

## **Solar Induced Climate Effects**

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## **Glossary**

*Anomaly.* The deviation of a parameter from its mean value over a defined reference period.

*Blackbody radiator.* A body that emits the maximum radiation possible for its temperature, at all wavelengths

*Chromosphere.* The lower solar atmosphere, within about 2000 km of the photosphere

*Cloud Condensation Nuclei.* An aerosol particle or air ion on which water can condense such that it grows into a cloud water droplet

*Diffuse Fraction.* The ratio of the intensity in shade divided by the intensity in direct sunlight; for clear skies the diffuse fraction approaches zero whereas for cloudy skies (and/or with heavy aerosol loading) the diffuse fraction approaches unity.

*El Niño Southern Oscillation (ENSO).* The extremes of this quasi-periodic (period of 3-7 years) coupled ocean-atmosphere circulation oscillation are El Niño and La Niña events in which the sea surface temperature in the equatorial Pacific is, respectively, warmer and colder than average. ENSO is one of the predominant causes of interannual variability of regional climates around the globe.

*Forbush Decrease.* A transient decrease in GCR fluxes reaching Earth lasting typically 1-4 days, caused by the shielding properties of transient events released from the solar atmosphere.

*Galactic Cosmic Rays (GCRs).* Charged particles ranging in mass from electrons and protons up to iron and silicon ions with energies typically of order 0.1-100 GeV. They are generated by explosive galactic events such as supernovae. The flux of GCRs at Earth is modulated by the extension of the solar magnetic field into interplanetary space.

*Global Albedo (A).* The fraction of the total electromagnetic energy from the Sun incident on the Earth that is reflected back into space.

*Global Circulation Model (GCM)* - Also called a General Climate Model. A numerical model of Earth's global climate system incorporating best available knowledge of the fluid dynamical, chemical and, increasingly, biological aspects of Earth's climate system.

*Global Mean Air Surface Temperature (GMST).* The average of the temperature measured 2m above the ground by a global network of meteorological stations. The number of stations available declines further back into the past and is consistently lower in the southern hemisphere. Note that it is usually expressed as an anomaly by taking global averages of the station temperature anomaly.

*Heliosphere.* The area of space surrounding the Sun and solar system dominated by the solar wind and the magnetic field of solar origin embedded in it.

*Jet Stream.* Narrow bands of fast westerly (eastward) wind in the upper troposphere caused by the combination of equatorial solar heating and Earth's rotation. There are two in each hemisphere: the polar jets are typically found at latitudes of 30-60° whereas the weaker subtropical jets are at 25-30°.

*Laschamp Event.* An example of a geomagnetic excursion that occurred around 40kyr ago. These events are "short-lived" (typically 1000-10,000 years in duration) decreases in the geomagnetic field intensity (often to below 20% of normal) with a variation in pole orientation of up to 45°, but no polarity reversal. Any confirmed and consistent paleoclimate signatures of climate change associated with this event would be very significant because the GCR flux reaching Earth's atmosphere would increase but with no simultaneous solar irradiance change.

*North Atlantic Oscillation (NAO).* An oscillation in the pattern and strengths of westerly winds and storm tracks in the north Atlantic. It is quantified by the fluctuations in sea level pressure between the Icelandic low and the Azores high. The NAO is very closely related to the Arctic Oscillation (AO – which is also called the Northern Annular Mode, NAM).

*Northern Annular Mode (NAM)* – also called the Arctic Oscillation: see "North Atlantic Oscillation"

*Open Solar Flux.* The magnetic field of solar origin that leaves the top of the solar atmosphere and fills the heliosphere.

*Paleoclimatology.* The reconstruction of past climate from a variety of sources such as tree growth from tree rings (dendrochronology); analysis of air bubbles trapped in snow and ice; chemical and isotopic analysis of speleothems, lake deposits, ocean sediments, ice rafted debris and corals; and documentary evidence.

*Photosphere.* The visible surface of the Sun (mean radius  $R_{\odot}$ )

*Radiative Forcing.* The change in the difference between the incoming radiation energy and the outgoing radiation energy per unit area at the atmospheric boundary between the troposphere and the stratosphere (the tropopause). It is measured in  $\text{Wm}^{-2}$ . Consider the case of a TSI change of  $\Delta S$ : the change in the total power incident on Earth is  $\Delta S \cdot \pi R_E^2$ , where  $R_E$  is a mean Earth radius. The change per unit surface area of the Earth is  $\Delta S \cdot \pi R_E^2 / (4\pi R_E^2) = \Delta S/4$ . The part not reflected back into space is  $\Delta S(1-A)/4$ , where  $A$  is Earth's global albedo. Therefore a TSI change of  $\Delta S$  corresponds to a radiative forcing change of  $\Delta S(1-A)/4$ . For other influences on climate the equivalent value can be computed in each case.

*Solar Energetic Particles (SEPs).* Charged particles ranging in mass from electrons and protons up to iron and silicon ions of energies of order 0.1-100 MeV. They are generated by transient events in the solar atmosphere and heliosphere.

*Solar Wind.* The continuous, supersonic and super Alfvénic outflow of thermal plasma (ionised gas) from the solar atmosphere driven by its high temperatures.

*Spectral Solar Irradiance (SSI).* The solar electromagnetic power at a given wavelength, per unit wavelength, falling on unit area normal to the Sun-Earth line (often considered in the UV band of the spectrum)

*Stratosphere.* Atmospheric layer at about 20-55 km altitude, between the tropopause and the stratopause.

*Super-Alfvénic.* In a plasma (ionised gas) a family of waves which modulate both the plasma and the magnetic field can propagate. These are called Alfvén waves and particles that move faster than them are called Super-Alfvénic.

