic change in CCN will be important for Earth's energy budget.

In order to explain how cosmic rays might affect the number of CCN, a mechanism is required. This is summarised in Figure 12. First, solar variability manifests itself as changes in the solar wind, which carries the Sun's magnetic field. The solar wind then modulates the cosmic ray flux, which is responsible for atmospheric ionisation (producing positive and negative ions). These charged particles help the formation and stabilisation of new small aerosols from trace gases in the atmosphere. One of the most important trace gases is sulphuric acid, which is produced naturally in the atmosphere by photochemistry.

In 2006, it was shown experimentally that cosmic rays help the initial formation ('nucleation') of small aerosols (1–2 nm), and it was found that by increasing the ionisation, the number density of nucleated aerosols increased as well.[54] These results were later confirmed by the CLOUD collaboration experiment at CERN in Geneva.[55]

For a while, it was thought that the increase in small aerosols ($\sim$3 nm in size) would au-

Figure 11: Low marine stratus clouds in the northern Pacific Ocean.

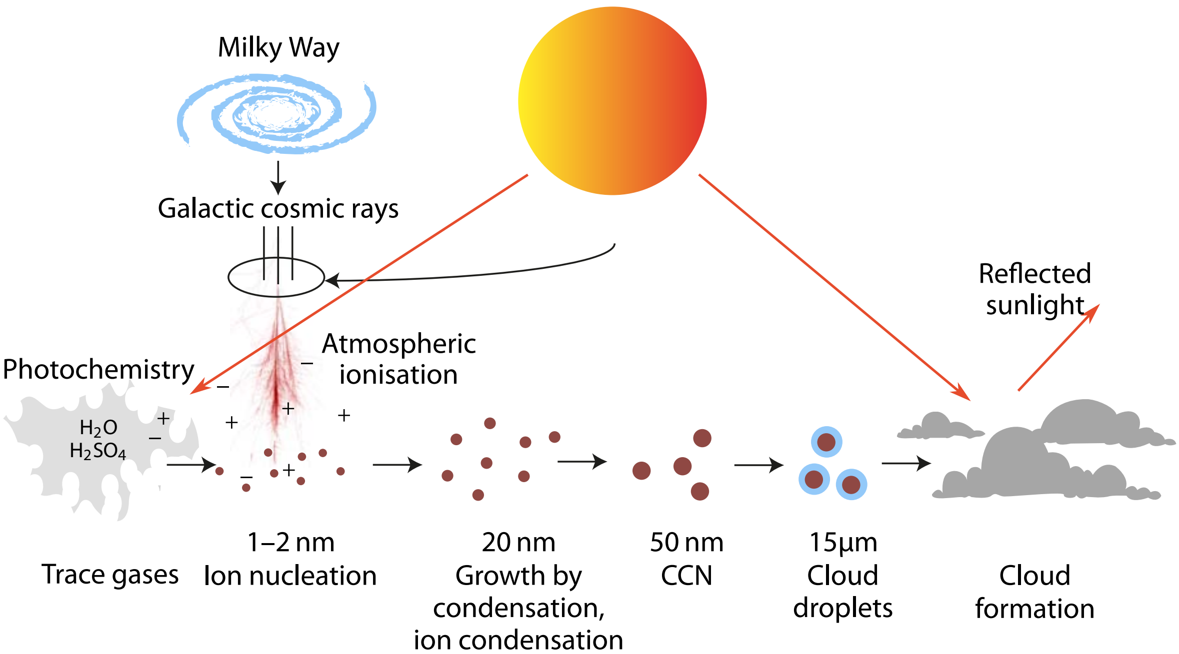


Figure 12: The physical mechanism linking solar activity variations to climate change. In summary, the link is: (a) a more active Sun, (b) stronger solar wind, (c) fewer cosmic rays, (d) less atmospheric ionisation, (e) less nucleation and slower growth, (f) fewer CCN, (g) clouds with less droplets, (h) less reflectivity, (i) less reflection of sunlight and a warmer Earth.

tomatically lead to an increase in the number of CCN (50–100 nm). However, numerical results from 'state of the art' aerosol simulations suggested that this was not the case.[56] Even large changes in aerosol nucleation (1–2 nm) appeared not to result in an increased number of CCN. The explanation for this negative result was that additional aerosols would lead to increased 'competition' for the available gases, resulting in slower growth and a larger probability of a small aerosol becoming incorporated into a larger one before reaching CCN size.

These numerical results have since been tested experimentally.[57] First the experiment simulated what would happen in the atmosphere without the presence of ions. Figure 13a shows how the molecular clusters fail to grow sufficiently to provide significant numbers of CCN of more than 50 nm in diameter.

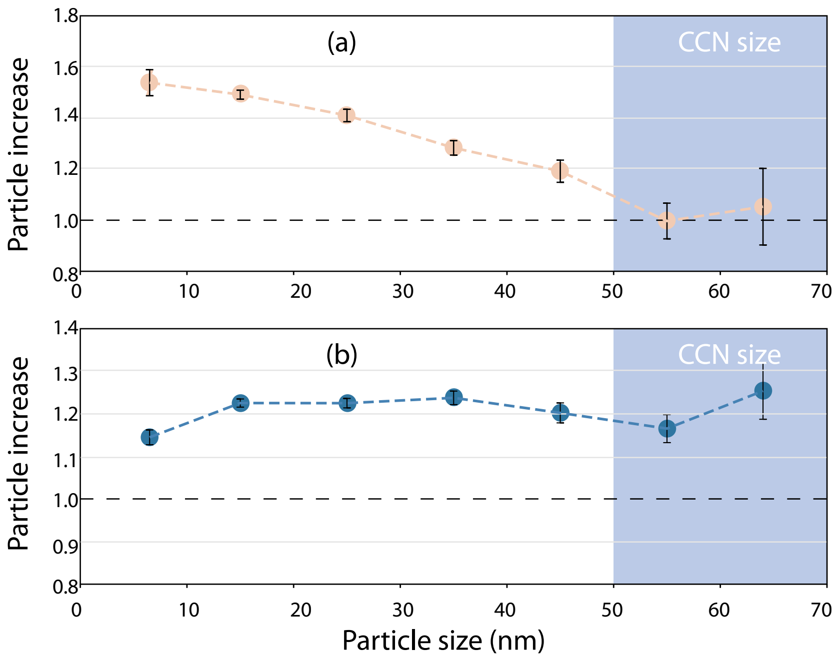


Figure 13: Experimental test of aerosol growth into CCN.
(a) Without ionisation; (b) with ionisation. Adapted from Svensmark (2012).[57]

This is what existing theories predict. But when the air in the chamber is exposed to ionising radiation, so as to simulate the effect of cosmic rays (Figure 13b), the clusters grow much more quickly to the sizes at which they will help water droplets form and make clouds. This result contradicts the numerical modelling results, and indicates that an important part of the ion-mechanism is missing from the theory.

