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Solar influences on Climate

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Executive summary

THE SUN PROVIDES THE ENERGY THAT DRIVES THE EARTH'S CLIMATE system. Variations in the composition and intensity of incident solar radiation hitting the Earth may produce changes in global and regional climate which are both different and additional to those from man-made climate change. In the current epoch, solar variation impacts on regional climate appear to be quite significant in, for example, Europe in winter, but on a global scale are likely to be much smaller than those due to increasing greenhouse gases.

What are the sources of variation in solar radiation?

There are two main sources of variation in solar radiation. First, there are internal stellar processes that affect the total radiant energy emitted by the Sun—i.e. solar activity. Second, changes in the Earth's orbit around the Sun over tens and hundreds of thousands of years directly affect the amount of radiant energy hitting the Earth and its distribution across the globe.

Do these changes affect the climate?

Annual or decadal variations in solar activity are correlated with sunspot activity. Sunspot numbers have been observed and recorded over hundreds of years, as have records of some other indicators of solar activity, such as aurorae. Evidence of variations in solar activity on millennial timescales can be found in the records of cosmogenic radionuclides in such long-lived natural features as ice cores from large ice sheets, tree rings and ocean sediments. Using careful statistical analysis it is now possible to identify decadal and centennial signals of solar variability in climate data. These suggest non-uniform responses across the globe, perhaps with the largest impacts in mid-latitudes.

The long-term orbital changes in incident radiation are also reflected in the geological record and are seen as the trigger for glacial-interglacial transitions, with their effect amplified by feedback mechanisms. For example,

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a warming of the planet due to an increase in solar irradiance probably results in the release of methane and carbon dioxide from stores in the oceans and icecaps, and these greenhouse gases can then produce additional warming.

Do we understand the processes involved?

From a global perspective the processes through which changes in incident solar radiation affect the temperature of the Earth's atmosphere, and the climate at the surface, are well understood. The spectral composition of the radiation is of crucial importance. For example, visible radiation reaches and warms the oceans and land surface, ultraviolet radiation is absorbed by atmospheric oxygen and ozone, while water vapour and carbon dioxide absorb infrared radiation. The production and destruction of some gases, such as stratospheric ozone, also depend on solar ultraviolet radiation.

However, the response of climate on regional scales to changes in the composition and intensity of incident solar radiation is more complex. This is an area of active research and, while significant progress has been made, definitive answers require further investigation into effects such as the role of stratospheric ozone, ocean-atmosphere interactions and the role of clouds.

Has the Sun contributed to global warming?

It is not possible to explain the warming of the past sixty years on the basis of changes in solar activity alone. Over the past 150 years an overall increase in solar activity has probably contributed to global warming, mainly during the first half of the twentieth century. The effect is, however, estimated to be much smaller than the total net human forcing of the climate system through the emission of greenhouse gases and other factors.

How will the Sun change in the future?

Over the next several decades there may be an overall (temporary) decline in solar activity but at this stage, this is speculative. Even if solar activity were to reach the record low levels seen in the 17th century Maunder Minimum (implying a reduction in the solar radiation absorbed, averaged over the globe, of 0.2-0.6 Wm^{-2}), it would only partially offset the increased climate warming projected through the uncontrolled anthropogenic emission of greenhouse gases (equivalent to a trapping of heat energy of around 4 Wm^{-2} over the next century[1]).

Introduction

Energy from the Sun in the form of electromagnetic radiation is the fundamental driver of the Earth's climate system. Variations in the frequency composition and intensity of incident solar radiation hitting the Earth may produce changes in both the global and regional climate which are different and additional to those from man-made climate change. There are two main sources of variation to consider.

First, there are internal stellar processes that affect the total radiant energy emitted by the Sun— i.e. what will be termed "solar activity".

Second, changes in the Earth's orbit around the Sun over tens and hundreds of thousands of years directly affect the amount of radiant energy hitting the Earth and its distribution across the globe.

Solar Activity

Understanding the role of variability in solar activity is essential for the interpretation of past climate and prediction of the future. In the past, although much had been written on relationships between sunspot numbers and the weather, the topic of solar influences on climate was often disregarded by meteorologists. This was due to a combination of factors, the most important of which was the lack of any robust measurements indicating that the solar radiation incident on Earth did indeed vary. There was also mistrust of the statistical validity of much of the supposed evidence and, importantly, no established scientific mechanisms whereby apparent changes in solar activity might induce detectable signals near the Earth's surface. Another concern of the emergent meteorological profession in the nineteenth century was to distance itself from the popular "astrometeorology" movement[2], which sought to predict the weather based on the positions of celestial bodies. Figure 1 shows a contemporary engraving depicting one of its practitioners as a figure of fun.

Figure 1. "Murphy the Dick-Tater, Alias the Weather Cock of the Walk" a satirical engraving from 1837 depicting astrometeorologist and almanac-writer Patrick Murphy who achieved fame for his (intermittently) successful 12-month weather predictions based on the positions of the Sun and planets[4].

This estrangement of studies of solar-climate links from mainstream scientific endeavour lasted until the late 20th century when the necessity of attributing causes to global warming meant increased international effort into distinguishing natural from human-induced factors. Nowadays, with improved measurements of both solar and climate parameters, evidence of a solar signal in the climate of the lower atmosphere has begun to emerge from the noise and computer models of the atmosphere are providing a route to understanding the complex and interconnected processes involved[3].

Effect of the Earth's orbit

The total amount of solar energy reaching the Earth in a given period of time—the solar energy flux—depends on the distance between the earth and the Sun and, as the Earth has an elliptical orbit, this varies during the year. Seasons exist because the Earth's axis is tilted from the direction perpendicular to the plane of its orbit: when one pole is tilted towards the Sun at a particular point in the orbit, it is summer in the associated hemisphere and winter in the other hemisphere. The seasons are then reversed at the opposite point in the orbit. These orbital properties are illustrated in Figure 2 along with the third key parameter of the Earth's orbit, precession, which measures the wobble of the Earth's axis affecting the timing of the seasons relative to the Earth's position in the elliptical orbit.

On timescales of many millennia the amount of radiation received at the Earth is altered by variations in these orbital parameters. In other words there are changes in the flow of solar energy reaching the Earth in a given time simply as a result of Earth-Sun geometry rather than due to any innate variations in solar emission.

The degree to which the orbit differs from a circle is measured by its ellipticity (or eccentricity): the smaller the value of the ellipticity the closer the orbit is to a circle. This varies over time and has a maximum value of about 6% but is currently lower, at about 1.7%. This means that the northern hemisphere receives about 7% less radiation in its summer, and 7% more in its winter, than the southern in its equivalent seasons because the Earth is closer to the Sun in January than in July. The eccentricity varies with periods of around 100,000 and 413,000 years due to the gravitational influence of the Moon and other planets. The tilt (or obliquity) varies cyclically with a period of about 41,000 years, and the precession of the seasons varies with periods of up to about 26,000 years.

Averaged over the globe the total solar energy hitting the Earth depends on its distance from the Sun, and therefore on the ellipticity, but the distribution of the radiation over the globe depends on the tilt and precession. The amount of energy arriving in summer at high latitudes determines whether the winter

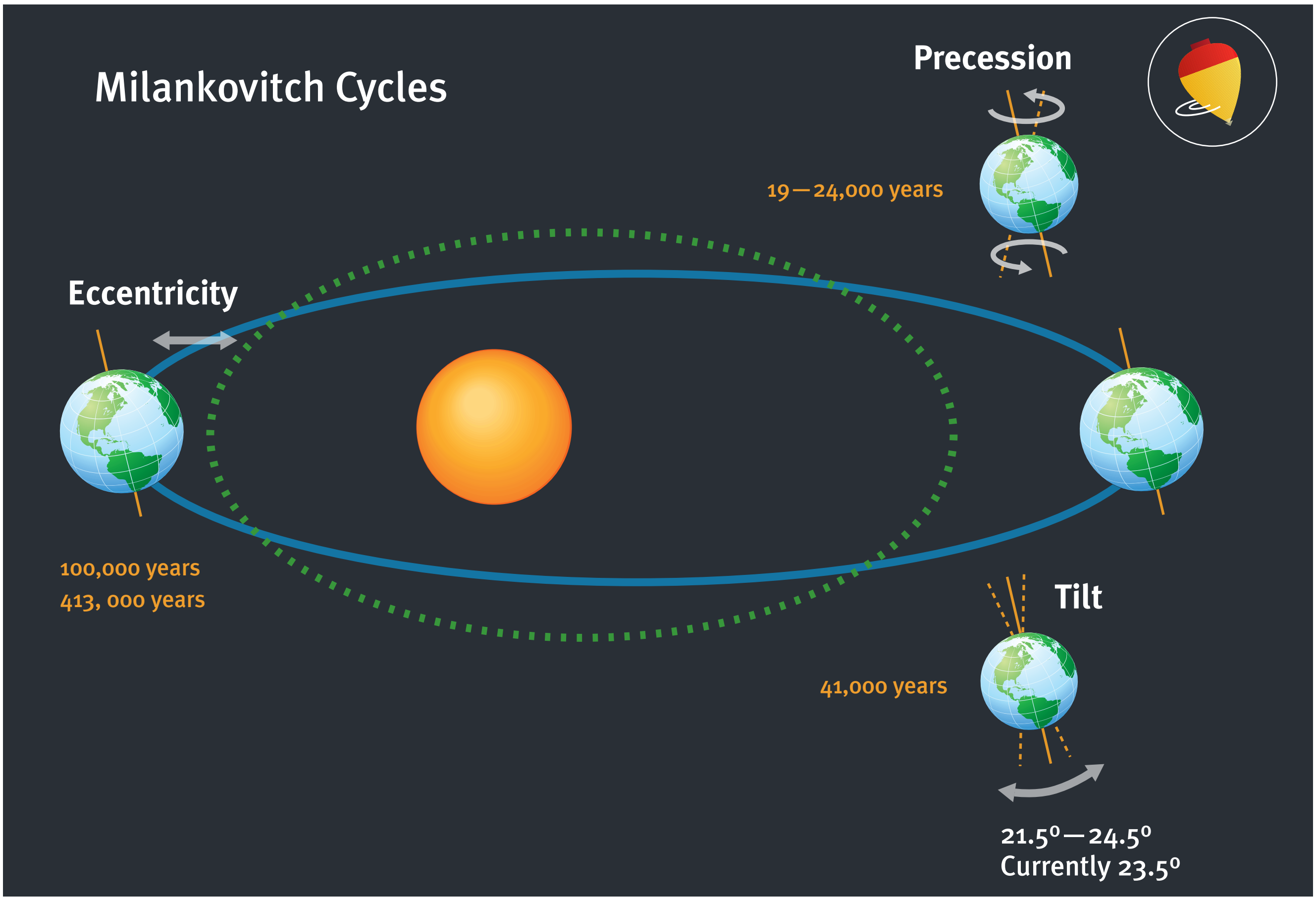


Figure 2. The Earth's orbit around the Sun, showing the key parameters eccentricity, tilt and precession[5].