*Total Solar Irradiance (TSI).* The total solar electromagnetic power falling on unit area normal to the Sun-Earth line

*Troposphere.* The Atmospheric layer between Earth's surface and the tropopause, which lies at an altitude of about 11 km at the poles and 17 km at the equator. All climate and weather processes reside in the troposphere.

## **Definition of the Subject**

Solar electromagnetic radiation powers Earth's climate system and, consequently, it is often naively assumed that changes in this solar output must be responsible for changes in Earth's climate. However, the Sun is close to a blackbody radiator and so emits according to its surface temperature and the huge thermal time constant of the outer part of the Sun limits the variability

in surface temperature and hence output. As a result, on all timescales of interest, changes in total power output are limited to small changes in effective surface temperature (associated with magnetic fields) and potential, although as yet undetected, solar radius variations. Larger variations are seen in the UV part of the spectrum which is emitted from the lower solar atmosphere (the chromosphere) and which influences Earth's stratosphere. There is interest in "top-down" mechanisms whereby solar UV irradiance modulates stratospheric temperatures and winds which, in turn, may influence the underlying troposphere where Earth's climate and weather reside. This contrasts with "bottom-up" effects in which the small total solar irradiance (dominated by the visible and near-IR) variations cause surface temperature changes which drive atmospheric circulations. In addition to these electromagnetic outputs, the Sun modulates energetic particle fluxes incident on the Earth. Solar Energetic Particles (SEP) are emitted by solar flares and from the shock fronts ahead of supersonic (and super-Alfvénic) ejections of material from the solar atmosphere. These SEPs enhance the destruction of polar stratospheric ozone which could be an additional form of top-down climate forcing. Even more energetic are Galactic Cosmic Rays (GCRs). These particles are not generated by the Sun, rather they originate at the shock fronts emanating from violent galactic events such as supernovae explosions; however, the expansion of the solar magnetic field into interplanetary space means that the Sun modulates the number of GCRs reaching Earth. These play a key role in enabling Earth's global electric (thunderstorm) circuit and it has been proposed that they also modulate the formation of clouds. Both electromagnetic and corpuscular solar effects are known to vary over the solar magnetic cycle which is typically between 10 and 14 yrs in length (with an average close to 11 yrs). The solar magnetic field polarity at any one phase of one of these activity cycles is opposite to that at the same phase of the next cycle and this influences some phenomena, for example GCRs, which therefore show a 22 yr ("Hale") cycle on average. Other phenomena, such as irradiance modulation, do not depend on the polarity of the magnetic field and so show only the basic 11-yr activity cycle. However, any effects on climate are much more significant for solar drifts over centennial timescales. This chapter discusses and evaluates potential effects on Earth's climate system of variations in these solar inputs. Because of the great variety of proposed mechanisms, the wide range of timescales studied (from days to millennia) and the many debates (often triggered by the application of inadequate statistical methods), the literature on this subject is vast, complex, divergent and rapidly changing: consequently the number of references cited in this review is very large (yet still only a small fraction of the total).

## Introduction

It is interesting to ponder what the author h-index<sup>1</sup> of the astronomer Sir Frederick William Herschel (1738–1822) would be. Certainly his 1801 paper [1], in which he speculated on a connection between sunspots and the regional climate of the UK, has been cited a great many times and continues to be cited regularly today. Herschel appears to have been more aware of the limitations of his apparent correlation (writing “this prediction ought not to be relied on by anyone”) than many who have subsequently cited his paper. He notes limitations to his speculation that many subsequent studies of solar influence on climate have failed to adequately consider. Specifically:

1. Sunspots are, at best, only indirectly related to the solar outputs that are relevant to climate. (Herschel attempts to build an argument about enhanced emission from sunspots which is now known to be incorrect).
2. The lack of suitable measurements of Earth’s global climate leads to the use of indirect proxies (Herschel used the price of wheat) and there are many other factors which can influence such proxies. (Note that some modern studies continue to try to use the price of wheat as a climate proxy [e.g., 2, 3]).
3. The datasets are not homogeneous and measurements show instrumental drifts and discrete jumps. (Herschel notes this in respect of the sunspot data available to him).
4. The climate data are usually regional and not global (Herschel used the price of wheat in the UK and not on the global market).
5. The climate data are usually for a limited season (in Herschel’s case, this is effectively the growing season of wheat).
6. Correlations readily occur by chance and the probability of that happening must be evaluated. In geophysics (including climate science) this test must allow for the “persistence” in the data time series. Also called “conservation”, this is a measure of the tendency of one data point to be similar to its predecessors, and it lowers the effective number of independent samples and hence the significance of any correlation. In addition, tests are needed to prevent “data snooping”, i.e. exploiting a feature in the data that turns out to be a statistical or instrumental artefact. To ensure wrong conclusions are

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<sup>1</sup> An author with an h-index of n means he/she has authored n publications each of which has been cited in other publications at least n times

not drawn from statistical coincidences, clear null hypotheses must be formulated and proper statistical tests performed [4, 5].

7. Even when the proxies are reliable indicators of a climate variable, there are a great many other influences on it besides solar variability. For example, Herschel neglected the effects of volcanic eruptions that occurred during the interval that he studied. Multiple regression analysis is often used [6-9] but these can be misleading if inter-correlations exist between the data series that are input into the study or if genuine factors are omitted. Naive regression analyses may also be misleading due to convoluted nonlinear response associated with feedback processes, the use of non-optimal regression techniques and the presence of internal system variability [10]. Hence such results need to be interpreted with caution and judgement.
8. The potential for selection effects mean one must ask “would the correlation coefficient be as high if an equivalent dataset were substituted?” (For example, in Herschel’s case, was the behaviour of the price of barley similar to that of wheat?). Selection effects can often arise (unintentionally or otherwise) from restricted data intervals. For example, Lockwood and Fröhlich [11] showed that whereas solar irradiance and cosmic ray trends before 1985 had been in the direction to those needed to explain the observed global temperature rise, after that date (which marks the peak of a grand solar maximum [12]) they have been in the opposite direction. Hence studies based only on data from before 1985 are more likely to be misleading.
9. Even a statistically significant correlation or detected periodic signal does not establish causality. Neither do lags and phases for coupled systems involving stationary oscillations. There are a huge number of publications looking at oscillations at periods close to that of the solar cycle and/or correlations with the solar cycle at a fixed lag. Tests of some of these reveal that they are unlikely to be driven by solar forcing, and that they are more likely to reflect other natural cycles of the climate system, such as the 14-year cycle, or a harmonic combination of multi-year cycles [13, 14].
10. Is there a realistic mechanism or series of mechanisms that could have given rise to the correlation? (Herschel’s proposal invoked solar physics, climate science, agricultural science and the effect of supply-and-demand in economics).