So the evidence is that ions help the growth of aerosols to CCN sizes, but how? The answer was only found very recently, theoretically and experimentally. The solution is to include a so-far-ignored contribution to growth of aerosols: from the mass of the ions. Ions are relatively scarce in the atmosphere, but the electromagnetic interaction between them and aerosols can compensate for the scarcity and make fusion between ions and aerosols much more likely. Even at low ionisation levels, about 5% of the growth rate of aerosols is due to ions. In the case of a near supernova, ionisation can be much greater, and the ion effect can be responsible for more than 50% of the growth rate. This will have a profound impact on the clouds and the Earth's temperature.[58]

These results are also supported by observations. On rare occasions, 'explosions' on the Sun, known as 'coronal mass ejections', result in a plasma cloud that passes the Earth, causing a sudden decrease in the cosmic ray flux that lasts for a week or two. Such events are called 'Forbush decreases', and are ideal to test the link between cosmic rays and clouds. Finding the strongest Forbush decreases and using three independent cloud satellite datasets and one dataset for aerosols, a clear response in clouds and aerosols to Forbush decreases is seen. Figure 14 shows the sum of the five strongest Forbush decreases (red curves) together with various signals observed in clouds (blue curves) in the days around the minimum in cosmic rays. The difference in the position of minima of the two curves is due to the time it takes aerosols to grow into cloud condensation nuclei. These results suggest that the whole chain – from solar activity, to cosmic rays, to aerosols (CCN), to clouds – is active in the Earth's atmosphere.[59,60] Moreover, they indicate that the cosmic ray–cloud link is capable of explaining the magnitude of around 1 W/m^2 of the observed forcing over the solar cycle.

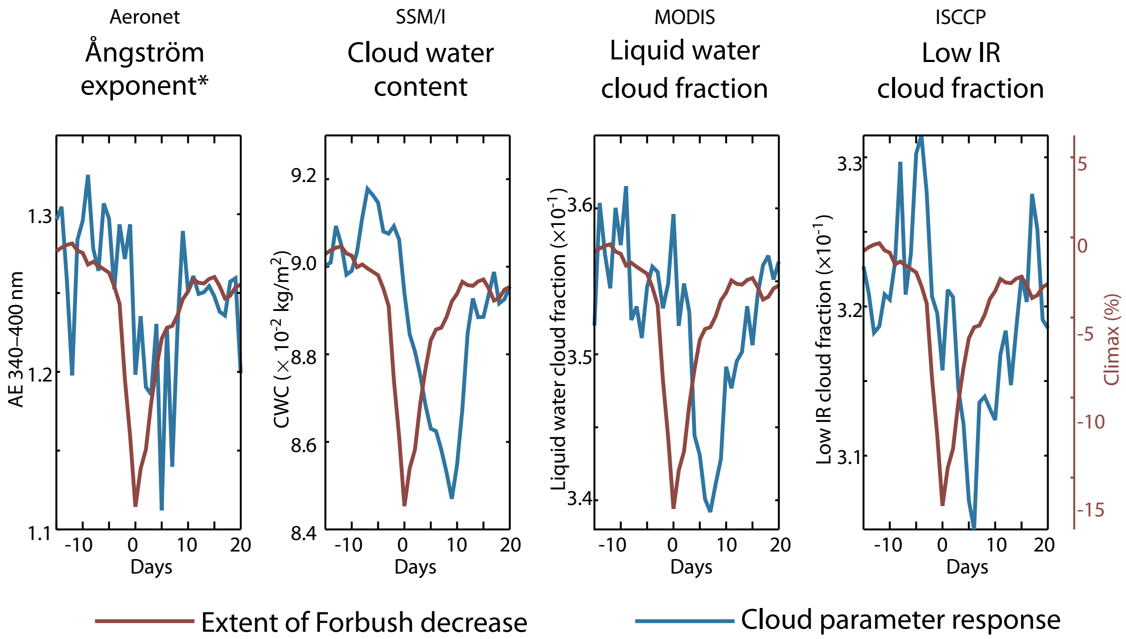


Figure 14: Changes in cloud parameters before and after Forbush decreases.

Changes in daily averages, averaged over the five strongest events between 1990 and 2005.[59]
The data shows that reductions in the cosmic ray flux translate into changes in cloud properties.
*The Ångström exponent measures the density of aerosols in the atmosphere.

Changes in the Earth's electrical circuit

Other ideas have been put forward to explain the Sun–climate link. One idea has to do with the Earth's electrical field, which is caused by the potential difference between the ionosphere and Earth's surface. This potential difference is maintained by thunderstorms, and results in a fair-weather current of atmospheric ions that discharges the potential difference. The atmospheric ions are mainly produced by cosmic rays, but the electrical circuit is also responsive to changes in the solar wind. It has been proposed that changes in the electrical current influences cloud microphysics, for example by affecting the freezing point of cloud droplets.[61] However, there are a few observations that support an effect of the electric field on cloud properties. Harrison and Ambaum[62] studied changes in the atmospheric potential at a location in the UK and cross-correlated the observations with the downwelling long wave radiation and diffuse short wave flux. Their data display a two-minute time delay in the cross-correlations and they suggest that this is evidence of the electric field affecting cloud properties.

6 Future solar activity

Predicting changes in solar activity is beyond our current capabilities. Even predicting the size of the next solar cycle is very uncertain. As an example, 105 predictions were made of the maximum number of sunspots for solar cycle 24 – the current instance of the 11-year cycle. The predictions were based on either statistical or physical dynamo models, and the collection of predictions had a form close to a normal distribution, with a mean and variance of 106 ± 31.[63] However, in the event, the observed maximum of cycle 24 was small: close to 82. This failure epitomises the problems facing those seeking to forecast solar activity.

With a maximum of 82 annually averaged sunspots during solar cycle 24, solar activity is now the lowest it has been in a century. In contrast, the period 1950–1995 had the highest solar activity in perhaps 1000 years. This is by no means a surprise, because both sunspots and cosmogenic isotopes show that solar activity can be highly variable. The interesting question is how low future solar activity might get. There are already suggestions that solar activity is moving towards a grand minimum along the lines of the Maunder Minimum, or perhaps a less severe one, like the Dalton Minimum (see Figure 2). Grand minima are by no means rare; they have likely occurred 7–9 times over the Holocene period (see, for example, Figure 7). It is therefore interesting to consider if the Sun is currently moving into a new grand minimum or just a period of low solar activity, and to think about the consequences for the Earth's climate. This depends, of course, on the actual physical mechanisms linking solar activity to climate.

There have been a number of modelling results aimed at predicting the future effect of solar activity. If small TSI variation is assumed, the predicted effects will of course be small and insignificant too.[64] Assuming a 0.25% drop in TSI, the model results indicate a small drop in projected temperatures in the year 2100: just 0.2–0.3 K.[65,66] However, at least one projection – based on a simple energy-balance calculation – suggests that the temperature will drop by a more significant $\sim$1 K and lead to a new little ice age. This calculation is based on a large change in TSI of 0.5%[67] (see discussion of TSI variations in Section 2).