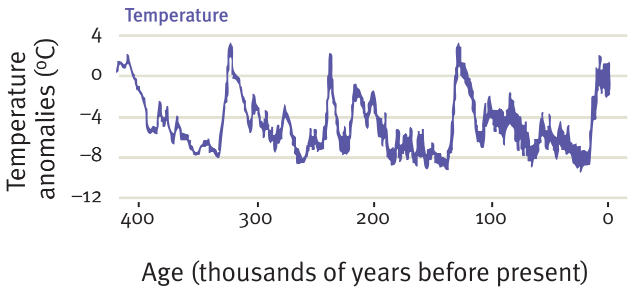


Figure 3. Temperature deduced from ^{18}O records in air bubbles trapped in the Vostok ice core[6].

growth of the ice cap will recede or whether the climate will be precipitated into an ice age. Thus changes to the seasonal irradiance, when amplified by other feedback mechanisms such as greenhouse gases released by the initial warming, can lead to much longer-term shifts in climatic regime.

Figure 3 shows how interglacial periods occur at intervals of approximately 100 thousand years, corresponding to variations in the eccentricity of the orbit. Cyclical variations in climate records with periods of around 19, 23, 41, 100 and 413 thousand years are generally referred to as Milankovitch cycles after the geophysicist who made the first detailed investigation of solar-climate links related to orbital variations.

The intensity and composition of solar radiation hitting Earth

At the current average distance of the Earth from the Sun, approximately 150 million kilometres, the flux of solar radiation (sometimes referred to as the "solar constant") is about 1365 Wm^{-2}. Of this 30% is reflected away from Earth, back to space, by bright surfaces including clouds and ice. The remainder is absorbed, warming the surface and the atmosphere. Much of the heat radiation emitted by the surface is trapped within the atmosphere by "greenhouse" gases, mainly water vapour but, in the absence of other changes, enough heat is emitted to space to balance the incoming solar radiation and establish a climate equilibrium.

While this balance is achieved globally, not every location on the Earth's surface is in energy balance and it is the distribution of the net radiation imbalances that drives the global circulations of the atmosphere and oceans. The distribution of daily-averaged solar radiation incident at the top of the atmosphere is shown in Figure 4 throughout the year by latitude. Most solar radiation arrives in the tropics, and in the summer hemisphere. Evidence of the ellipticity of the Earth's orbit can also be seen in the greater irradiance in the southern summer than the northern latitudes (the northern are at the top of the figure). The winds and weather patterns adjust to transport heat away from these regions to the regions of lower

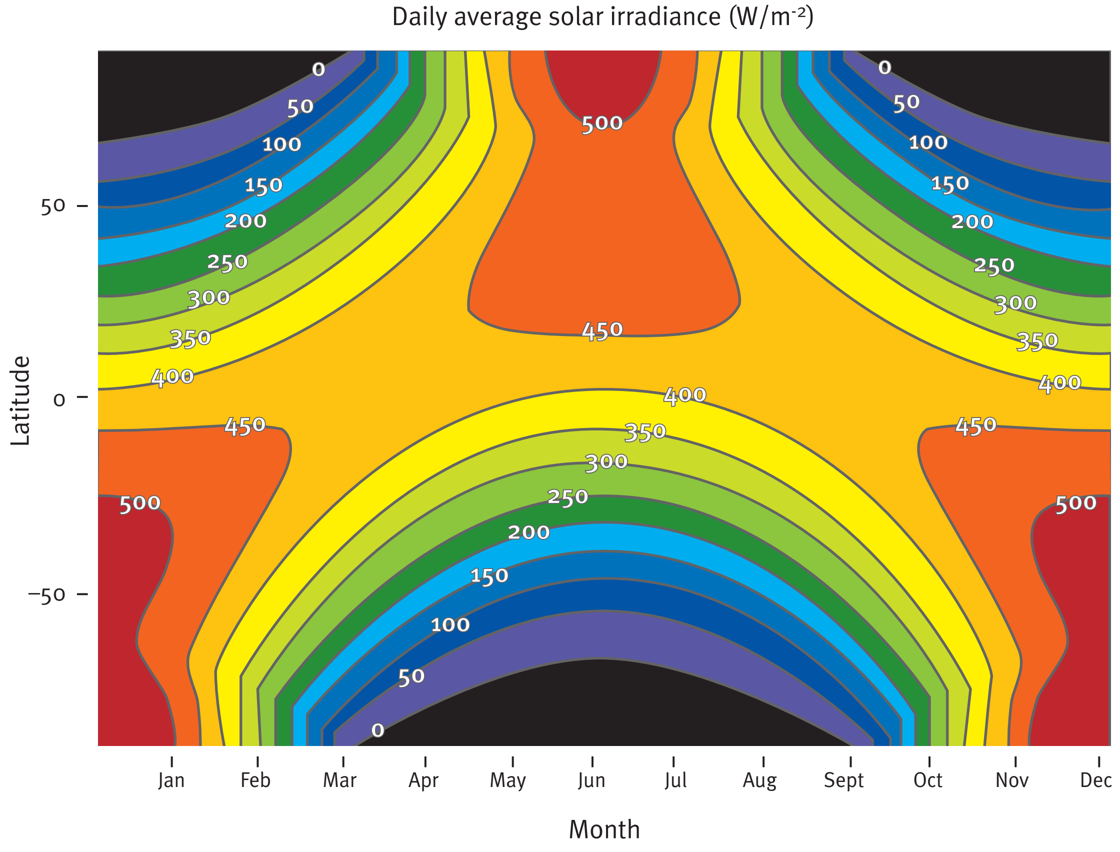


Figure 4. Daily average solar radiation (Wm^{-2}) entering the top of the atmosphere as a function of time of year and latitude.

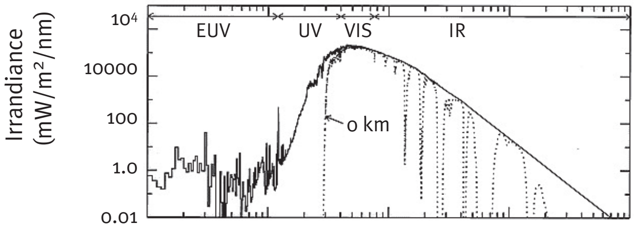
irradiance. Thus the distribution of solar irradiance over the globe is important in establishing both the mean climate and its variability.

The solid line in Figure 5(a) shows the amount of solar radiation at each wavelength received at the top of the Earth's atmosphere across the spectrum from wavelengths in the extreme ultraviolet (EUV), through ultraviolet (UV) and visible (VIS) to infrared (IR). The wavelength is given in nanometres (nm), where 1 nm is one billionth of a metre. The spectrum peaks in the visible region (i.e. light) but with significant components at shorter wavelengths in the ultraviolet and at longer wavelengths in the infrared. Also shown by a dashed line in Figure 5(a) is the solar radiation that actually reaches the surface of the Earth. From this it is clear that much of the visible radiation is unaffected by the atmosphere but most of the UV (at wavelengths less than about 300 nm) is absorbed before reaching the surface. The presence of water vapour, carbon dioxide and ozone absorption bands in the IR prevents the transmission of radiation to the surface in several well-defined bands.

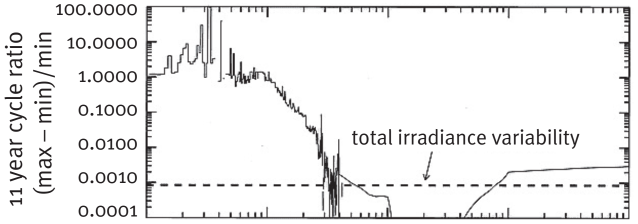
Figure 5 (c) presents the height within the atmosphere at which greatest absorption of solar radiation takes place at each wavelength. Infrared effects take place close to the ground, so do not appear in this plot, but the absorption of ultraviolet radiation between 20 and 200 km altitude is clear. At wavelengths less than 242 nm much of this absorption is by oxygen molecules (O_2), which leads to the production of ozone (O_3). The ozone itself absorbs longer ultraviolet wavelength radiation resulting in local heating.

These photochemical interactions between the incoming radiation and the molecules composing the atmosphere are fundamental in determining the vertical temperature structure of the atmosphere shown in Figure 6. The atmosphere becomes cooler with height from the surface to around 12km; this is the troposphere which contains 80% of the mass of the atmosphere, nearly all the cloud and where most weather activity takes place. Above the troposphere is the stratosphere, a very stable region in which temperature increases with height due to the presence of the ozone layer and the associated absorption of ultraviolet radiation. Above the stratosphere in the mesosphere

(a) Solar spectral irradiance



(b) Spectral irradiance variability



(c) Terrestrial optical depth unity

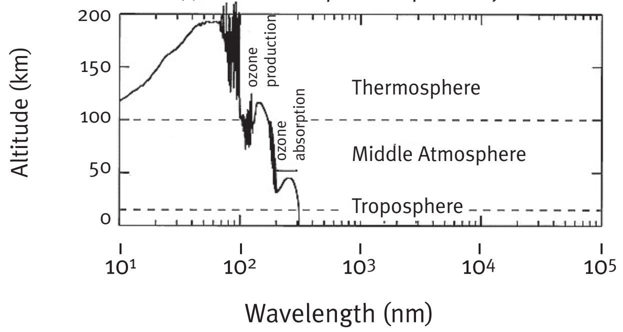


Figure 5. (a) Solar spectrum at the top of the atmosphere (solid line) and at the Earth's surface (dashed line). (b) Fractional difference in solar spectral irradiance between maximum and minimum of the 11-year cycle. (c) Altitude at which peak absorption takes place of solar radiation at each wavelength[7].