The reason why the citation rate for Herschel’s speculation is so high is that a great many subsequent studies have explored the same ideas. The growth in modern day interest can be traced to John A. "Jack" Eddy (1931-2009). (Incidentally, Eddy’s h-index is known and is just

13, but his most influential paper, published in 1976 [15], has been cited 797 times at the time of writing<sup>2</sup>). The academic reputation of the field of Sun-climate relations is poor because many, perhaps most, studies do not address all, or even some, of the limitations listed above. It is also a field that in recent years has been corrupted by unwelcome political and financial influence as climate change sceptics have seized upon solar effects as an excuse for inaction on anthropogenic effects. In particular, figures and statistics with known errors, limitations and inaccuracies are repeatedly reproduced on the internet and in the media [16]. None of this makes any difference to the scientific reality, or otherwise, of mechanisms connecting solar variability and Earth's climate; however, it does make evaluation of the evidence much more difficult. Recent reviews have been presented by Reid (2000), Rind (2002), Haigh (2003, 2007), Beer (2006), Foukal et al. (2006), de Jaeger (2008) and Gray et al. (2010) [17-24].

### **Solar Variability**

Solar outputs reaching Earth undergo periodic variations over a range of time scales. These include the 27-day variation due to solar rotation, the decadal-scale solar magnetic (sunspot) and Hale cycles and oscillations between grand solar maxima and minima on timescales of several centuries. How a key climate parameter, such as the Global Mean Air Surface Temperature (GMAST), varies in response to these solar variations will depend on its response timescale. Estimates of the GMAST response time have varied from less than 1 year to several decades [25-28]. Knutti et al. [29] discuss the time constants of different parts of the climate system: short time scales (1 year or less) apply to atmospheric adjustments and land surface processes; medium time scales (of order decades) to the melting of sea ice; and long time scales (many decades) to warming of the whole ocean surface layer. Ocean warming effects are complex because of mixing behaviour [30] but an effective timescale of 5-20 years has been predicted [31]. The climate response modelling [32] and analysis of pre-industrial data [33, 34] has yielded response times of up to 10 yr. Hence it is clear that responses to 27-day solar variations will be damped to undetectable levels in GMAST whereas the centennial solar variations should be reflected almost in full. The extent to which the solar cycle variations will be damped is still a matter of debate. Lockwood and Fröhlich [11] showed that solar trends since 1985 have been in the opposite direction to that needed to explain the observed GMAST rise. This could be explained by solar forcing only (with large amplification) using a very long (of order several decades) response time, but that would also mean that all associations of decadal scale

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<sup>2</sup> Citation analysis using Web of Science, May 2010.

oscillations in GMAST with the solar cycle were coincidental as the true solar cycle signal would be highly damped [35]. Hence there is a paradox: attributing large fractions of the centennial global warming to solar changes means that decadal-scale correlations on global scales must be regarded as coincidences, whereas accepting the validity of evidence for a solar cycle global climate response would mean that recent climate trends were not related to solar changes. This does not mean that components of the global system, which may have a shorter response time than GMAST, would not show solar cycle variations.

Elsewhere in this Section on Solar Radiation, the article by Fröhlich discusses the observations of total solar irradiance (TSI) covering 3 solar cycles. This variability is well explained by the effects of magnetic structures threading the photosphere [36, 37], i.e. the darkening effect of sunspots and the brightening effect of smaller magnetic flux tubes called faculae. To evaluate the solar contribution of TSI variability to centennial climate change requires its reconstruction over the past few centuries. Figure 1 shows a collection of TSI reconstructions covering the interval from just before the Maunder minimum (the period in the second half of the 17<sup>th</sup> century when almost no sunspots were seen) up to the present day. The figure shows that estimates of the magnitude of the centennial drift in TSI have declined: initial estimates were based on a limited survey of putative Sun-like stars [38, 39]. However, larger surveys with stricter criteria for Sun-like stellar analogues did not reproduce the key result employed in these early TSI reconstructions [40, 41]. As a result, information on long-term drift of the solar magnetic field from geomagnetic activity [42, 12, 43] was employed in the later reconstructions. Reliable geomagnetic activity data are available back to 1868 and can be used to derive the open solar flux (OSF), the magnetic flux leaving the top of the solar atmosphere. OSF correlates well with TSI over the solar cycle [44, 45] and recent studies indicate that observed TSI may also reflect some of the longer-term drift in OSF [46]. Modelling of the OSF variation [47-51] showed that the total flux threading the photosphere could be constrained by the OSF variation and this could be combined with sunspot observations to reconstruct TSI back to 1600. Figure 1 shows that these second methods are yielding considerably smaller changes in TSI since the Maunder minimum than the early reconstructions based on stellar analogues.