The influence of a possible grand minimum has also been studied relative to the IPCC's anthropogenic greenhouse gas emission scenarios.

7 Discussion

Based on the numerous studies that demonstrate a close correlation between solar activity and climate, it seems safe to say that solar activity is important for climate variability (see Section 3). In particular, the many studies examining the Holocene period (the last 10,000 years) demonstrate remarkable agreement between solar variation and climate, as illustrated in Figures 6 and 7. The main scientific problem today is therefore to quantify and understand the solar influence on climate.

It should be noted that the observed climate variation on century-to-millennia timescales is not reflected in atmospheric carbon dioxide levels: according to ice-core data, these have been relatively constant.[68] It is therefore unlikely that variations in carbon dioxide concentration have had any influence on the climate variability on these timescales.

Impact of solar activity

Climate models including only small changes in TSI, of the order of 0.1%, suggest that the solar contribution to climate variation is small, and that anthropogenic greenhouse gases, aerosols, and volcanoes are the main cause of recent and future climate changes. Some temperature reconstructions over the last millennium, such as those by Michael Mann and colleagues,[22,69] and climate model runs for the same period, show little or no trace of the Little Ice Age (see Figure 5), and are therefore unsurprisingly consistent with a small solar TSI forcing. However, temperature reconstructions with a small change (0.1–0.2 K) between the Medieval Warm Period and the Little Ice Age are inconsistent with a large number of other climate reconstructions.[23,34,41,70–76] For example, temperature reconstructions using boreholes are some the most robust paleoclimate indicators available, because they are a direct physical record of temperature changes occurring at the surface. The study of Huang *et al.* is based on hundreds of boreholes from all continents (except Antarctica) and gives strong evidence for a temperature difference of 1.0–1.5 K between the Medieval Warm Period and the Little Ice Age (see Figure 5).[23] In addition Mann's temperature reconstructions[22,69] have been seriously questioned.[77–81] Temperature variations of the order of 1.0–1.5 K between periods of high and low solar activity, as seen repeatedly over the Holocene period (see Figure 7), seem much more likely than the limited changes suggested in those studies.

This suggests that either there are larger TSI variations on long timescales and/or that there is an indirect solar mechanism operating in the atmosphere. The consensus value for variation in TSI , at around 0.1%, seems small, and, if true, TSI variations cannot explain observed climate changes.[16] In contrast, there are TSI reconstructions that suggest much larger variations, of the order of 0.4%, which would be important for climate variability.[14,15] As discussed in Section 2, the basis for thinking there may be such large changes is the possibility that the irradiance from the quiet Sun varies significantly in time. However, this is at present a hypothesis with no observational support. It is to be hoped that future observations can constrain possible TSI variations.

Since solar activity has had a large impact on past climate, it should not be too controversial to assume that the 20th century increase in solar activity must also have had an influence on the observed temperature increase. If the Sun has had a significant influence over the 20th century temperature increase, then climate sensitivity has to be on the low side. Ziskina and Shaviv[82] used a simple model to estimate the relevant forcing over the 20th century, by constraining the fits to the observed temperature, including anthropogenic (greenhouse gases and aerosols) and a solar contribution. The result is a 20th century solar forcing of 0.8 ± 0.4 W/m^2 and a climate sensitivity of 0.25 ± 0.09 K/(Wm^{-2}). These numbers should be compared with the IPCC-estimated radiative forcing on climate from solar activity between 1750 and 2011 of around 0.05 W/m^2 and a climate sensitivity of 0.9 ± 0.3 K/(Wm^{-2}).[1] Therefore, with a larger role for the Sun, the implications on future climate change will be significant. Such a result should warrant further research into the solar impact on climate.

The situation is better constrained in the modern period – after 1978 – where TSI has been measured by satellites, giving secure observational evidence for a 0.1% change over the solar cycle. It is found that the energy that enters the oceans over a solar cycle is 5–7 times larger than the 0.1% change in TSI.[38] This means two things:

- the solar contribution to the energy that enters the oceans is larger than from TSI alone by almost an order of magnitude[38,83]
- there must be a mechanism capable of amplifying solar activity (see Section 4).

A number of amplifying mechanisms have been suggested.

Solar UV mechanism

One mechanism is based on changes in the UV part of the solar spectrum. During solar maxima, the energy in the UV spectrum can be several percent higher than during solar minima. The increase in UV is absorbed in the stratosphere, which then gets warmer. This results in changes in the dynamical circulation of the stratosphere, such that energy is transported down into the troposphere, where it may influence surface temperatures.[43] The UV mechanism has been tested by extensive numerical modelling,[44,45] and it is found that the effect on the troposphere appears to be too weak to explain the observed changes in the global radiative budget over the solar cycle. The UV mechanism is the most mature theory put forward to explain solar amplification, in the sense that the physics is understood, and that the mechanism has been tested in global circulation models.

Cosmic ray clouds mechanism

Another possible mechanism is changes to Earth's cloud cover due to solar modulation of cosmic rays.[50–52] In 1996, satellite observations showed that Earth's cloud cover changed by around 2%, in phase with changes in cosmic rays, over a solar cycle. Such a variation corresponds to a change in radiative forcing of around 1 W/m^2, which would be in agreement with the observed changes in energy entering the oceans (see Figure 9). The fundamental idea is that cosmic ray ionisation in the atmosphere is important for the formation[54,55] and growth of small aerosols into CCN, which are necessary for the formation of cloud droplets and thereby clouds.[58] Changing the number density of CCN changes the cloud microphysics, which in turn changes both the radiative properties and the lifetime of clouds (see Figure 12).

There is now theoretical, experimental and observational evidence to support the cosmic ray–cloud link,[57,58] although it should be mentioned that satellite observations of cloud changes on 11-year timescales are by no means entirely reliable due to inherent calibration problems. However, in support of the theory, the whole link from solar activity, to cosmic ray ionisation to aerosols to clouds, has been observed in connection with Forbush decreases on timescales of a week.[59,60] The cosmic ray variations in response to the stronger Forbush decreases are of similar size to the variations seen over the 11-year solar cycle and result in a change in cloud cover of approximately 2%.[60]

Cloud variations are one of the most difficult and uncertain features of the climate system, and therefore cosmic rays and their effect on clouds will add important new understanding of this area. There have been attempts to include the effect of ionisation on the nucleation of small aerosols in large numerical models,[56,84,85] but important physical processes are missing.[58]