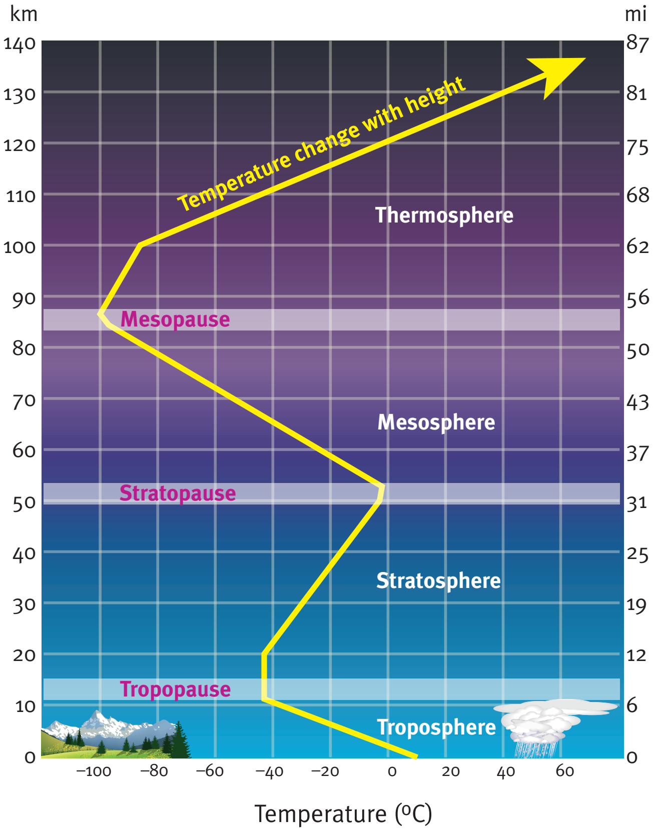


Figure 6. Average temperature of the atmosphere as a function of height showing how it defines the boundaries of the troposphere, stratosphere, mesosphere and thermosphere[8].

only about 0.1% of the total mass of atmosphere remains—with temperatures declining between about 50 and 85km where they reach their coldest values. Beyond this in the thermosphere, absorption of shorter wavelength ultraviolet radiation by the very rarefied atmosphere results in a steep increase in temperature.

Thus the total radiant energy arriving at Earth from the Sun, and also its spectral composition, are fundamental in determining the thermal structure of the atmosphere. It is clearly reasonable to ask how changes in solar activity might affect this temperature structure.

The inconstant sun

Indicators of solar activity

If we are to understand the impact of the Sun on climate, we need historical data on solar activity and to understand how this relates to changes in the level and composition of energy emitted by the Sun. Scientists have studied a number of different indicators of solar activity over the years. Perhaps the most well known is the sunspot number, but there are other useful indicators, some of which are shown in Figure 7. These indicators differ not only in the effect that they characterise but also in terms of the time period over which they provide data.

Sunspots, dark features on the solar disk (for example see the left-hand-side of Figure 8) have been reported since ancient times but it was not until the invention of the telescope in the early 17th century that they were unequivocally identified as features on the solar surface, rather than as other bodies moving between the Earth and the Sun.

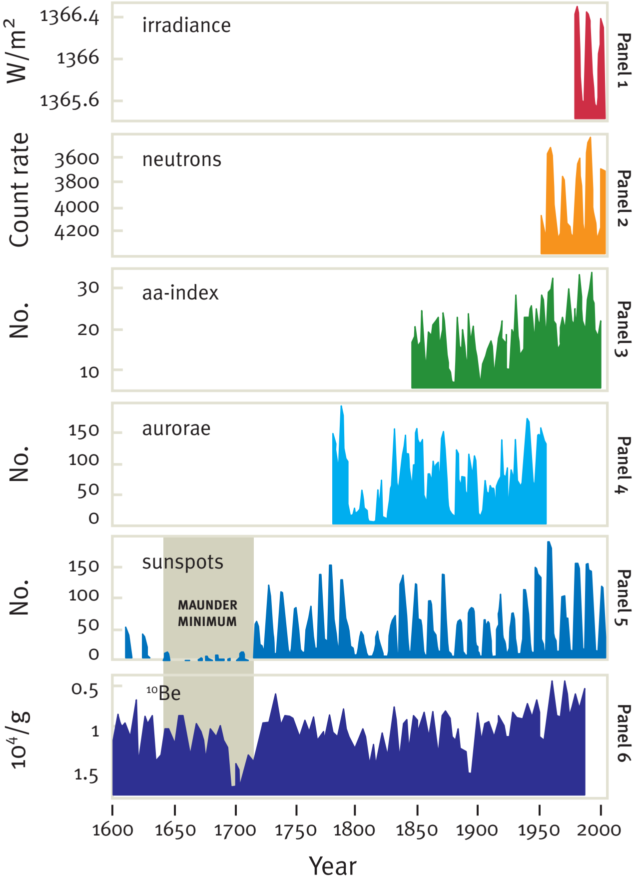


Figure 7. Total solar irradiance, galactic cosmic ray neutron count, geomagnetic aa-index, incidence of aurorae, sunspot number, and cosmogenic isotope ^{10}Be concentration as functions of time. Note that the scales for neutron flux and ^{10}Be are inverted as cosmic ray incidence at Earth is higher when the Sun is less active[9].

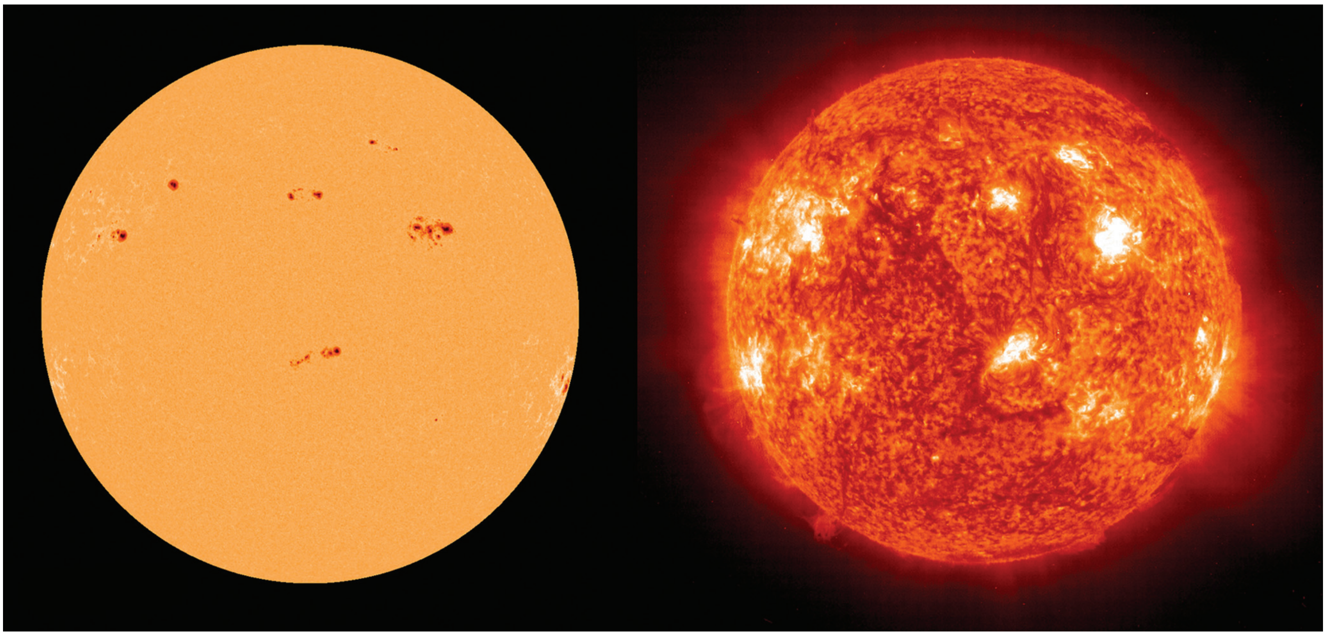


Figure 8. The Sun observed on 20 March 2000, near the maximum of the most recent solar activity cycle. Left: in visible light, showing sunspots; Right: in the ultraviolet, revealing areas of intense activity associated with the sunspots[10].

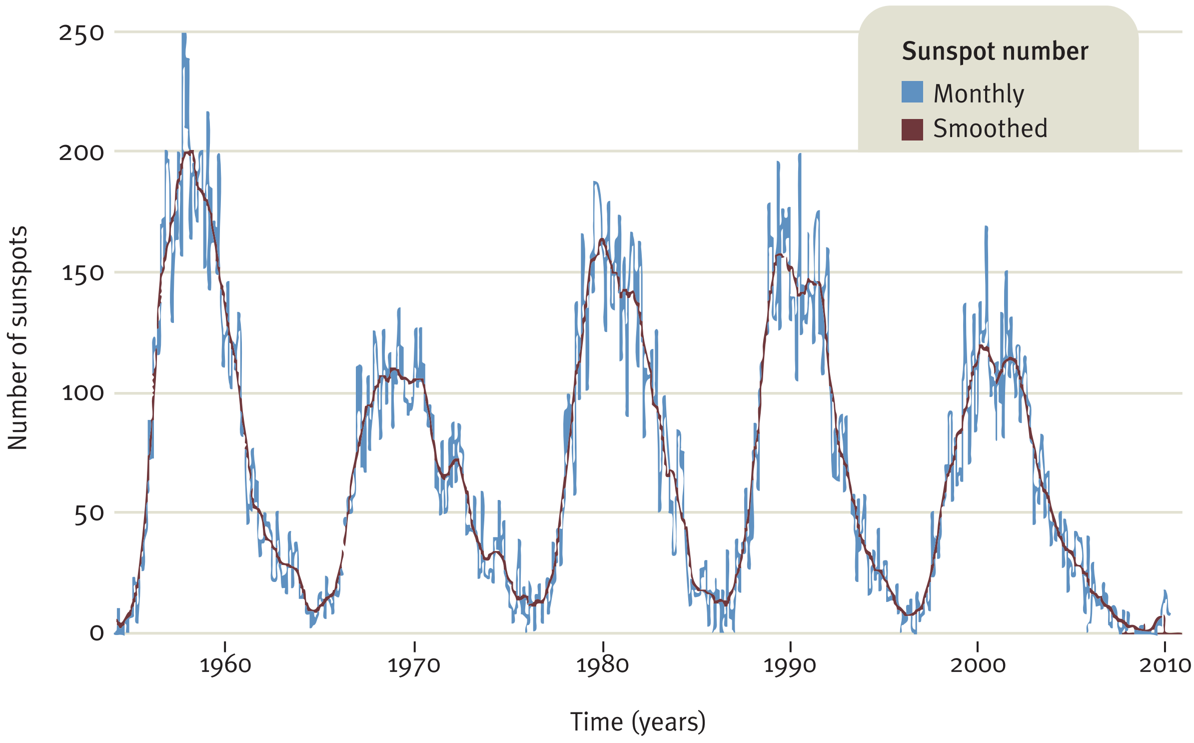


Figure 9. Number of sunspots over the most recent five solar activity cycles [11].

The number of sunspots has been carefully recorded and it is clear that the Sun is not the unchanging body traditionally assumed pre-Galileo. Figure 9 shows the sunspot record over the past 56 years revealing a cyclic behaviour with sunspot number (SSN) growing and decaying on a timescale of 9-13 years. This has become known as the 11-year cycle, or simply the solar cycle. Records over the past four centuries (Figure 7, panel 5) show this behaviour has been persistent over that entire period but that the amplitude of the cycle is very variable. Of particular note is the period near the end of the 17th century, where the numbers declined to near zero for several decades (the Maunder Minimum), the low activity near the start of the 19th century (the Dalton Minimum), and the relatively high activity over the most recent fifty years. Much circumstantial evidence has been published linking periods of higher (or lower) sunspot number with anomalous weather, on both the "11-year" cycle and longer timescales.