In evaluating some reported associations between TSI and climate, it is important to note the implications of the debate about the intercalibration of TSI data across the “ACRIM gap” in modern TSI data composites (see figure 1 in the article by Fröhlich), after the end of the available data from the ACRIM1 space-based radiometer but before its successor, ACRIM2,

started to take data. These composites use many of the same raw data series but differ in the degree to which they allow for instrument degradation and in the instrument intercalibrations. Lockwood and Fröhlich [35] note that the anticorrelation between TSI and GCR fluxes (see below) is found for the reconstructed TSI data time series known as the “PMOD data composite” but does not hold for the alternative “ACRIM” composite [52, 53]. Scafetta and Willson (2009) [54] argue that the long-term reconstruction of TSI by Krivova et al. (2007) [55] supports the ACRIM composite but Krivova et al. (2009) [56] and Wenzler et al. (2009) [57] point out that the more precise TSI reconstruction from modern magnetograph data is inconsistent with the ACRIM composite but consistent with the PMOD composite. The implications of this debate are discussed later in relation to figure (2).

The UV part of the solar spectrum is much more variable than TSI and is an essential factor that modulates ozone abundance, temperatures and winds in Earth’s stratosphere (see review by Gray et al. [24]). Composites of UV spectral solar irradiance (SSI) had shown little variation in the spectral shape, such that they exhibit a similar waveform to TSI [58, 59] and this has been reflected in centennial reconstructions of SSI [60]. However, recent observations of the descent into the current unusual solar minimum [61] cast doubt on this as they show more variability in the UV and considerable change in spectral shape [62], although the validity of these data has been questioned [63]. If valid, they imply that at the wavelengths responsible for stratospheric modulation, centennial variation may be greater than previously thought [295]. There is debate about the degree of centennial drift in historic observations of the UV Ca “K” absorption line [64-66] but this may, anyway, be of limited relevance because the absorption arises higher in the solar atmosphere than the UV continuum emission.

The degree of uncertainty in long-term variability of TSI and SSI should be noted.

Reconstructions allow for the effect of large active regions (groups of dark sunspots surrounded by bright faculae) which vary with the decadal- and centennial-scale changes in the large-scale solar dynamo. However, the long-term variability and effect of small-scale fields in the quiet Sun (away from active regions) driven by the turbulent, small-scale dynamo [67] is not well known. Furthermore, it has been suggested that magnetic fields below the solar surface may have an influence [68] and although the success of modelling TSI variations using surface fields means there is no evidence for these “shadow effects” over recent solar cycles, this does not necessarily mean that they could not have an effect on longer timescales. Another potential source of additional long-term drift arises from changes in the solar radius,  $R_{\odot}$ . A great many

studies over many years have searched for such variations, both over recent solar cycles and, using eclipse data, on centennial timescales. These studies are inconclusive and often contradictory: it is unclear that any changes detected are bigger than the experimental uncertainties. For example, there are a number of reports that  $R_{\odot}$  increases with solar activity [69] whereas other measurements show the reverse or no consistent change [70, 71]. Bruls and Solanki (2004) [72] demonstrated that surface luminosity features can perturb many techniques and the results from helioseismology show small and inconsistent changes [73]. The best observations place an upper limit of about 0.01% on variations in  $R_{\odot}$  over decades [73-76] and reports of larger changes (e.g., [77]) remain controversial.

As well as being used in reconstructions of TSI, the OSF is highly anticorrelated with the flux of GCRs incident on Earth [78]. As discussed later, GCRs have been proposed as a direct modulator of Earth's climate; however, the anticorrelation of GCRs with OSF and irradiance means that GCRs may just be a proxy indicator of TSI and SSI variations. Indeed, the cosmogenic isotopes that GCRs produce are routinely used in paleoclimate studies as a proxy indicator of irradiance [79]. Lockwood [80] showed that the relationship between cosmogenic isotope production and TSI is monotonic but may not be linear, depending on the effect of unknowns in the long-term irradiance behaviour discussed above. Steinhilber et al. [81] have recently reconstructed TSI variability on centennial scales using cosmogenic isotope data and for recent centuries their results are similar to the modern TSI reconstructions shown in figure 1. A number of cosmogenic isotope data sequences have been generated [82–84]. A key point to note is that the Maunder minimum is just one of a number of “grand solar minima” (and far from the deepest one in the record over the last  $10^4$  years), whereas modern space-based measurements are all within a “grand solar maximum”. There has been debate as to the degree to which the current grand maximum is an exceptional one in terms of its amplitude [85, 86]. However, it is clear that its duration is relatively long and hence a return to more average solar conditions is somewhat overdue [87]. The OSF variation suggests that this decline commenced around 1985 [12] and that the recent solar minimum (between cycles 23 and 24), which was exceptionally low compared to previous examples during the space age [61], is a symptom of that decline. From the composite of cosmogenic isotope records by Steinhilber et al. [84], Lockwood [61] estimates that there is about an 8% chance of a rapid return to Maunder minimum conditions within the next 50 years.

One last solar output is the continuous, but highly variable, stream of low-energy thermal particles in the solar wind which has been invoked in some climate studies (e.g., [88, 89]). The power incident of Earth's atmosphere delivered by the solar wind is smaller than that from solar electromagnetic radiation by a factor of between  $10^4$  and  $10^5$  [90]. Nevertheless, energy extracted from the solar wind undoubtedly dominates the uppermost atmosphere (the thermosphere), but this contains a tiny fraction of the total mass of the atmosphere. Other studies find relationships with geomagnetic activity (caused by electrical currents in the upper atmosphere): for example, Bochníček and Hejda [91] report variations in the North Atlantic Oscillation (NAO) to be more related to geomagnetic activity than sunspots. Thejll et al. [92] also investigated correlations between geomagnetic activity indices and the NAO and found significant correlations in winter for some but not all years. However, solar wind and geomagnetic activity are both highly correlated with OSF which, in turn, is highly correlated with spectral and total solar irradiance (and also correlated with SEP occurrence and anticorrelated with GCR flux). Given that the total masses in the troposphere, stratosphere and thermosphere are approximately 80%, 19.9% and 0.1% of the total atmospheric mass, any mechanism connecting the solar wind and climate would require a mechanism of truly extraordinary amplification; hence any relationships are most likely to be due to other, correlated, solar outputs.