Although there are uncertainties in all of the above observations, they collectively give a consistent picture, indicating an effect of ionisation on Earth's cloud cover, which in turn can strongly influence climate and Earth's temperature. Nonetheless, the idea of a cosmic-ray link to climate has been questioned,[86–89] and can still give rise to debate. But as more data from observations and experiments are obtained, the case for the link has only become stronger. For example, if the cosmic ray–climate link is real, then any variation of the cosmic ray flux, including those which have nothing to do with solar activity, will translate into changes in the climate as well. Over geological timescales, large variations in the cosmic ray flux arise from the changing galactic environment around the solar system. A comparison between reconstructions of the cosmic ray flux[4] and climate[5] over these long timescales demonstrates that, over the past 500 million years,[6] ice ages have arisen in periods when the cosmic ray flux was high, as the theory predicts.[90–93] Even the solar system's movement in and out of the galactic plane can be observed in the climate record.[94,95]

Electric field mechanism

The effects of the electrical circuit on Earth's climate have also been suggested as a possible driver of climate. The global atmospheric electrical circuit and its interaction with cloud microphysics (and hence the cosmic ray effect) is an interesting area of climate science, but needs observations and experiments to enable an assessment of its importance.[61,96,97]

8 Conclusion

Over the last 20 years, much progress has been made in understanding the role of the Sun in the Earth's climate. In particular, the frequent changes between states of low and high solar activity over the last 10,000 years are clearly seen in empirical climate records. Of these climate changes, the best known are the Medieval Warm Period (950–1250 AD) and the Little Ice Age (1300–1850 AD), which are associated with a high and low state of solar activity, respectively. The temperature change between the two periods is of the order of 1.0–1.5 K. This shows that solar activity has had a large impact on climate. The above statement is in direct contrast to the IPCC, which estimates the solar forcing over the 20th century as only 0.05 W/m^2, which is too small to have a climatic effect. One is therefore left with the conundrum of not having an explanation for the difference in climate between the Medieval Warm Period and Little Ice Age. But this result is obtained by restricting solar activity to only minute changes in total solar irradiance.

There are other mechanisms by which solar activity can influence climate. One mechanism is based on changes in solar UV radiation. However, the conclusion seems to be that the effect of UV changes is too weak to explain the energy that enters the oceans over the solar cycle. In contrast, the amplification of solar activity by cosmic ray ionisation affecting cloud cover has the potential to explain the observed changes. This mechanism is now supported by theory, experiment, and observations. Sudden changes in cosmic ray flux in connection with Forbush decreases allow us to see the changes in each stage along the chain of the theory: from solar activity, to ionisation changes, to aerosols, and then to cloud changes.

In addition, the impact of cosmic rays on the radiative budget is found to be an order of magnitude larger than the TSI changes. Additional support for a cosmic ray–climate connection is the remarkable agreement that is seen on timescales of millions and even billions of years, during which the cosmic ray flux is governed by changes in the stellar environment of the solar system; in other words, it is independent of solar activity. This leads to the conclusion that a microphysical mechanism involving cosmic rays and clouds is operating in the

Earth's atmosphere, and that this mechanism has the potential to explain a significant part of the observed climate variability in relation to solar activity.

An open question is how large secular changes in total solar irradiance can be. Current estimates range from 0.1% to outlier estimates of 0.5%; the latter would be important for climate variation. A small TSI variation, on the other hand, would mean that TSI is not responsible for climate variability. Perhaps future observations will be able to constrain TSI variability better.

Climate science in general is, at present, highly politicised, with many special interests involved. It should therefore be no surprise that the above conclusion on the role of the Sun in climate is strongly disputed. The core problem is that if the Sun has had a large influence over the Holocene period, then it should also have had a significant influence in the 20th century warming, with the consequence that the climate sensitivity to carbon dioxide would be on the low side. The observed decline in solar activity would then also be responsible for the observed slowing of warming in recent years.

Needless to say, more research into the physical mechanisms linking solar activity to climate is needed. It is useless to pretend that the problem of solar influence has been solved. The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes is the effect of clouds, and research into the solar effect on climate will add significantly to understanding in this area. Such efforts are only possible by acknowledging that this is a genuine and important scientific problem and by allocating sufficient research funds to its investigation.

9 Appendix: A simple ocean model calculation

The following simple calculation illustrates why variations in TSI are too small to explain the observed variations in ocean temperature over the 11-year cycle. For a more comprehensive treatment, see Shaviv (2008).[38]

The solar constant at the top of the Earth's atmosphere is measured at:

$$S_0 = 1365 \text{ W/m}^2 \tag{1}$$

This energy needs to be distributed over the Earth's surface

$$S = S_0 \frac{\pi r^2}{4\pi r^2}(1-\alpha) = \frac{S_0}{4}0.7 \approx 239 \text{ W/m}^2 \tag{2}$$

where $\alpha \approx 0.3$ is the Earth's average albedo from ice, clouds, land and ocean. Over a solar cycle the irradiance from the Sun changes by ≈0.1%, corresponding to 1.4 W/m^2. Using the same arguments as above, the change at the surface becomes:

$$\Delta S = \frac{\Delta S_0}{4}0.7 \approx 0.24 \text{ W/m}^2 \tag{3}$$

This is the change from peak to peak. The amplitude over a solar cycle is then

$$\Delta S_A \approx 0.1 \text{ W/m}^2 \tag{4}$$

So now we have the change in energy that on average goes into the ocean during a solar cycle due to solar irradiance changes. We will now use a simple model[83] to estimate the expected temperature change ΔT caused by a periodic solar irradiance signal over the 11-year period:

$$\frac{d\Delta T}{dt} + K\ \Delta T = \frac{\Delta S_A}{\rho\ H\ C_P}\cos(\omega t) \tag{5}$$

where ΔT is the change in temperature, K is a dissipative timescale for energy loss to the deep ocean and to the atmosphere. H is the average depth of the mixed layer of the oceans and C_p is the heat capacity of water at constant pressure, and finally ρ is the density of water (see Figure 15. The assumption is that in the mixed layer the water is well mixed and therefore the temperature can be described by a single number ΔT.