Another proxy indicator is the number of aurorae; natural light displays commonly called the Northern or Southern Lights. Aurorae are produced when energetic particles in the solar wind—a stream of high-energy, ionised particles emitted by the Sun—interact with the atmosphere and are more frequently observed when the Sun is more active (shown in Figure 7, panel 4). Aurorae are also associated with an electric current in the upper atmosphere which causes disturbances in the Earth's magnetic field. This effect is quantified by the so-called aa-index (shown in Figure 7, panel 3).

The solar wind and the solar magnetic field provide protection for the Earth from galactic cosmic rays (GCRs), which are high energy charged particles originating outside the solar system. There is therefore an inverse relationship between solar activity and the incidence of GCRs. Another indicator of solar activity then is derived from surface measurements of neutrons produced by the impact of GCRs on the atmosphere. This data series extends back to around 1950 (Figure 7, panel 2) and shows a close inverse relationship to sunspot number.

Longer term records of GCRs are provided by another indicator comprising measurements of cosmogenic isotopes such as Beryllium-10 (^{10}Be—Figure 7, panel 6) and Carbon-14 (^{14}C) which are formed by interactions of the cosmic rays with atomic nuclei in the atmosphere. Deposits of these isotopes can be measured in surface features, such as ice cores and tree rings, in annual layers dating back thousands of years and so potentially present a unique record of solar activity. The main difficulty in the application of cosmogenic nuclides is that they contain information not only on their production by GCRs, but also on the various geophysical and chemical processes that influence their deposition. Thus they are influenced by the very climate signals on which any solar influence might be investigated. However, the various processes influencing each nuclide are very different so that by combining them it is possible to separate these effects and thus to construct a reliable solar activity index[12].

Another commonly-used indicator of solar activity—though not included in Figure 7—is solar radio flux, specifically at a wavelength of 10.7 cm. Good measurements of this have been made at the Earth's surface since the late 1950s.

Each solar index quantifies a different aspect of solar behaviour. For example GCRs are influenced by the solar magnetic field far away from the Sun whereas irradiance and sunspot number are determined by the magnetic field at the solar surface. Sunspot number decreases to near zero at the minimum of each 11-year activity cycle but irradiance is only altered by a small fraction. Investigation of the difference between the indices, and how meteorological parameters vary with them, may help to identify the physical processes involved in producing a solar influence on climate. A review of the relationships between some solar indices is given by Lockwood[13].

Solar radiation

The proxy measures discussed above provide useful signals of solar activity but they do not provide any clear indication of the physical processes whereby the hypothesised solar influence on climate might take place.

The most obvious candidate for such a mechanism is a variation in the total solar energy incident on the atmosphere. Measurements of solar radiation at the Earth's surface, however, have not been able to provide the accuracy required as they are subject to uncertainties and fluctuations in atmospheric absorption that swamp the small variations in the solar signal. Direct measurements of total solar irradiance (TSI) made from satellites outside the Earth's atmosphere began in 1978 and the data from all available missions is shown in Figure 10(a). The measurements from each instrument show consistent variations of approximately 0.08% (~1.1 Wm^{-2}) in TSI over an 11-year cycle but significant uncertainties remain with regard to the absolute value of TSI. In particular, data from the newest instrument, the Total Irradiance Monitor (TIM) on the SORCE satellite, is giving values 4 or 5 Wm^{-2} lower than other contemporaneous instruments which disagree among themselves by about 1 Wm^{-2}.

This uncertainty, related to the calibration of the instruments and their degradation over time, is a serious problem underlying current solar-climate research and makes it particularly difficult to establish the existence of any underlying trend in TSI over the past two solar cycles. Attempts to combine the different TSI measurements to provide a longer-term record have consequently encountered difficulties with one [14] showing essentially no difference in TSI values between the cycle minima occurring in 1986 and 1996 (see bottom panel of Figure 10) and another [15] suggesting an increase in irradiance of 0.045% between these dates. The latter implies an increase in the net energy entering the top of the atmosphere of about 0.1 Wm^{-2}per decade, or about one-third that due to the increase in concentrations of greenhouse gases (decadal trend averaged over the past 50 years). Data for the current solar minimum, however, suggest that values in 2009 were lower than in 1996 implying no upward secular trend in TSI. One composite is shown in Figure 10(b) and also in the top panel of Figure 7.

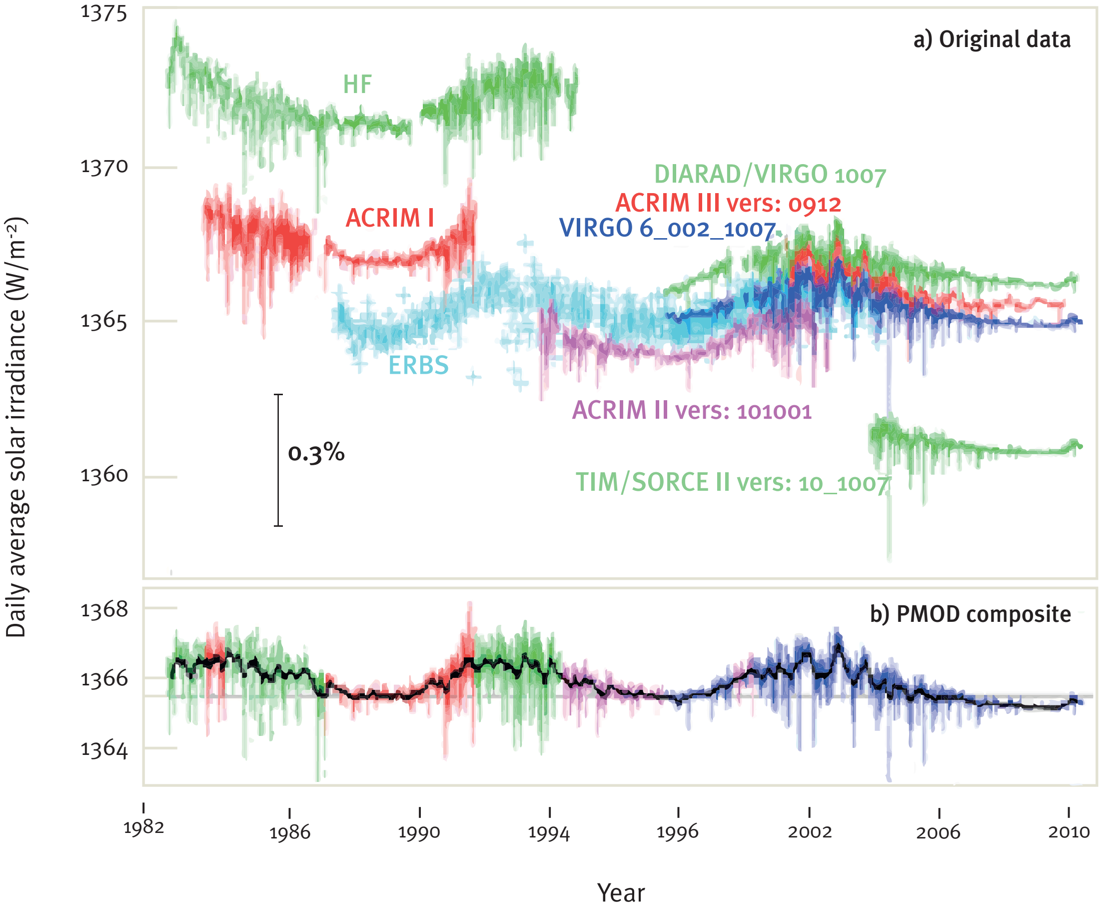


Figure 10. (a) Daily-averaged total solar irradiance (Wm^{-2}) from 1978 to present: all measurements made from satellites. (b) Composite record obtained by inter-calibration of the data from the individual instruments[16].

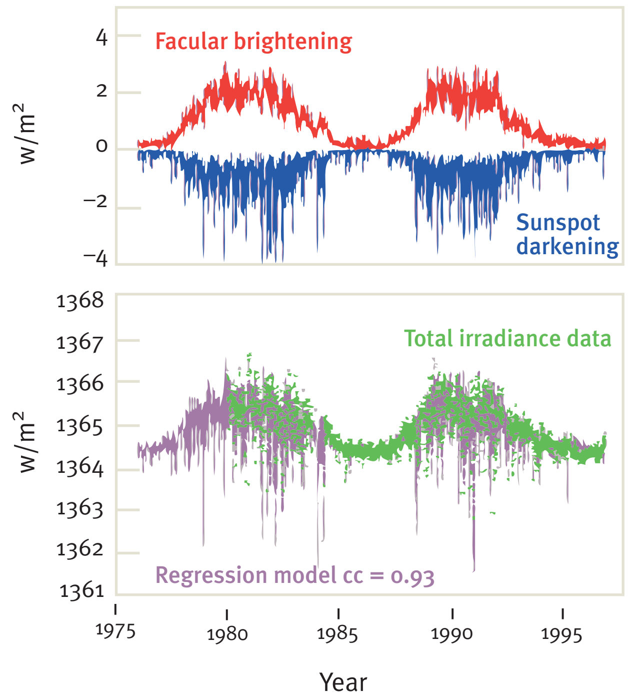


Figure 11. Upper panel: irradiance variations over two solar cycles estimated from the two primary influences of facular brightening and sunspot darkening. Second panel: in purple the sum of these (plus a background TSI value of 1364.4 Wm^{-2}) overlaid (in green) by a composite of the satellite measurements. The horizontal axis indicates years from 1975 to 1997[17].

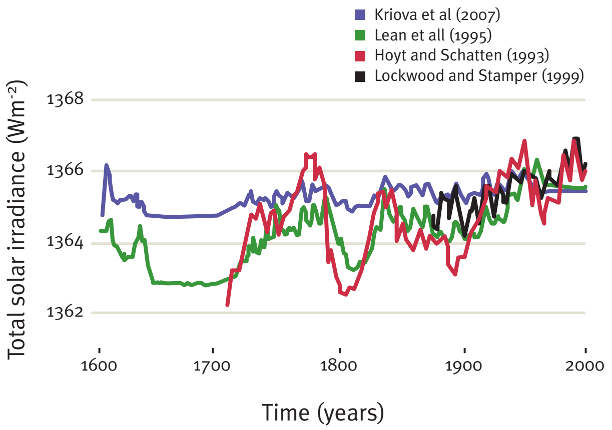


Figure 12. Some examples of estimates of past variations of Total Solar Irradiance. Each curve is constructed using a different assumption concerning how the long-term variation in TSI relates to a particular (observed) indicator of solar activity. The proxy indicators include sunspot number, solar cycle length, solar magnetic flux and the methods range from entirely empirical (calibrated with recent satellite measurements of TSI) to physically-based models of the Sun[3].