### **Paleoclimate Studies**

A great many studies have indicated that solar variations had an effect on pre-industrial climate throughout the Holocene (the warm interval since the last ice age). These studies have been made in many parts of the world and employ a huge variety of paleoclimate proxies [93–120]. Studies on timescales of up to 1-2 thousand years are, in some ways, optimum since such periods are short enough to avoid complications from changes in the geomagnetic field and Earth's orbit [121]. In all cases, the solar change is evaluated from cosmogenic isotopes. The most interesting of these studies employed terrestrial data that are indicators of more than just local climate. For example, Bond et al. [102] studied the average abundance of ice-rafted debris (IRD), as measured in the cores of ocean bed sediment throughout the middle and North Atlantic. IRD are glasses, grains and crystals that are gouged out by known glaciers, which are then carved off in icebergs and deposited in the sediment when and where the icebergs melt. The sediment is dated using microfossils found at the same level in the core. The abundances of this IRD are sensitive

indicators of currents, winds and temperatures throughout the North Atlantic and reveal high, and highly significant, correlations with both the  $^{10}\text{Be}$  and  $^{14}\text{C}$  cosmogenic isotopes. A second example has been obtained from the deviation of the oxygen isotope ratio from a reference standard variation,  $\delta^{18}\text{O}$ , as measured in stalagmites in Oman and China in two separate studies [103 and 116]. These studies reveal an exceptional correspondence with the cosmogenic isotopes on all time scales between decades and several thousand years. The  $\delta^{18}\text{O}$  is, in each case, a proxy for local rainfall [122] and reveals enhanced precipitation caused by small north-south migrations of the intertropical convergence zone. Large effects are seen because the latitudinal gradients around the sites are large. The fact that the effect is seen at widely spaced locations is evidence for coherent shifts in the latitude of the monsoon belt.

These correlations of paleoclimate indicators are found for both the  $^{14}\text{C}$  and  $^{10}\text{Be}$  cosmogenic isotopes. The  $^{10}\text{Be}$  is a spallation product of galactic cosmic rays hitting atmospheric O, N and Ar atoms; the  $^{14}\text{C}$  is produced by thermal neutrons, generated by cosmic rays, interacting with N. About two thirds of the  $^{10}\text{Be}$  is formed in the stratosphere and about one third in the troposphere from where precipitation times into the reservoirs are typically 1 year and 1 week, respectively, and the deposition into any one reservoir is influenced by climate conditions [123-126]. On the other hand, the  $^{14}\text{C}$  generated by GCRs takes part in the carbon cycle and is exchanged with the two major reservoirs, the oceans and the biomass. Hence, the transport and deposition into the reservoirs where they are detected (for example, ancient tree trunks for  $^{14}\text{C}$  and ice sheets or ocean sediments in the case of  $^{10}\text{Be}$ ) are vastly different for these two major cosmogenic isotopes. As a result, the possibility that the isotope abundances in their respective reservoirs are similarly influenced by climate during their terrestrial life history can be discounted because the transport and deposition of each is so different. Thus, it is concluded that the correlations are found for both isotopes because of the one common denominator in their production, namely the incident cosmic ray flux.

One method used to try to understand global climate change from local and regional paleoclimate indicators is “forward prediction of proxies” in which global circulation models (GCMs) are used to simulate the time series of one or more proxies at a number of locations. These modelled time series are then compared to the observed proxy data. In many of these studies, the climate proxies used relate to tropical hydrology and the connections have not yet been fully explained. Shindell et al. [127] used a coupled ocean-atmosphere-composition model,

forced by sustained multi-decadal irradiance increases, to show that greater tropical temperatures alter the hydrologic cycle, enhancing the climatological precipitation maxima in the tropics while drying the subtropical regions. The model captures the pattern inferred from paleoclimate records. This may explain drought conditions experienced by the Mayans, Moche, and Ancestral Puebloans civilizations during the late “medieval maximum” (900–1250) and other cultures, which experienced a weakened monsoon during the “Little Ice Age” (c. 1400–1750).

The flux of the GCRs that generate the cosmogenic isotopes is modulated by three influences [121]: (1) the interstellar flux of GCRs incident on the Sun’s heliosphere; (2) the GCR shielding by the heliosphere; and (3) the GCR shielding by the Earth’s geomagnetic field. The spatial scale of interstellar GCR flux variation in our galaxy is sufficiently large that, compared to distances moved by the solar system through the galaxy, the incident GCR variations on timescales of million years (Myr) and smaller can be neglected. The geomagnetic field shield has varied on timescales of 10 kyr. This variation has, in the main, been gradual during the Holocene [128, 129], although there have been shorter-lived weakenings of the field (which may be geomagnetic reversal onsets that did not develop) such as the Laschamp event around 40 kyr ago [130]. These events complicate the cosmogenic isotope record [131,132] but are not consistent with the variations seen on timescales of order 1 kyr and less seen, for example by Bond *et al.* [102], Neff *et al.* [103] and Wang *et al.* [116]. This being the case, most of the variations on these timescales arise from heliospheric shielding, i.e. the Sun. To study solar variability effects during the Holocene, several studies have corrected the cosmogenic isotope record to allow for the secular geomagnetic variations [e.g., 81, 84].

With paleoclimate studies, it is important to bear in mind all ten of the potential pitfalls listed in the introduction. An additional problem with the data sequences, which is not a factor for direct observations, is dating [133]. Because record dates are uncertain, “wobble matching” is often used [134, 135]. Even if this is done with great care, such that the date of any one data point is not moved by more than the accurately computed dating uncertainty, there is inevitably a selection effect at work. This is because the adjustments are made to improve correlations and not to degrade them. For this reason, there is a marked tendency for correlations to degrade as the accuracy of the dating is improved.