Solving the above equation by Fourier transformation gives (inserting, $\Delta T = \Delta T_\omega \exp(i\omega)$):

$$\Delta T = \frac{\Delta S_A}{\rho\ H\ C_P(\omega^2 + K^2)^{1/2}}\cos(\omega t + \theta) \tag{6}$$

The above equation also gives the amplitude in the temperature response to a solar-cycle variation in irradiance, and the phase shift θ is related to the dissipative scale K and ω via

$$\tan\theta = \omega/K \tag{7}$$

Observing the phase shift can therefore give us the dissipative scale K. The relevant constants are:

$$\begin{aligned} K &= 1 \text{ year}^{-1} = 3.1 \cdot 10^{-8} \text{ s}^{-1} \\ H &= 50 \text{ m} \\ C_P &= 4.2 \cdot 10^3 \text{ WsK}^{-1}/\text{kg} \\ \rho &= 1.0 \cdot 10^3 \text{ kg/m}^3 \\ \omega &= 2\pi/11.0 \text{ years}^{-1} = 1.8 \cdot 10^{-8} \text{ s}^{-1} \end{aligned} \tag{8}$$

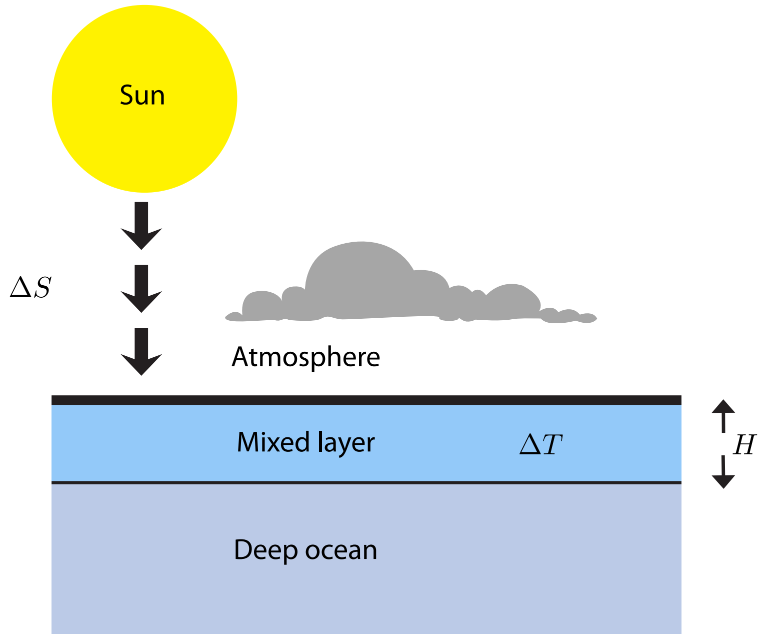


Figure 15: Schematic of the mixed layer in the oceans.
ΔS is the variation of the energy that goes into the oceans. H is the height of the mixed layer, here set to 50 m.

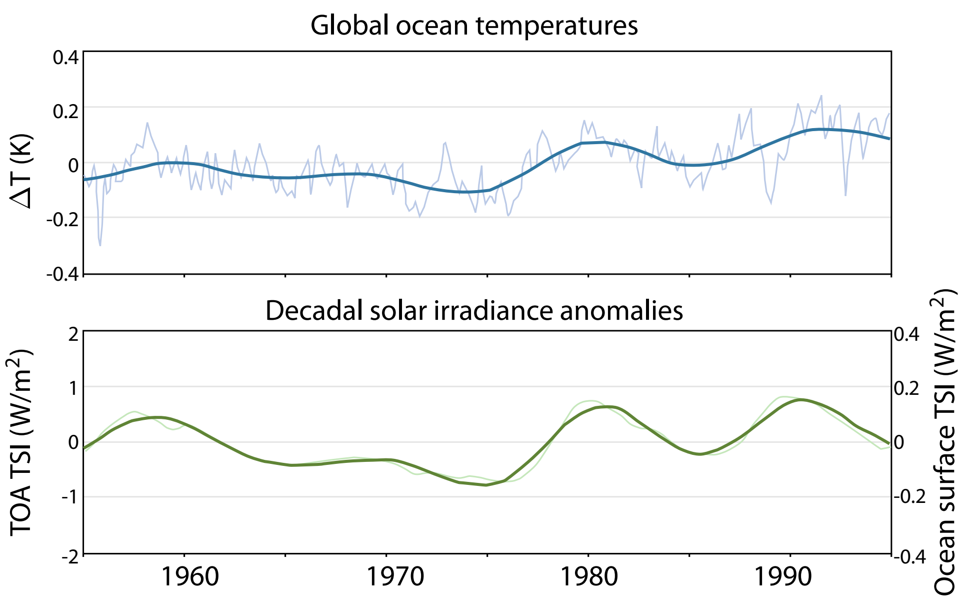


Figure 16: Correlation of temperature and TSI.
Top panel: Observations of temperature variations over a 40 year period. Notice that the amplitude of the solar signal is of the order 0.05–0.08 K. Bottom panel: reconstruction of TSI. Here the left-hand axis is the change at the top of the atmosphere, whereas the right-hand side is the energy at the surface of the oceans. Notice that the amplitude is of the order 0.1 W/m^2. Figure adapted from White *et al.*[83]

Inserting these values into Eqn (6) gives an amplitude of

$$\Delta T_\omega \approx 0.01 \text{ K} \tag{9}$$

The phase shift between the solar signal and the temperature response is $\approx$30°.

However, observations show that the amplitude of the temperature change during a solar cycle is in the range 0.05–0.08 K (see Figure 16).

So the solar signal found is $\approx$5–7 times larger than the change in solar irradiance alone. The fundamental question is, therefore, *what amplifies the solar signal?*

Bibliography

1. G Myhre, D Shindell, FM Bréon *et al.*, 'Anthropogenic and natural radiative forcing,' in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T Stocker, D Qin, GK Plattner *et al.*, (eds). Cambridge University Press, 2013.
2. LJ Gray, J Beer, M Geller *et al.*, 'Solar influences on climate,' *Reviews of Geophysics*, 2010, vol. 48.
3. DV Hoyt and KH Schatten, 'Group sunspot numbers: A new solar activity reconstruction,' *Solar Physics*, 1998, vol. 179, pp. 189–219. URL: https://doi.org/10.1023/A:1005007527816
4. L Svalgaard and KH Schatten, 'Reconstruction of the sunspot group number: The backbone method,' *Solar Physics*, 2016, vol. 291, pp. 2653–2684. URL: https://doi.org/10.1007/s11207-015-0815-8
5. IG Usoskin, GA Kovaltsov, M Lockwood *et al.*, 'A new calibrated sunspot group series since 1749: Statistics of active day fractions,' *Solar Physics*, 2016, vol. 291. URL: https://doi.org/10.1007/s11207-015-0838-1
6. DV Hoyt and KH Schatten, 'Group sunspot numbers: A new solar activity reconstruction,' *Solar Physics*, 1998, vol. 181, p. 491. URL: https://doi.org/10.1023/A:1005056326158
7. F Clette, L Svalgaard, JM Vaquero *et al.*, 'Revisiting the sunspot number. a 400-year perspective on the solar cycle,' *Space Science Reviews*, 2014, vol. 186, pp. 35–103.
8. KG McCracken and J Beer, 'The annual cosmic-radiation intensities 1391–2014; the annual heliospheric magnetic field strengths 1391–1983, and identification of solar cosmic-ray events in the cosmogenic record 1800–1983,' *Solar Physics*, 2015, vol. 290, pp. 3051–3069.
9. C Fröhlich, 'Solar irradiance variability since 1978,' *Space Science Reviews*, 2006, vol. 125, pp. 53–65. URL: https://doi.org/10.1007/s11214-006-9046-5
10. RC Willson and AV Mordvinov, 'Secular total solar irradiance trend during solar cycles 21–23,' *Geophysical Research Letters*, 2002, vol. 30. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002GL016038
11. N Scafetta and RC Willson, 'ACRIM-gap and TSI trend issue resolved using a surface magnetic flux TSI proxy model,' *Geophysical Research Letters*, 2008, vol. 36. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008GL036307
12. O Coddington, JL Lean, P Pilewskie *et al.*, 'A solar irradiance climate data record,' *Bulletin of the American Meteorological Society*, 2016, vol. 97, pp. 1265–1282. URL: https://doi.org/10.1175/BAMS-D-14-00265.1