Even with these shortcomings, comparison of the TSI measurements with sunspot numbers shows that the Sun emits more radiation when it is more active. Given that most solar radiation is emitted at visible wavelengths (see solar spectrum in Figure 5, panel a) and that sunspots appear dark, it is not obvious why this should be the case. The explanation is indicated by the image of the Sun at an ultraviolet wavelength in Figure 8, which reveals that associated with sunspots are larger areas of intense ultraviolet emission, called faculae. The impact of these on the emitted radiation can be seen in Figure 5(b): the fractional change in radiation over the 11-year cycle is much larger at shorter wavelengths. The compensating contributions of facular brightening and sunspot darkening to the variations in TSI are indicated in Figure 11.

To assess the potential influence of the Sun on the climate on longer timescales it is necessary to know TSI further back into the past than is available from the satellite data shown in Figure 10. The proxy indicators of solar variability discussed above have therefore been used to produce an estimate of its temporal variation over the past centuries. There are several different approaches taken to “reconstructing” the TSI, all employing a substantial degree of empiricism and in all of which the proxy data (such as sunspot number) are calibrated against the recent satellite TSI measurements, despite the problems with this data outlined above. Some examples of TSI time series reconstructed over the past four centuries are given in Figure 12. The estimates diverge as they go back in time due to the different assumptions made about the state of the Sun during the Maunder Minimum in the latter part of the 17th century. This uncertainty is a major problem in gaining a precise understanding the role of the Sun in recent global warming and projections for its future influence in the context of man-made climate change.

In assessing the climate change impact of different factors a useful parameter is Radiative Forcing (RF). This gives a measure of the imbalance in the radiation budget at the top of the atmosphere caused by the introduction of a particular factor. For example, the introduction of increasing concentrations of greenhouse gases traps outgoing heat radiation, increasing the net energy flow into the Earth’s atmosphere and therefore implying a positive RF. Conversely an increase in the amount of radiation reflected back to space, due to an enhancement in the area of reflective surfaces such as ice caps or white clouds over the sea, would result in a negative RF.

The Intergovernmental Panel on Climate Change (IPCC) in its 2007 report[1] summarises RF since 1750 due to a range of anthropogenic factors, see Figure 13. The contributions are dominated by the effects of the increasing concentrations of greenhouse gases, which over that period have introduced a positive RF totalling about 2.5 Wm^{-2}. Other components are smaller, and generally less certain, with some having a negative effect.

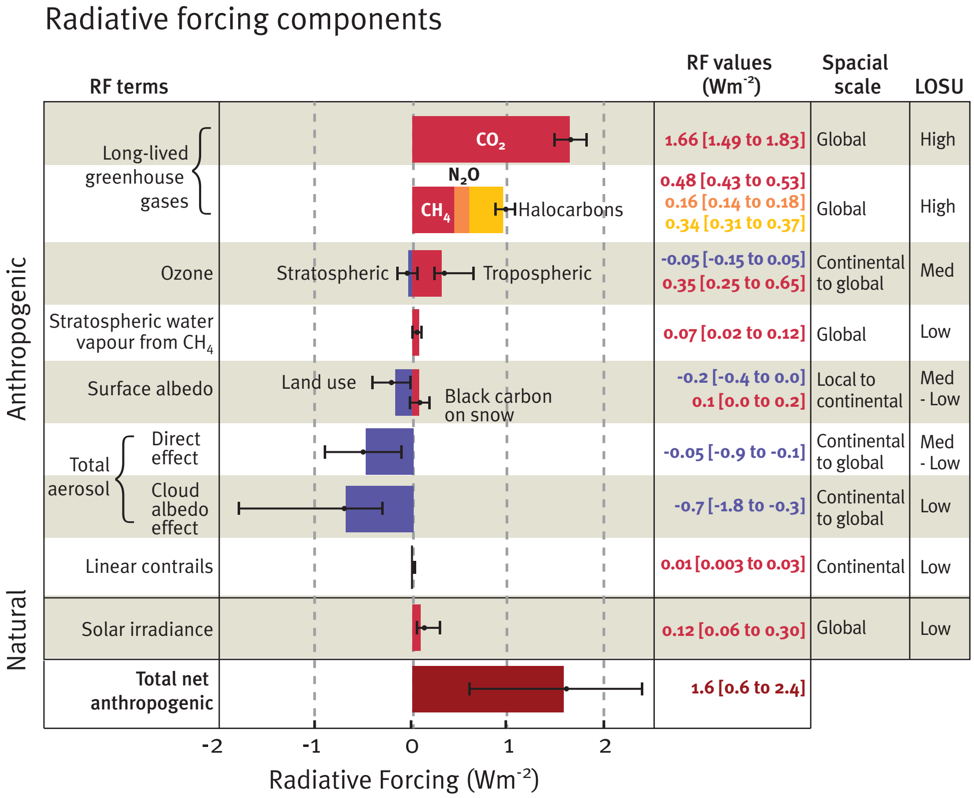


Figure 13. Radiative forcing estimates 1750-2005[1].

A large negative contribution, but with a wide uncertainty in its value – ranging between -0.3 and -1.8 Wm^{-2}, comes from the reflective effect of the cloud produced by condensation of droplets on particulate matter (aerosol).

Figure 12 shows values of 1362.8 and 1364.7 Wm^{-2} as estimates for TSI during the Maunder Minimum of the late 17th century, lower by 3.2 and 1.3 Wm^{-2}, respectively, than the current value of 1366.0 Wm^{-2}. In order to estimate solar RF, however, it is necessary to take two other factors into account. Firstly, to average over the globe it is necessary to divide by a factor of four (the ratio of the surface area of the whole earth to that of a circle with the same radius, the latter being the size of the area subtended to the Sun). A further reduction of about 30% is necessary to account for radiation reflected back to space. Thus the range of 1.3-3.2 Wm^{-2} for the increase in TSI translates into a range 0.2-0.6 Wm^{-2} for solar RF since the Maunder Minimum. Since the year 1750, the date used by the IPCC to represent the pre-industrial climate, the range of TSI increase is about 0.4-1.5 Wm^{-2} giving a solar RF of 0.07-0.27 Wm^{-2} since that date. The IPCC range of 0.06-0.3 Wm^{-2} (see Figure 13) is consistent with this but it should be noted that the solar value included in the well-publicised IPCC figure might be larger, or smaller, if a different year were assumed for the pre-industrial start-date. Nevertheless, it is clear that over recent centuries solar radiative forcing is much smaller than that due to greenhouse gas increases associated with human activity.

The IPCC report also indicates a "Level of Scientific Understanding" (LOSU, see last column in Figure 13) for each factor. The science behind greenhouse gas warming is well understood, so it has a high LOSU rating, but solar RF is given a low LOSU indicating that there might be other factors not yet known about, or fully accounted for.

Solar influence on surface climate

Any assessment of climate variability and climate change depends crucially on the existence and accuracy of records of meteorological parameters. Ideally records would consist of long time series of measurements made by well-calibrated instruments located with high density across the globe. In practice, of course, this ideal cannot be met. Measurements with global coverage have only been made since the start of the satellite era about thirty years ago. Instrumental records have been kept over the past few centuries at a few locations in Europe. For longer periods, and in remote regions, as with establishing a history of solar activity, climate records have to be reconstructed from indirect measures, or proxies (see Box A). These proxies, and the information they provide on surface temperature over a range of timescales, will be discussed in the sections below.

A key concern of contemporary climate science is to attribute cause(s), including the contribution of solar variability, to the observed variations in temperature. A number of approaches have been used and in all cases great care needs to be taken to ascertain the statistical validity of the results in the context of innate (natural) variability in the temperature data. The simplest approach is to calculate the correlation of the time series of temperature with that of the factor of interest; here a prime concern must be in acknowledging the potential of chance cor-

Box A. Records of global surface temperature

Over times preceding the availability of instrumental records, global temperatures have been deduced from indirect indicators. These proxies provide information about weather conditions at a particular location through records of a physical, biological or chemical response to them. Records of temperature dating back hundreds of thousands of years have been derived from analysis of oxygen isotopes in ice cores obtained from Greenland and Antarctica. Evidence of very long term temperature variations can also be obtained from the width of tree rings or isotopic abundances in ocean sediments, corals or fossil pollen.

The use of proxies in the construction of a global temperature record requires careful treatment of the data [18]. Each record represents one locality on the globe and certain proxies, by their nature, will only provide data in specific geographical regions. Different proxies permit scientists to resolve change at different timescales over different periods. For example, ocean sediments indicate variations over millions of years, and can provide resolution of changes taking place over periods of about 1000 years, while tree rings provide annual resolution but are limited in extent to about 10,000 years. Some proxies may indicate the temperature only in a particular season of the year. Thus huge effort is required both in dating and in spatial and seasonal infilling. Differences between the available global temperature reconstructions, such as shown in Figure 15, can be ascribed not only to the use of different data sources but also to the varying assumptions or methods used in the interpolations.

Calibration of a proxy is achieved by matching it against observed temperatures in the period over which both are available. So, for example, a high correlation between tree ring width and global observations of temperature over the period 1880 to 1960 provides confidence in the temperature record reconstructed from tree rings back over 1000 years. A divergence between temperature measurements and some tree ring data since 1960 has, on the one hand, raised doubts over the reliability of this proxy and, on the other, been assumed to indicate that the measured global warming has been exaggerated. Current research suggests that tree rings can be used as a useful proxy before 1960 but that since then some other factor (perhaps air pollution or drought stress) has restricted growth despite an undisputed global warming[19].

relation and of the role of other factors. Another commonly used approach is that of multiple linear regression analysis which seeks to derive simultaneously the magnitudes of signals due to a number of pre-determined factors. Confidence in the results can be improved by taking into account known uncertainties in both the data and the forcing factors.

Millennial timescales

On these long timescales charges in the Earth's orbit, as well as variations in solar activity, must be considered. Figure 3 has already presented an example from ice core records to show how interglacial periods tend to be associated with higher irradiance in summer high latitudes, although the picture is complex. Figure 3 also illustrates how the recovery from a cold period (an "ice age") proceeds much faster than the rate at which it originally developed. This is probably due to a feedback effect whereby an initial warming is amplified by the release of the natural greenhouse gases carbon dioxide and methane from cold storage. In this case the initial warming is assumed due to an increase in solar irradiance but the amplification would also take place in response to any other factor initiating a warming, such as the greenhouse gases produced by human activity.

Ocean sediments have been used to reveal a history of the circulation of the North Atlantic by analysis of the minerals believed to have been deposited by drift ice[20]. With regional cooling the rafted ice propagates further south where it melts, depositing the minerals. These materials also preserve information on cosmic ray flux, and thus solar activity, in isotopes such as ^{10}Be and ^{14}C. Thus simultaneous records of climate and solar activity over thousands of years may be retrieved. An example is given in Figure 14, which shows fluctuations on the 1,000 year timescale well correlated between the two records, suggesting a long-term solar influence on North Atlantic climate.