## Observations Solar Effects in Earth's Atmosphere

This review does not cover the great volume of literature describing and detailing the correlations and connections between solar activity and the ozone concentration, UV heating and consequent temperatures and dynamics in the stratosphere. Instead, the reader is referred to the recent comprehensive review by Gray et al. (2010) [24]. A later section will discuss mechanisms whereby these stratospheric changes could influence the much larger air mass of the underlying troposphere. This section evaluates the connections between solar variability and the troposphere (on local, regional and global scales) that have been reported.

A hugely-cited cited<sup>3</sup> paper by Friis-Christensen and Lassen (1991) [136], reporting a correlation between GMAST and solar cycle length  $L$ , highlights several of the problems discussed in the introduction. Firstly, one has to worry about selection effects and the mechanism. Why would  $L$  be relevant to climate-effective solar outputs (or was it used only because a correlation was found for  $L$  only)? But a more serious problem relates to the data handling and its effects on the significance of the correlation. Some of the  $L$  values in this paper were smoothed using a very long time constant filter. Such smoothing introduces great persistence into the data to the extent that the correlation has no significance [137]. Such correlations can arise, and may even continue for a while, by chance. Lack of significance does not prove the correlation is not present. If it is real it will continue to hold while more data are taken until statistical significance tells us that it has some validity. However, if it is not real it will eventually fail, as was found in this case [138, 139].

As well as persistence of the data series, using a large number of fit variables also reduces the significance of a correlation. This is one issue for multiple regression fits of terrestrial parameters using a combination of one or more solar and other parameters. Scafetta and West (2007) and Scafetta (2009) [140, 141 and a series of previous papers cited therein] (hereafter referred to as SW) propose in their so-called “phenomenological” methods that multiple time constants are required from which they derived multivariate fits that give up to 65% of the GMAST attributable to TSI change (see figure 2). However, SW do not evaluate the significance of the resulting correlations given that they employ a larger number of solar fit variables (the amplitude and time constant of each of the responses). Full understanding needs to also consider the effect of other known external inputs into the climate system (volcanoes, man-

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<sup>3</sup> Cited 405 times in Citation analysis using Web of Science, May 2010.

made aerosols, greenhouse gasses, land use etc.) and ensure that fits are not influenced by internal variability and oscillations such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). Many other multivariate fits in this area also fail to test the significance of the best-fit correlation against a well-posed null hypothesis and a properly defined noise model; however, the papers of SW have attracted particular attention because they derive much larger solar contributions to the temperature change. The largest estimates of the solar contribution by SW required use of the ACRIM TSI composite, rather than the PMOD composite, and tests show that both other data and proxies are more consistent with the PMOD composite [35, 61, 57]. This is just one of a number of arbitrary choices made by SW: Benestad and Schmidt (2009) [10] have found that the methodology used in the SW papers is not robust, and sensitivity tests performed on some of SW's choices showed that errors are significantly larger than SW report. They applied the SW procedure to GMAST modelled from known inputs and found that it returned very much larger solar variations than were initially input into the model. As for all multivariate fits, the addition of internal variability and additional forcings greatly confounded the accuracy of the SW procedure. Benestad and Schmidt find that the most likely contribution from solar forcing to GMAST is  $7 \pm 1\%$  for the 20th century and is negligible for warming since 1980 (see figure 2). This degree of solar influence is consistent with many modelling and detection-attribution studies (see below) and broadly in line with the computed ratio of solar to anthropogenic radiative forcings: the IPCC report of 2007 assessed that the change in solar radiative forcing over the interval 1750–2005 was in the range  $0.06\text{--}0.30 \text{ W m}^{-2}$  (at the 90% confidence level) with a most likely value of  $0.12 \text{ W m}^{-2}$  (consistent with the later TSI reconstructions in figure 2), whereas the net anthropogenic forcing is in the range  $0.6\text{--}2.4 \text{ W m}^{-2}$  [142, 143]. The TSI change of  $1.3 \text{ W m}^{-2}$  derived by Krivova et al. [55] for this interval gives a slightly larger radiative forcing of  $0.21 \text{ W m}^{-2}$ . These forcings should be compared with a total required value to explain the observed GMAST rise, including all feedbacks, of  $5.1 \text{ W m}^{-2}$  [61]. The conclusion that global climate early in the 20<sup>th</sup> century may show some solar influence, but that in recent decades it has been swamped by anthropogenic effects, is consistent with a great many studies, ranging from correlation studies [8, 9, 144, 145] to detection-attribution studies using GCMs [e.g. 142, 146-150].

The majority of reports of solar signals in global and regional climate are of solar cycle variations and so are subject to the major caveat that these can be easily confused with internal decadal-scale oscillations of the climate system [13, 14]. A statistically-significant solar cycle signal throughout the troposphere was reported by Coughlin [152]. Camp and Tung [153]

showed significant (and large) differences between mean GMAST for composite surface temperature maps at low and high sunspot activity levels. Such a signal can also be seen in both the ECMWF ERA40 and NCEP/NCAR re-analysis datasets, in which observations have been assimilated with model data [154]. This signal is weaker in the ERA40 set and varies regionally [153, 155]. Both temperature and mean zonal winds at all heights in the troposphere and stratosphere show significant decadal signal estimated from a multiple regression analysis [156, 157].

A great many studies have reported solar cycle signals in oscillatory modes and features in Earth's troposphere, including: the Northern Annular Mode, NAM [158–160] and the related north Atlantic Oscillation, NAO [161, 162]; the Indian Ocean monsoon [163]; the Southern Annular Mode, SAM [164]; tropical circulation [165-167]; Pacific variability patterns [168-173], in particular, the El Niño Southern Oscillation, ENSO [174, 175]. In addition, observations of temperature variations in the ocean mixing layer are thought to be evidence for resonant responses and “bottom-up” mechanisms [176-179], suggesting a strengthening of the Hadley circulation induced by an increased equator-to-pole temperature gradient.