13. G Kopp, N Krivova, CJ Wu *et al.*, 'The impact of the revised sunspot record on solar irradiance reconstructions,' *Solar Physics*, 2016, vol. 291, pp. 2951–2965.
14. AI Shapiro, W Schmutz, E Rozanov *et al.*, 'A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing,' *Astronomy & Astrophysics*, 2011, vol. 529, p. A67. URL: https://doi.org/10.1051/0004-6361/201016173
15. T Egorova, W Schmutz, E Rozanov *et al.*, 'Revised historical solar irradiance forcing,' *Astronomy & Astrophysics*, 2018, vol. 615, p. A85.
16. CJ Schrijver, WC Livingston, TN Woods *et al.*, 'The minimal solar activity in 2008–2009 and its implications for long-term climate modeling,' *Geophysical Research Letters*, 2011, vol. 38. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011GL046658
17. PG Judge, GW Lockwood, RR Radick *et al.*, 'Confronting a solar irradiance reconstruction with solar and stellar data,' *Astronomy & Astrophysics*, 2012, vol. 544, p. A88.
18. P Foukal and L Milano, 'A measurement of the quiet network contribution to solar irradiance variation,' *Geophysical Research Letters*, 2001, vol. 28, pp. 883–886. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000GL012072
19. P Foukal, 'A new look at solar irradiance variation,' *Solar Physics*, 2012, vol. 279, pp. 365–381. URL: https://doi.org/10.1007/s11207-012-0017-6
20. JA Eddy, 'The Maunder Minimum,' *Science*, 1976, vol. 192, pp. 1189–1202.
21. A Moberg, DM Sonechkin, K Holmgren *et al.*, 'Highly variable northern hemisphere temperatures reconstructed from low- and high-resolution proxy data,' *Nature*, 2005, vol. 433, p. 613. URL: http://dx.doi.org/10.1038/nature03265
22. ME Mann and PD Jones, 'Global surface temperatures over the past two millennia,' *Geophysical Research Letters*, 2003, vol. 30. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2003GL017814
23. SP Huang, HN Pollack, and PY Shen, 'A late quaternary climate reconstruction based on borehole heat flux data, borehole temperature data, and the instrumental record,' *Geophysical Research Letters*, 2008, vol. 35.
24. CP Morice, JJ Kennedy, NA Rayner *et al.*, 'Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set,' *Journal of Geophysical Research: Atmospheres*, 2011, vol. 117. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011JD017187
25. G Delaygue and E Bard, 'An Antarctic view of Beryllium-10 and solar activity for the past millennium,' *Climate Dynamics*, 2011, vol. 36, pp. 2201–2218.
26. J Beer, ST Baumgartner, B Dittrich-Hannen *et al.*, 'Solar variability traced by cosmogenic isotopes,' *International Astronomical Union Colloquium*, 1994, vol. 143, pp. 291–300.
27. U Neff, SJ Burns, A Mangini *et al.*, 'Strong coherence between solar variability and the monsoon in Oman between 9 and 6kyr ago,' *Nature*, 2001, vol. 411, pp. 290–293.
28. D Fleitmann, SJ Burns, M Mudelsee *et al.*, 'Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman,' *Science*, 2003, vol. 300, pp. 1737–1739. URL: http://science.sciencemag.org/content/300/5626/1737
29. Y Wang, H Cheng, RL Edwards *et al.*, 'The Holocene Asian monsoon: Links to solar changes and North Atlantic climate,' *Science*, 2005, vol. 308, pp. 854–857. URL: http://science.sciencemag.org/content/308/5723/854

30. F Duan, Y Wang, CC Shen *et al.*, 'Evidence for solar cycles in a late Holocene speleothem record from Dongge Cave, China,' *Scientific Reports*, 2014, vol. 4, pp. 5159 EP –. URL: http://dx.doi.org/10.1038/srep05159

31. P Zhang, H Cheng, RL Edwards *et al.*, 'A test of climate, sun, and culture relationships from an 1810-year Chinese cave record,' *Science*, 2008, vol. 322, pp. 940–942.

32. DA Hodell, M Brenner, JH Curtis *et al.*, 'Solar forcing of drought frequency in the Maya lowlands,' *Science*, 2001, vol. 292, pp. 1367–1370. URL: http://science.sciencemag.org/content/292/5520/1367

33. GH Haug, D Günther, LC Peterson *et al.*, 'Climate and the collapse of Maya civilization,' *Science*, 2003, vol. 299, pp. 1731–1735. URL: http://science.sciencemag.org/content/299/5613/1731

34. HH Lamb, 'The early medieval warm epoch and its sequel,' *Palaeegeography, Palaeoclimatology, Palaeecology*, 1965, vol. 1, pp. 13–37.

35. BM Fagan, *The Little Ice Age: How Climate Made History, 1300–1850*. Basic Books, 2000.

36. G Bond, B Kromer, J Beer *et al.*, 'Persistent solar influence on North Atlantic climate during the Holocene,' *Science*, 2001, vol. 294, pp. 2130–2136.

37. F Adolphi, R Muscheler, A Svensson *et al.*, 'Persistent link between solar activity and Greenland climate during the last glacial maximum,' *Nature Geoscience*, 2014, vol. 7, p. 662. URL: http://dx.doi.org/10.1038/ngeo2225

38. NJ Shaviv, 'Using the oceans as a calorimeter to quantify the solar radiative forcing,' *Journal of Geophysical Research*, 2008, vol. 113.

39. D Howard, NJ Shaviv, and H Svensmark, 'The solar and Southern Oscillation components in the satellite altimetry data,' *Journal of Geophysical Research (Space Physics)*, 2015, vol. 120, pp. 3297–3306.

40. H Svensmark, 'Influence of cosmic rays on Earth's climate,' *Physical Review Letters*, 1998, vol. 81, pp. 5027–5030.

41. D Dahl-Jensen, K Mosegaard, N Gundestrup *et al.*, 'Past temperatures directly from the Greenland ice sheet,' *Science*, 1998, vol. 282, p. 268.

42. JL Lean and MT DeLand, 'How does the sun's spectrum vary?' *Journal of Climate*, 2012, vol. 25, pp. 2555–2560. URL: https://doi.org/10.1175/JCLI-D-11-00571.1

43. JD Haigh, 'The role of stratospheric ozone in modulating the solar radiative forcing of climate,' *Nature*, 1994, vol. 370, p. 544.