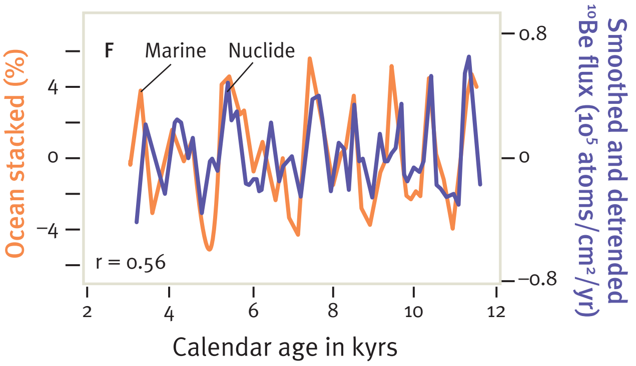


Figure 14. Records extracted from ocean sediments in the North Atlantic of solar activity measured by ^{10}Be (purple) and of deposits of ice-rafted minerals (orange)[34].

Centennial timescales

On these timescales, long-term changes in the Earth's orbit may be disregarded. Figure 15 presents reconstructions of the Northern Hemisphere surface temperature record over the past millennium produced using a variety of proxy datasets. There are some large differences between the different reconstructions, especially in long-term variability, but there is general agreement that current temperatures are higher than they have been for at least the past two millennia. Other directly observed climate records suggesting that the climate has been changing over the past century include the retreat of mountain glaciers, sea level rise, thinner Arctic ice sheets and an increased frequency of extreme precipitation events.

It has frequently been remarked that the Maunder Minimum in sunspot numbers in the second half of the seventeenth century coincided with what is sometimes referred to as the "Little Ice Age" during which most of the proxy records show cooler temperatures. Care needs to be taken in such interpretation, however, as other factors might have contributed. For example, the higher levels of volcanism prevalent during the 17th century would also have introduced a cooling tendency due to a veil of particles injected into the stratosphere reflecting the Sun's radiation back to space [22].

One attempt to separate the different factors in the past century is presented in Figure 16. This suggests that the Sun may have introduced an overall global warming (disregarding 11-year cycle modulation) of approximately 0.07 °C before about 1960 but had little effect since. Over the whole period the temperature has increased by about 1°C so the fractional contribution to warming ascribed to the Sun is consistent with the proportions shown in Figure 13.

The solar result does depend fundamentally on the assumed temporal variation of the solar forcing and, as evidenced by Figure 12, there is some scope for choice. Studies using other solar indices have produced a larger signal of temperature increase before mid-century, and a better match between observations and regression model during that period than that shown between the black and orange curves in Figure 16.

Crucially, however, it is not possible to reproduce the global warming of recent decades without including anthropogenic effects and this conclusion is confirmed by those using more sophisticated non-linear statistical techniques[23].

Computer models of the global circulation of the atmosphere have also been utilised to identify the causes of trends in the temperature record. When all the time-evolving natural (solar and volcanic) and anthropogenic (greenhouse gases, sulphate aerosol) influences are included in the simulations the models are generally able to reproduce, within the bounds of observational uncertainty and natural variability, the temporal variation of global average surface temperature over the twentieth century. Separation of the effects of natural and anthropogenic forcing suggests that the solar contribution is particularly

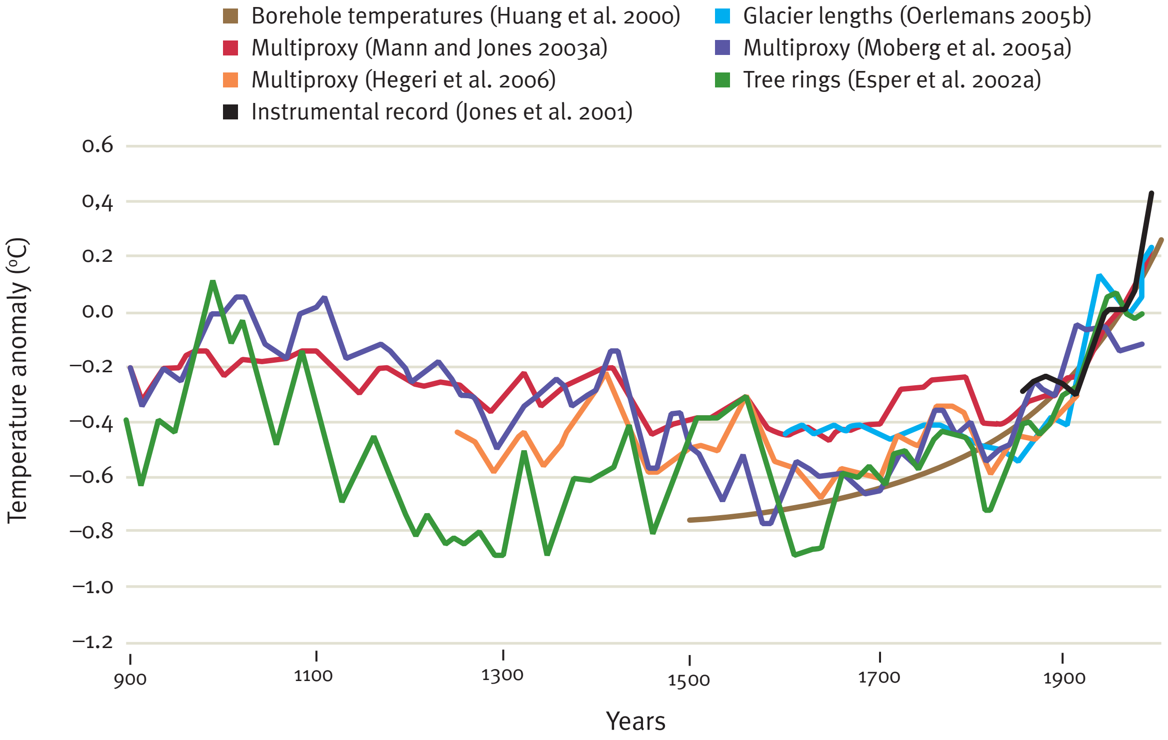


Figure 15. Northern Hemisphere or global surface temperature over the past millennium. The thick black curve (1856-present) is from measurements; the other curves are reconstructions based on climate proxy data[21].

significant to the observed warming over the period 1900-1940 (see Figure 17). Consistent with the regression analysis, however, the models cannot reproduce the warming over the past few decades with natural factors alone.

The same analysis as presented in Figure 17 carried out separately for individual continents shows very similar responses to that for the global mean. On smaller scales, however, the temperature trends show considerable regional variability. For example the 17th century cooling shown in Figure 15 was not distributed uniformly: the pattern in surface temperatures appears to be symptomatic of the negative phase of the North Atlantic Oscillation (see Box B)[25]. This suggests that the Sun may have a measurable influence on northern European climate. A recent analysis of the 350 year record of temperatures in central England concurs with this, showing that cold winters tend to be associated with low solar activity[26]. There is plenty of circumstantial evidence that changes in solar activity influence climate over the longer term on regional scales across the globe. This includes, in paleo-records, correspondence between higher solar activity and stronger Asian monsoons, higher rainfall in Oman and drought in equatorial east Africa and the western USA. It is clear that local impacts may be far greater than would be implied by the rather small global average temperature changes.

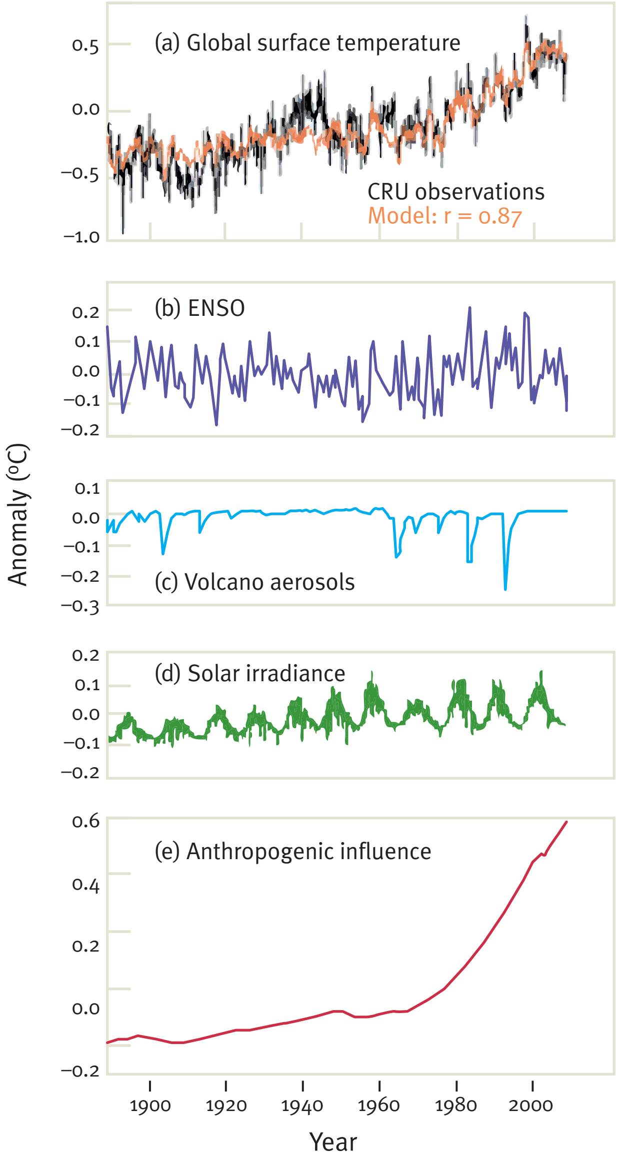


Figure 16. (a) Global monthly mean temperature record (black) and reconstruction from multiple regression analysis (orange). The regression contributions are shown for (b) ENSO - El Niño-Southern Oscillation, (c) volcanic, (d) solar and (d) anthropogenic (greenhouse gas & particulates) influences (at appropriate lags)[24].

Some indicators of solar activity, e.g. of the complex magnetic properties of the Sun and their effect out to the edge of the solar system, suggest that there has been an overall downturn since about 1985[27]. This would have tended to drive global temperatures downwards since that time, making the Sun even less likely to be responsible for recent warming.