### **Regional Climate Effects**

Using both a climate model and empirical reconstructions, Shindell et al. [180, 181] found that even though solar-induced GMAST changes are small (about 0.3° to 0.4°C), regional temperature changes associated with solar variability can be quite large. In the model, these occur primarily through a forced shift toward the low index state of the Arctic Oscillation/North Atlantic Oscillation as solar irradiance decreases. This leads to colder temperatures over the Northern Hemisphere continents, especially in winter (1° to 2°C), in agreement with historical records and proxy data for surface temperatures. Using a stratosphere-resolving GCM, these authors also found that long-term regional changes during the preindustrial period appear to have been dominated by solar forcing [182]. Studies by Mann et al. [183] and Trout et al. [184] have recently supported this idea for the little ice age and medieval maximum, respectively, although other modelling of the medieval maximum suggests that the role of solar changes is not as great as might be expected compared to other factors such as land use [185].

For post-industrial measurements, North and Stevens [186] applied optimal signal detection theory to data from 36 regions around the globe and found the solar signal was small and not highly significant. On the other hand, multivariate fits by Lean and Rind [8] do find strong solar responses in certain regions. Of these regions, this review concentrates on Europe for which the instrumental record is strongest. In this area, as for global responses, the issues of robust procedures and appropriate statistical methods are key considerations. For example, statistically significant signatures of multidecadal solar activity changes in atmospheric temperatures in Europe have recently been reported by Kossobokov et al. [187] and Le Mouél et al. [188-190] but Yiou et al. [4] and Legras et al. [5] argue that they do not survive proper null-hypothesis testing.

Figure 3 stresses how different the behaviour of a regional/seasonal climate in Europe can be from the global or hemispheric mean. The fluctuations for different regions tend to cancel, giving global means that are less variable, more clearly revealing the trends. The plot uses winter means,  $T_{DJF}$ , of the Central England Temperatures (CET), which is the world's longest instrumental record and extends back to 1659, at the start of the Maunder minimum. The CET covers a spatial scale of  $\approx 300$  km, which makes it a "small regional" climate indicator. In winter, the North Atlantic Oscillation (NAO), and associated changes in thermal advection, contribute to a large fraction of the observed variability of CET [191]. Comparison of parts (a) and (b) show that  $T_{DJF}$  correlates with both open solar flux and the hemispheric mean surface temperature  $\Delta T_N$ . However, the correlation is weak in both cases. Lockwood et al. [192] show that there is a subtle solar influence on winter CET in that it is statistically significant that more cold winters, relative to the hemispheric trend, occur when the open solar flux is low (i.e., when TSI and UV SSI are low and GCR fluxes are high – see figure 3c). A number of mechanisms are possible (discussed in the following sections). Early instrumental records from the Maunder minimum indicate an increased frequency of easterly winds influencing the UK temperatures. This has also been deduced from indirect proxies [193], including the spatial patterns of changes in recorded harvest dates [194]. This suggests a link with the incidence of long-lived winter "blocking events" in the eastern Atlantic at low solar activity. Blocking episodes comprise extensive and quasi-stationary anticyclones that can persist for several weeks, leading to extended cold periods in winter as the mild maritime westerly winds are replaced by continental north-easterlies and the land surface cools under cloudless skies. Long-lived Atlantic blocking events at more eastward locations have been found to be more prevalent at sunspot minimum than at higher solar activity, and this leads to colder winters in Europe [195]. This evidence

suggests that changes in the occurrence of blocking could be acting to amplify the solar-induced perturbations to the tropospheric jet stream. Other evidence supports this idea. For example, the effects of the changed position and frequency of blocking events may be seen as a manifestation of modes of low-frequency circulation variability that have been found to respond to solar activity, giving increased/decreased frequencies of easterly/westerly circulation patterns over Europe under low solar activity conditions [196, 197]. Winter CET values are known to be strongly modulated by the NAO [191] and modelling has shown that stratospheric trends over recent decades, along with downward links to surface, are indeed strong enough to explain much of the prominent trend in the NAO and hence regional winter climate in Europe between the 1960s and the 1990s [198]. The GCM runs experiments by Rind et al. [199] produce a relative negative phase of the North Atlantic Oscillation/Arctic Oscillation (NAO/AO) during the Maunder Minimum which contributes to the lower European winter temperatures.

### **Modelling Studies and Detection-Attribution**

GCMs have developed rapidly over the last two decades, and this has changed the details of the predictions of solar effects. Predicted solar-induced changes in GMAST have generally been small, even for the larger drifts in solar radiative forcing predicted by the early TSI reconstructions [25]. Full comparisons are complex because the TSI reconstructions have evolved at the same time as have the complexity and resolution of the models. As expected, weaker solar effects are found for the smaller TSI drift predicted by the more recent reconstructions: for example, compare the results and inputs of Wigley and Raper [25], Zorita et al. [200] and Stendel et al. [201]. Examples of recent GCM experiments giving a relatively large bottom-up solar effect have been presented by Rind et al. [199]. The input solar forcing change between the Maunder minimum and the present day used was  $0.68 \text{ W m}^{-2}$  (with an input of  $1.9 \text{ W m}^{-2}$  from anthropogenic forcing change). This solar forcing is relatively large, compared with the range  $0.06\text{--}0.30 \text{ W m}^{-2}$  quoted by Hergel et al. [142] and Solomon et al. [143], and the experiments generally gave a large solar contribution (near 30%) to the total GMAST rise (the total rise being larger than observed). The tropical response, in particular, was much greater than observed, consistent with the excessive TSI change input to the experiments.