44. H Lee and AK Smith, 'Simulation of the combined effects of solar cycle, quasi-biennial oscillation, and volcanic forcing on stratospheric ozone changes in recent decades,' *Journal of Geophysical Research (Atmospheres)*, 2003, vol. 108, p. 4049.

45. JD Haigh, M Blackburn, and R Day, 'The response of tropospheric circulation to perturbations in lower-stratospheric temperature,' *Journal of Climate*, 2005, vol. 18, pp. 3672–3685.

46. D Rind, J Lean, J Lerner *et al.*, 'Exploring the stratospheric/tropospheric response to solar forcing,' *Journal of Geophysical Research: Atmospheres*, 2008, vol. 113. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JD010114

47. H Svensmark, 'Cosmoclimatology: a new theory emerges,' *Astronomy and Geophysics*, 2007, vol. 48, pp. 010 000–1.
48. N Marsh and H Svensmark, 'Galactic cosmic ray and El Niño-Southern Oscillation trends in International Satellite Cloud Climatology Project D2 low-cloud properties,' *Journal of Geophysical Research (Atmospheres)*, 2003, vol. 108, p. 4195.
49. AT Evan, AK Heidinger, and DJ Vimont, 'Arguments against a physical long-term trend in global ISCCP cloud amounts,' *Geophysical Research Letters*, 2007, vol. 34. URL: http://dx.doi.org/10.1029/2006GL028083
50. ER Ney, 'Cosmic radiation and the weather,' *Nature*, 1959, vol. 183, p. 451.
51. RE Dickinson, 'Solar variability and the lower atmosphere.' *Bulletin of the American Meteorological Society*, 1975, vol. 56, pp. 1240–1248.
52. H Svensmark and E Friis-Christensen, 'Variation of cosmic ray flux and global cloud coverage – a missing link in solar-climate relationships.' *Journal of Atmospheric and Solar-Terrestrial Physics*, 1997, vol. 59, pp. 1225–1232.
53. N Marsh and H Svensmark, 'Cosmic rays, clouds, and climate,' *Space Science Reviews*, 2000, vol. 94, pp. 215–230.
54. H Svensmark, JOP Pedersen, ND Marsh *et al.*, 'Experimental evidence for the role of ions in particle nucleation under atmospheric conditions,' *Royal Society of London Proceedings Series A*, 2007, vol. 463, pp. 385–396.
55. J Kirkby, J Curtius, J Almeida *et al.*, 'Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation,' *Nature*, 2011, vol. 476, pp. 429–433.
56. J Pierce and P Adams, 'Can cosmic rays affect cloud condensation nuclei by altering new particle formation rates?' *Geophysical Research Letters*, 2009, vol. 36, p. L09820.
57. H Svensmark, MB Enghoff, and JOP Pedersen, 'Response of cloud condensation nuclei to changes in ion-nucleation,' *Physics Letters A*, 2013, vol. 377, pp. 2343–2347. URL: http://www.sciencedirect.com/science/article/pii/S0375960113006294
58. H Svensmark, MB Enghoff, NJ Shaviv *et al.*, 'Increased ionization supports growth of aerosols into cloud condensation nuclei,' *Nature Communications*, 2017, vol. 8, p. 2199. URL: https://doi.org/10.1038/s41467-017-02082-2
59. H Svensmark, T Bondo, and J Svensmark, 'Cosmic ray decreases affect atmospheric aerosols and clouds,' *Geophysical Research Letters*, 2009, vol. 36, p. 15101.
60. J Svensmark, MB Enghoff, NJ Shaviv *et al.*, 'The response of clouds and aerosols to cosmic ray decreases,' *Journal of Geophysical Research: Space Physics*, 2016, vol. 121, pp. 8152–8181. URL: http://dx.doi.org/10.1002/2016JA022689
61. BA Tinsley, G Burns, and L Zhou, 'The role of the global electric circuit in solar and internal forcing of clouds and climate,' *Advances in Space Research*, 2007, vol. 40, pp. 1126 – 1139. URL: http://www.sciencedirect.com/science/article/pii/S0273117707001135
62. RG Harrison and MHPA Ambaum, 'Observed atmospheric electricity effect on clouds,' *Environmental Research Letters*, 2009, vol. 4, p. 014003. URL: http://stacks.iop.org/1748-9326/4/i=1/a=014003
63. WD Pesnell, 'Predictions of solar cycle 24: How are we doing?' *Space Weather*, 2016, vol. 14, pp. 10–21. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015SW001304

64. JL Lean and DH Rind, 'How will Earth's surface temperature change in future decades?' *Geophysical Research Letters*, 2009, vol. 36. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009GL038932

65. G Feulner and S Rahmstorf, 'On the effect of a new grand minimum of solar activity on the future climate on Earth,' *Geophysical Research Letters*, 2010, vol. 37. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010GL042710

66. GA Meehl, JM Arblaster, and DR Marsh, 'Could a future 'Grand Solar Minimum' like the Maunder Minimum stop global warming?' *Geophysical Research Letters*, 2013, vol. 40, pp. 1789–1793.

67. H Abdussamatov, 'Grand minimum of the total solar irradiance leads to the little ice age,' *Journal of Geology & Geosciences*, 2013, vol. 113.

68. A Indermühle, TF Stocker, F Joos *et al.*, 'Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica,' *Nature*, 1999, vol. 398, pp. 121–126.

69. ME Mann, RS Bradley, and MK Hughes, 'Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations,' *Geophys. Rev. Lett.*, 1999, vol. 26, pp. 759–762.

70. S Huang, H Pollack, and P Shen, 'Temperature trends over the past five centuries reconstructed from borehole temperatures,' *Nature*, 2000, vol. 403, p. 756.

71. WS Broecker, 'Was the Medieval Warm Period global?' *Science*, 2001, vol. 291, pp. 1497–1499. URL: http://science.sciencemag.org/content/291/5508/1497

72. W Soon and S Baliunas, 'Proxy climatic and environmental changes of the past 1000 years,' *Climate Research*, 2003, vol. 23, pp. 89–110.