Solar cycle, or decadal, timescales

A large number of studies have purported to show variations in meteorological parameters in phase with the “11-year” solar cycle. Many of these rely on a simple correlation, or linear regression, or on picking out a circa 11-year component in a spectral analysis. Some are statistically questionable and others show signals that appear over a certain interval of time only to disappear, or even reverse, over another interval. Particularly contentious are solar signals detected in sea

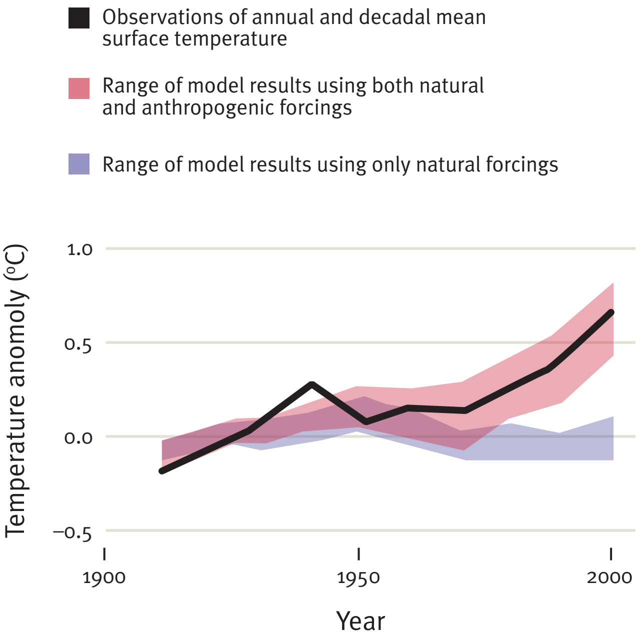


Figure 17. Annual and decadal mean surface temperature from observations (black line) and calculated using a number of global climate models. The model calculations were carried out using all forcings (pink) and only natural forcings (purple), the spread indicates uncertainties, including internal variability, assessed from multiple simulations[1].

Box B. Patterns of climate variability

Some regions of the globe exhibit quasi-oscillatory behaviour in climate properties. These are natural patterns (sometimes referred to as modes of variability) each with identifiable characteristics which can be measured to give an indication of the strength of the pattern at any moment in time. The amplitudes and timings may be influenced by climate change. The list below is not complete but outlines the modes mentioned in this report:

El Niño-Southern Oscillation (ENSO)
Primarily characterised by a periodic warming/cooling of the eastern tropical Pacific Ocean, this mode also incorporates an in-phase variation in the east-west gradient of surface air pressure over the western Pacific Ocean in the southern hemisphere tropics. ENSO is also associated with extreme weather (floods, droughts) over many other parts of the world. Its period varies between 3 and 7 years.

North Atlantic Oscillation (NAO)
Variations in the latitudinal gradient of surface pressure over the North Atlantic Ocean affect the position and strength of the storm track and play an influential role in the climate of western Europe. NAO variation is not regular.

Southern Annular Mode (SAM)
A variation in the mid- to high latitude difference in surface pressure is associated with southern polar temperatures and the strength of circumpolar winds.

Quasi-Biennial Oscillation (QBO)
This is not a variation in surface climate but in the winds in the tropical lower stratosphere. These are observed to switch from westerly to easterly with a period of 24-28 months with the anomaly propagating downwards from about 35 km to 20 km at around 1 km per month.

surface temperatures. Some studies of the tropical Pacific Ocean[28,29] suggest that it does not warm uniformly at higher solar activity but shows regions of warming and cooling. There are, however, considerable problems in distinguishing this signal from that of the El Niño-Southern Oscillation (ENSO)[30] – see Box B. A further complication arises from the possibility that the state of the Sun actually moderates ENSO variability. This might be through a change in ocean circulations induced by longitudinally asymmetric changes in sea surface temperatures [31], although as this takes several years to become established it is not clear that it would be feasible on solar cycle timescales.

There are also naturally-occurring decadal scale oscillations in ocean circulations which might be confused with a solar cycle signal. Alternatively, solar cycle forcing might produce a resonant excitation of these modes of variability [32].

One recent multiple regression analysis of factors influencing sea surface temperatures[25] shows very little 11-year solar cycle signal in the tropics but significant impacts in mid-latitudes. This is consistent with a similar analysis of surface air temperatures [33] which shows preferential warming in regions approximately in the range 30-60° latitude in both hemispheres.

Even if a statistically robust correlation is established, a causal link still needs to be found and recently there have been considerable efforts to advance understanding into how these solar signals might arise. With regard to sea surface temperatures the mechanisms are usually thought to be "bottom-up" in the sense that solar radiation heats the sea surface and the atmosphere responds through thermodynamic processes which impact the hydrological cycle, tropical climate and ocean circulations.

Other mechanisms proposed to explain the influence of solar activity on the lower atmosphere, referred to as "top-down", involve dynamical influences between the upper and lower layers of the atmosphere. The next section looks at the evidence for a solar influence throughout the atmosphere and at possible top-down mechanisms.

Solar signals throughout the atmosphere

Measurements of solar irradiance in the visible and ultraviolet spectral regions show that the amplitude of solar cycle variability is far greater at shorter wavelengths (Figure 5, panel b). The result of this is that the response of atmospheric temperatures to solar variability is large in the far reaches of the upper atmosphere, with, for example, variations of 400 K over the 11-year cycle being typical at an altitude of 300 km, reflecting the large variations in the far- and extreme ultraviolet radiation that is predominantly absorbed in that region. At lower altitudes the fractional change in absorbed radiation is smaller and the atmosphere less rarefied so that the response is smaller. Measurements made from satellites suggest a temperature increase of up to about 1 K in the upper stratosphere (40-50 km, see Figure 6) at solar maximum; a much smaller (possibly even a negative) change around 25-30 km with an increase of a few tenths of a degree in the lower stratosphere. However, precise values vary between datasets.

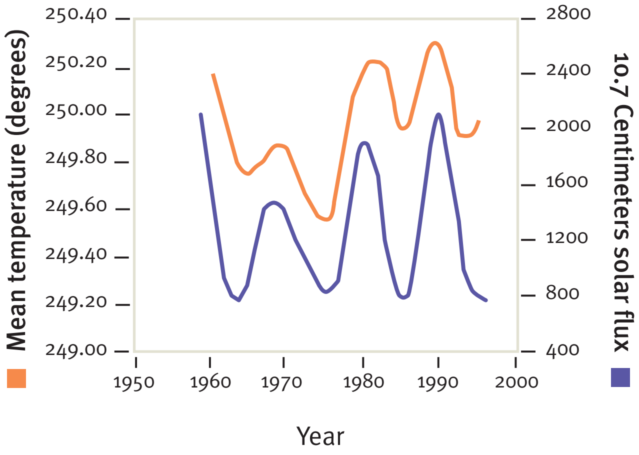


Figure 18. Time series of the mean temperature of the summer northern hemisphere upper troposphere (750-200 hPa) orange line) and the solar 10.7 cm flux (purple line)[34].

Figure 18 presents two curves. The purple one is a measure of solar activity: the solar flux at the radio wavelength of 10.7 cm indicating about three and a half solar cycles. The orange curve shows the mean summer-time temperature of the upper troposphere (between about 2.5 and 10 km altitude) averaged over the whole northern hemisphere and indicating a variation in phase with solar activity with an amplitude of 0.2 – 0.4 °C.

The averaging over the hemisphere, however, hides the fact that the signal of solar variability is not uniformly distributed. The distribution of the temperature variation as a function of latitude and altitude is shown in Figure 19, which presents the solar signal from an analysis of longitudinally-averaged temperatures for 1978-2002 [35]. The solar response shows largest warming in the stratosphere and bands of warming, of more than 0.4 K, throughout the troposphere in mid-latitudes. Associated with the temperature response is a signal in the average westerly wind [36] with an 11-year solar cycle influence, in which the effect of increasing solar activity is to weaken the jet stream winds which flow west-east near the tropopause and to move them slightly polewards.

As the jet streams are related to the mid-latitude storm tracks, which have a strong influence on the weather in these regions, it is clear that the Sun may have significant influence on the weather in those mid-latitude localities. A similar response has been found in climate model studies of the effects of varying solar ultraviolet radiation[37,38].

Vertical coupling through the atmosphere

Increases in solar ultraviolet radiation directly heat the upper stratosphere and also influence the overturning circulation of the atmosphere such that the tropical lower stratosphere warms. The resulting change of thermal structure in the region of the tropopause (see Figure 6) provides a number of indirect routes whereby solar influences on the upper atmosphere might affect the climate below— i.e. vertical coupling. The mechanisms whereby any downward influence takes place are the subject of active current research and may also help in understanding the impacts of climate change and ozone depletion.

One fruitful area has been the use of simplified models of the atmosphere focussing on the processes involved in linking, or coupling, different atmospheric regions. In one such study[36] a heating of the stratosphere was imposed and a response found in temperature not only of the stratosphere but throughout the troposphere—with the vertical bands of warming characteristic of the observed solar signal (Figure 19). Coherent changes in the latitudinal location and width of the mid-latitude jetstream, and its associated storm-track, were also detected. A further investigation into the mechanisms involved[40] showed that crucial to the response was a feedback between the momentum transferred in the atmosphere by upward-propagating waves associated with weather systems and the westerly wind. Similar models have been used to investigate stratosphere-troposphere coupling processes in the context of the polar modes of variability[41].

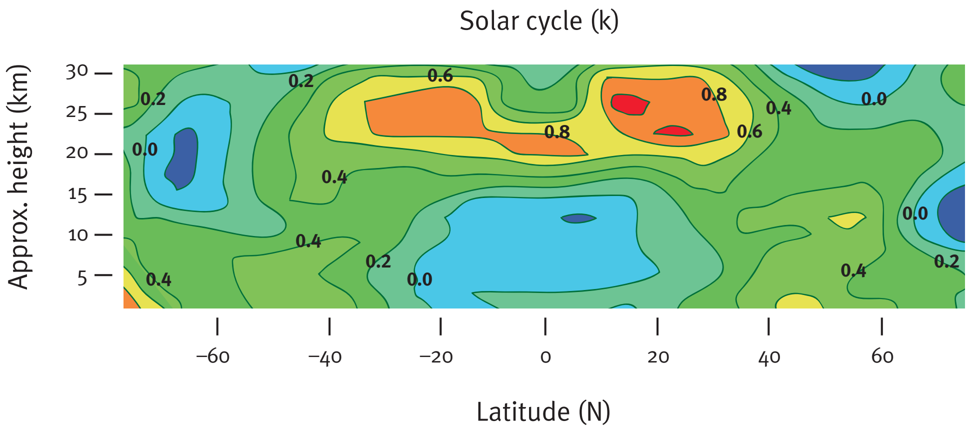


Figure 19. Maximum difference between the peaks and troughs of solar cycles in zonal mean temperatures (°C) 1979-2002 derived, using multiple linear regression analysis of NCEP Reanalysis data[39], adapted from[35].

During the winter the polar stratosphere becomes very cold and a vortex of strong westerly winds blowing around the pole is established. The date in spring when this vortex finally breaks down is very variable but plays a key role in the global circulation of the stratosphere. Furthermore, observations from satellites suggest that this perturbation propagates downwards, possibly into the lower atmosphere [42]. Variations in solar UV influence temperatures in the upper stratosphere such that the polar vortex winds strengthen in response to enhanced solar activity [43] and thus provide another route whereby the direct influence of solar radiation higher in the atmosphere may influence the climate below, having an impact on the jet stream winds and establishing weather patterns identified with the positive phase of the NAO and SAM.

A heating of the tropical lower stratosphere provides a more stable lid to the troposphere and this may influence climate by inhibiting tropical convection and influencing the state of ENSO[44]; this idea remains to be investigated further.
A major conclusion of all these studies is that heating of the stratosphere by changes in solar UV, or indeed by any other factor, can affect the atmosphere below and this can be experienced in changing weather patterns near the surface.

The Sun, cosmic rays and clouds

Clouds play a major part in establishing the heat and radiation budgets of the atmosphere. They transport latent heat from the oceans to the atmosphere and have a large effect on the Earth's radiation balance. They reflect about 15% of the incoming solar radiation directly back to space, thus tending to cool the surface, but they also trap infrared radiation acting in a similar way to greenhouse gases to warm the surface. The net radiative effect of a cloud depends on its altitude, location and microphysical properties. Thin high clouds (at altitudes greater than about 6 km) generally generate a net heating effect, and thick low clouds (altitudes below 2 km) produce a cooling.

Any factor influencing cloud cover clearly has the potential to significantly affect climate and it has been proposed that cosmic rays could provide a mechanism for this through their role in atmospheric ionisation. Cosmic rays generate ions throughout the lower atmosphere and it is well-documented[45] that this ionisation is altered by solar activity over 11-year cycles—with greater ionisation when the Sun is less active because of the inverse relationship of cosmic rays with solar activity (as discussed above). Two different routes might result in this ionisation influencing cloud cover. The first[46] involves the preferential growth of ionised particles to a size which is energetically favourable for cloud droplet formation. This idea was reinvigorated by a study suggesting a correlation of tropical marine low cloud cover and cosmic radiation[47], although this relationship has subsequently been challenged[48]. Subsequent to the ionisation several consecutive processes need to take place to result in the necessary enhancement in concentration of cloud condensation nuclei[49] but, while laboratory and modelling studies suggest that these are plausible, there is currently no evidence to suggest that this mechanism can produce the signal suggested by this study[47].

The second path whereby ionisation might influence cloud cover involves changes in the global electrical circuit. This circuit involves currents flowing between the surface and the ionosphere initiated by thunderstorm activity and with a return current in fair weather regions. The presence of (non-thunderstorm) cloud in the clear regions increases atmospheric conductivity[50] and there is some evidence of a modulation due to ionisation by cosmic rays. Near the edges of clouds charge can accumulate and this can influence both evaporation of cloud droplets and interactions between them[51,52]. Again the mechanisms are plausible but evidence for a significant impact remains elusive.

Research Agenda

Understanding the role of solar variability in solar activity is essential to the interpretation of past climate and prediction of the future. While solar activity cannot explain global warming over the last 60 years, future developments in solar activity might either amplify or moderate future climate change due to anthropogenic emissions of greenhouse gases. This might well have important policy implications for the pace and scale of our mitigation response to anthropogenic climate change. Solar activity changes might also play a role in regional climate that we need to understand in the context of informing climate adaptation efforts. The following are some of the most important issues that require further work.

Solar radiation

Knowledge of the solar radiation incident on the Earth is an essential prerequisite of any quantitative studies of the Sun's impact on climate but there are discrepancies of 4-5 Wm^{-2} between current contemporaneous observations of TSI (Figure 10) and a wide spread of estimates of its values back in time to the period of low activity, the Maunder Minimum (Figure 12). Continuing efforts to obtain measurements of high accuracy and precision are needed, alongside further effort in understanding the relationship between activity indicators and irradiance.

Recently questions have also been raised about the variability of the solar spectrum, arising from measurements made by the SIM instrument on the SORCE satellite. These show, over the period 2003-2007 (i.e. during the declining phase of the most recent solar cycle), a much larger decline in the ultraviolet component of incident solar radiation than would be anticipated from current understanding (such as presented in Figure 5, panel b) and an *increase* in visible wavelength radiation[53]. This suggests an inverse relationship between solar radiative forcing of climate and solar activity over that period[54]. These new data provide an entirely different picture than currently accepted of how solar irradiance varies, although there is no evidence to ascertain whether such behaviour has occurred before. If this was also the case during previous multi-decadal periods of low solar activity then assessments of the solar influence on climate would need to be revisited[54], but this would be unlikely to challenge current understanding that global warming over the past century can be largely ascribed to human activity.

> Understanding the role of solar variability is essential to the interpretation of past climate and prediction of the future

Mechanisms for solar-climate links

The three fundamentally different mechanisms proposed to explain the observed regional impacts of solar variability, as outlined above, are at different stages of maturity. The basic tenet of the first of these (“bottom-up” mechanisms)—that increases in visible radiation will heat the sea surface—is uncontroversial. However, the proposed subsequent response, involving changes to tropical atmospheric and ocean circulations to produce a signal similar to the cold phase of the ENSO cycle, needs more detailed studies of both observational and model evidence before it can be accepted.

The second type (“top-down” mechanisms) similarly have a robust first stage *viz.* heating of the stratosphere by increased ultraviolet radiation and the subsequent coupling processes are better understood. Nevertheless, there are remaining gaps in knowledge including details of the stratospheric ozone and temperature signals, the roles of, and interactions between, the various coupling processes and the magnitude of specific regional impacts.

The third mechanism, involving responses in cloudiness to solar-induced changes in atmospheric ionisation by galactic cosmic rays, requires more evidence before any of the proposed pathways can be considered both operational and effective. For the path via ion-induced condensation nuclei it is necessary to determine to what extent this could have a significant effect in the context of other droplet growth mechanisms, requiring a more detailed understanding of the successive processes involved. For the mechanisms involving the electric circuit, more observational evidence is required of cloud edge properties, especially including charge and droplet sizes. All the cloud scenarios need to be assessed within models of cloud microphysics incorporating the various complex interactions involved.

Climate models

In order properly to represent the effects of solar variability on global climate, general circulation models (GCMs) need to incorporate representations of the physical processes identified as being important. Many of the coupled ocean-atmosphere climate models, such as used in simulations for the Intergovernmental Panel on Climate Change assessment reports[1], have very approximate representations of the stratosphere and/or poor spectral resolution in their treatment of solar radiation so would be unlikely to capture any ultraviolet effects. Some GCMs appear to be overly productive of ENSO cycles, which might confuse any solar signal in sea surface temperatures. In no GCM is there a treatment of galactic cosmic rays or of the atmospheric electric field, although some incorporate parameterisations of cloud-particle interactions which might be extended to include ionisation effects if they are found to be important. Thus, a number of improvements in climate models are likely to become necessary in order for them to provide a more faithful representation of solar impacts.

Observational records

Confirmation of hypotheses and validation of models can only be obtained by the continuing acquisition of long-term, well-calibrated measurements of atmospheric properties, including temperature, cloud properties and ozone concentration, with sufficient spatial and temporal resolution. These need to be acquired alongside properly calibrated solar spectral data.

Conclusions

There is a need for a thorough understanding of how the Sun affects climate. This is important because it has long and short term influences and we need to know how these interact with anthropogenic effects. It is also important to understand natural factors in climate variability to give a basis upon which its future state might be predicted.

Observations from both satellites and the ground, alongside theoretical advances and developments in models, are helping to progress understanding of the Sun’s behaviour. In particular there have been significant advances in how different activity indicators relate to the physical processes involved in the evolution of the solar magnetic field, sunspots and radiation over the 11-year cycle. On longer timescales there are still uncertainties in underlying trends in solar irradiance, partly due to problems of instrumental calibration and inter-calibration, and, as a result, the reconstruction of past values of solar irradiance is still prone to uncertainty.

This means that the value for the solar radiative forcing of climate change over the past one and a half centuries cannot be precisely established. Nevertheless, the results of statistical studies of global temperature records concur with those from climate models that, while increases in solar activity probably contributed 7-30% of the global warming apparent over the century leading up to the 1960s, the warming in the latter part of the 20th century is almost entirely due to the increasing concentrations of greenhouse gases from human activity.

Regional impacts of solar variability are more difficult to establish but there is accumulating evidence that higher levels of solar activity are associated with increased likelihood of certain changes in tropical circulation patterns and poleward shifts in the mid-latitude storm tracks. Impacts on the polar modes of variability (North Atlantic Oscillation and Southern Annular Mode) have also been observed. A coupling between solar effects and the El Niño-Southern Oscillation remains controversial.

Understanding the physical processes involved in solar-climate connections is crucial to the interpretation of meteorological records, and to the prediction of aspects of the future climate. There are several candidate mechanisms proposed to explain the observed regional impacts of solar variability and scientific research is making advances in understanding each of these mechanisms. Currently the theory involving heating of the stratosphere by solar ultraviolet radiation, with effects transmitted by changes in winds and circulation down to the surface, is the most well-developed. This is not, however, exclusive of other proposed mechanisms and any or all of them may be acting to varying extents.

Some indicators of solar activity suggest that there has been an overall downturn since about 1985, and also that the Sun may currently be moving away from a Grand Maximum state and towards a Grand Minimum, like the Maunder Minimum, which it might reach within several decades. This raises the issue that the Sun might buy some time for the world to adjust to greenhouse gas–induced global warming. It would be rash, however, to become complacent on this basis for several reasons. Firstly, predictions of solar activity are notoriously difficult and prone to error. Secondly, it is not necessarily the case that an Earth with a global net radiation balance but different radiative components (*viz.* less absorbed solar radiation but more "greenhouse" trapping of infrared radiation) will have the same climate; indeed, some model studies of "geoengineering" approaches to mitigating climate change, which seek to artificially mange the amount of solar radiation entering the troposphere, have found significant differences in the hydrological cycle and monsoons [55]. Thirdly, the time bought would probably be a decade or so at most, and on timescales of a few centuries the Sun is likely to return to a Maximum state resulting in a climate, with a much higher greenhouse gas loading, considerably warmer than at present.

About the author

Joanna studied at Oxford University (MA 1975, DPhil 1980) and Imperial College (MSc 1977) and joined Imperial as a lecturer in 1984; she was appointed Professor of Atmospheric Physics in 2001 and Head of the Department of Physics in 2009. She has published widely in the area of radiative transfer in the atmosphere, climate modelling, radiative forcing of climate change and the influence of solar irradiance variability on climate. She has been Vice-President of the Royal Meteorological Society, Editor of *Quarterly Journal of the Royal Meteorological Society*, a Lead Author of the Intergovernmental Panel on Climate Change Third Assessment and acted on many UK and international panels. Currently she is the UK representative to the International Association of Meteorology and Atmospheric Sciences, Editor of the American Meteorological Society's *Journal of the Atmospheric Sciences* and a Member of the Royal Society's Climate Change Advisory Group. She is a Fellow of the Institute of Physics and of the Royal Meteorological Society and in 2004 she received the Institute of Physics Charles Chree Medal and Prize for her work on solar influences on climate.

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