73. DW Oppo, Y Rosenthal, and BK Linsley, '2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool,' *Nature*, 2009, vol. 460, p. 1113. URL: http://dx.doi.org/10.1038/nature08233

74. B Christiansen, 'Reconstructing the NH mean temperature: Can underestimation of trends and variability be avoided?' *Journal of Climate*, 2011, vol. 24, pp. 674–692. URL: https://doi.org/10.1175/2010JCLI3646.1

75. B Christiansen and FC Ljungqvist, 'Reconstruction of the extratropical nh mean temperature over the last millennium with a method that preserves low-frequency variability,' *Journal of Climate*, 2011, vol. 24, pp. 6013–6034. URL: https://doi.org/10.1175/2011JCLI4145.1

76. S Lüning, M Gałka, and F Vahrenholt, 'Warming and cooling: The Medieval Climate Anomaly in Africa and Arabia,' *Paleoceanography*, 2017, vol. 32, pp. 1219–1235. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017PA003237

77. S McIntyre and R McKitrick, 'Corrections to the Mann *et. al.* (1998) proxy data base and Northern Hemispheric average temperature series,' *Energy & Environment*, 2003, vol. 14, pp. 751–771. URL: https://doi.org/10.1260/095830503322793632

78. H von Storch, E Zorita, JM Jones *et al.*, 'Reconstructing past climate from noisy data,' *Science*, 2004, vol. 306, pp. 679–682. URL: http://science.sciencemag.org/content/306/5696/679

79. S McIntyre and R McKitrick, 'Hockey sticks, principal components, and spurious significance,' *Geophysical Research Letters*, 2005, vol. 32. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004GL021750

80. S McIntyre and R McKitrick, 'The M&M critique of the MBH98 Northern Hemisphere climate index: Update and implications,' *Energy & Environment*, 2005, vol. 16, pp. 69–100. URL: https://doi.org/10.1260/0958305053516226

81. H von Storch and E Zorita, 'Comment on 'hockey sticks, principal components, and spurious significance' by S. McIntyre and R. McKitrick,' *Geophysical Research Letters*, 2005, vol. 32. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005GL022753

82. S Ziskin and N Shaviv, 'Quantifying the role of solar radiative forcing over the 20th century,' *Advances in Space Research*, 2011.

83. B White, J Lean, DR Cayan *et al.*, 'Response of global upper ocean temperature to changing solar irradiance,' *Journal of Geophysical Research: Oceans*, 1997, vol. 102, pp. 3255–3266. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/96JC03549

84. J Kazil, ER Lovejoy, MC Barth *et al.*, 'Aerosol nucleation over oceans and the role of galactic cosmic rays,' *Atmospheric Chemistry and Physics*, 2006, vol. 6, pp. 4905–4924.

85. E Snow-Kropla, J Pierce, D Westervelt *et al.*, 'Cosmic rays, aerosol formation and cloud-condensation nuclei: sensitivities to model uncertainties,' *Atmospheric Chemistry and Physics*, 2011, vol. 11, pp. 4001–4013.

86. JE Kristjánsson, CW Stjern, F Stordal *et al.*, 'Cosmic rays, cloud condensation nuclei and clouds - a reassessment using MODIS data,' *Atmospheric Chemistry & Physics*, 2008, vol. 8, pp. 7373–7387.

87. T Sloan and AW Wolfendale, 'Testing the proposed causal link between cosmic rays and cloud cover,' *Environmental Research Letters*, 2008, vol. 3, p. 044001.

88. J Calogovic, C Albert, F Arnold *et al.*, 'Sudden cosmic ray decreases: No change of global cloud cover,' *Geophysical Research Letters*, 2010, vol. 37, p. 3802.

89. B Laken, D Kniveton, and A Wolfendale, 'Forbush decreases, solar irradiance variations, and anomalous cloud changes,' *Journal of Geophysical Research*, 2011, vol. 116, p. D09201.

90. NJ Shaviv, 'Cosmic ray diffusion from the galactic spiral arms, iron meteorites, and a possible climatic connection,' *Physics Review Letters*, 2002, vol. 89, p. 051102.

91. NJ Shaviv, 'The spiral structure of the Milky Way, cosmic rays, and ice age epochs on Earth,' *New Astronomy*, 2003, vol. 8, pp. 39–77.

92. NJ Shaviv and J Veizer, 'A celestial driver of Phanerozoic climate?' *GSA Today*, 2003, pp. 4–11.

93. H Svensmark, 'Evidence of nearby supernovae affecting life on earth,' *Monthly Notices of the Royal Astronomical Society*, 2012, vol. 423, pp. 1234–1253. URL: http://mnras.oxfordjournals.org/content/423/2/1234.abstract

94. H Svensmark, 'Imprint of Galactic dynamics on Earth's climate,' *Astronomische Nachrichten*, 2006, vol. 327, p. 866.

95. NJ Shaviv, A Prokoph, and J Veizer, 'Is the solar system's galactic motion imprinted in the Phanerozoic climate?' *Scientific Reports*, 2014, vol. 4, p. 6150. URL: http://dx.doi.org/10.1038/srep06150

96. BA Tinsley and RA Heelis, 'Correlations of atmospheric dynamics with solar activity evidence for a connection via the solar wind, atmospheric electricity, and cloud microphysics,' *Journal of Geophysical Research: Atmospheres*, 1993, vol. 98, pp. 10 375–10 384. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/93JD00627

97. RG Harrison, 'The global atmospheric electrical circuit and climate,' *Surveys in Geophysics*, 2004, vol. 25, pp. 441–484.

About the Global Warming Policy Foundation

The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

GWPF REPORTS

1	Montford	The Climategate Inquiries
2	Ridley	The Shale Gas Shock
3	Hughes	The Myth of Green Jobs
4	McKitrick	What Is Wrong With the IPCC?
5	Booker	The BBC and Climate Change
6	Montford	Nullius in Verba: The Royal Society and Climate Change
7	Goklany	Global Warming Policies Might Be Bad for Your Health
8	Hughes	Why Is Wind Power So Expensive?
9	Lilley	What Is Wrong With Stern?
10	Whitehouse	The Global Warming Standstill
11	Khandekar	The Global Warming-Extreme Weather Link
12	Lewis and Crok	Oversensitive
13	Lewis and Crok	A Sensitive Matter
14	Montford and Shade	Climate Control: Brainwashing in Schools
15	De Lange and Carter	Sea-level Change: Living with Uncertainty
16	Montford	Unintended Consequences of Climate Change Policy
17	Lewin	Hubert Lamb and the Transformation of Climate Science
18	Goklany	Carbon Dioxide: The Good News
19	Adams	The Truth About China
20	Laframboise	Peer Review: Why Scepticism is Essential
21	Constable	Energy Intensive Users: Climate Policy Casualties
22	Lilley	£300 Billion: The Cost of the Climate Change Act
23	Humlum	The State of the Climate in 2016
24	Curry et al.	Assumptions, Policy Implications and the Scientific Method
25	Hughes	The Bottomless Pit: The Economics of CCS
26	Tsonis	The Little Boy: El Niño and Natural Climate Change
27	Darwall	The Anti-development Bank
28	Booker	Global Warming: A Case Study in Groupthink
29	Crockford	The State of the Polar Bear Report 2017
30	Humlum	State of the Climate 2017
31	Darwall	The Climate Change Act at Ten
32	Crockford	The State of the Polar Bear Report 2018
33	Svensmark	Force Majeure: The Sun's Role in Climate Change

For further information about the Global Warming Policy Foundation, please visit our website at www.thegwpf.org.
The GWPF is a registered charity, number 1131448.