Rind et al. [202] used a model with a coupled stratosphere at four different resolutions to investigate various aspects of top-down solar cycle influence on the troposphere/stratosphere

system. The results show that the stratospheric response is highly repeatable and significant. Stratospheric westerly wind increases were found to extend down into the troposphere and in some experiments the jet stream weakened and moved poleward. The predominant tropospheric response consisted of a warming of the troposphere, with coherent changes in regional precipitation. The tropospheric response was often not great, but was similar in all the different simulations. All runs revealed both top-down and bottom-up solar effects but they account for only a small percentage of the total GMAST variance. A model described by Meehl et al. [169–171] includes ocean-atmosphere coupling and a stratosphere, and so can include both top-down and bottom-up solar forcing. This model suggests potential resonant connections between solar forcing and the ENSO oscillation.

Model predictions are a key part of “detection-attribution” studies, in which the effect of varying an input to the GCM must be detected above the internal variability of the climate system modelled by the GCM. Results do depend on which GCM is used, although there is also a considerable degree of agreement between the different models. In many studies, the input forcings are multiplied by variable amplification “ $\beta$ ” factors to get the best fit to the variation of the global spatial pattern of surface temperature. For example, studies by Stott et al. [146] found that for solar forcing  $\beta = 3$  was required, but this unexplained amplification of the solar radiative forcing may have been overestimated because of the characteristics of the GCM used (see review by Ingram [150]) and/or because of instrumental problems with the data sequence [286]. A comprehensive review of detection-attribution methods and results has been given by Hegerl et al. [203].

### **Stratosphere – Troposphere Coupling and Top-Down Solar Forcing of Climate.**

Dynamical coupling across the tropopause [204] means that stratospheric forcing can influence the underlying troposphere [e.g., 205–207], and under some circumstances, robust tropospheric responses are indeed predicted by the models. Observational studies show that stratospheric perturbations (e.g., stratospheric warmings) typically last for at least a month and on average affect the troposphere within approximately two weeks [208]. Tropospheric jet streams have been shown to be sensitive to the solar forcing of stratospheric temperatures [209, 210, 19, 20]. This could occur through disturbances to the stratospheric polar vortex [211], which can propagate downwards to affect the tropospheric jets [212–214], or through the effects of tropical

stratospheric temperature changes on the refraction of tropospheric eddies [215, 216]. Models [e.g. 181] predict that perturbations can descend from the stratosphere to the surface by altering the propagation of planetary waves coming up from the surface—an effect that has been observed in data [217]. However, models that do not yield realistic stratospheric dynamics fail to capture these wave flux changes. The tropospheric response is reduced when planetary waves are suppressed in the stratosphere by additional damping or when the strength of the stratospheric jet is increased. The models show that the stratosphere could play a crucial role in recent trends. For example, Scaife et al. [198] have demonstrated that stratospheric trends over recent decades, along with downward links to surface, are indeed strong enough to explain much of the prominent trend in the NAO and hence regional winter climate in Europe between the 1960s and the 1990s. Such effects are not just found in the northern hemisphere [218].

A wide variety of tropospheric responses have been suggested [e.g., 219–222]. A predicted effect on tropospheric jet stream latitude is that increased heating of the equatorial stratosphere causes a slight poleward motion, an effect that has been reproduced in simple GCM simulations [223], deduced from other data [224], and has been suggested as a cause of equatorial precipitation changes in the little ice age [225].

The solar influence on winter European temperatures, discussed in the section above, suggests that the occurrence of the blocking phenomenon could be acting to amplify the solar-induced perturbations to the tropospheric jet stream [226]. Solar cycle control of the location, strength and occurrence of blocking events has been detected by Barriopedro et al. [195].

### **Cosmic Ray Modulation of Clouds**

A long-standing suggestion is that cosmic rays can aid the formation of clouds (see reviews by Carslaw et al., [227] and Kirkby, [228]). This would be a highly significant effect because clouds modulate Earth's energy balance by (1) changing Earth's albedo,  $A$ , and (2) by enhancing the IR greenhouse trapping effect. The balance between these two competing effects is dependent on the cloud altitude: for low clouds the albedo effect dominates whereas the lower temperature of higher altitude clouds means that the greenhouse trapping dominates. Variations in Earth's albedo are particularly poorly known [229, 230]. A great many papers have been written about low-altitude global cloud cover arguing that it shows a statistically significant solar cycle

variation, consistent with GCR modulation of the growth of cloud condensation nuclei [231–235]. Other studies find no significant effect [236–241]. A third set of studies find significant correlations but only in restricted regions [242, 243], whereas a fourth set reports a solar cycle variation but find it to be more consistent with solar UV irradiance variability [245, 242, 246]. Voiculescu et al. [247] argue that both UV and GCRs have an effect. Harrison [248] detected a 1.68-year oscillation in the long diffuse fraction data series from the Lerwick (maritime) station—an oscillation found in the open solar flux and GCR fluxes but not in the SSI or TSI variations [78], hence supporting a direct effect of GCRs. It is expected that the effect would be more significant in clean maritime air where there is a shortage of CCNs for water vapour to condense on, and thus air ions generated by GCRs may be a more significant factor in maritime regions [249, 250].

The arguments against such direct cosmic ray-cloud connection have been: (1) Given the atmospheric supersaturations, there is no established mechanism that can cause the effect; (2) the inter-calibrations involved in the composite cloud cover dataset used render it unsuitable for this type of long-term variability analysis [e.g. 251]; (3) the data sequences are too short and so the significance of the correlations is low or marginal. (For example, Sun and Bradley [239, 240] show that the uniquely high cosmic ray-cloud cover correlation in the period 1983–1999 over the Atlantic Ocean, is greatly weakened when an extended data set is used); (4) Periods of low geomagnetic field, particularly the Laschamp event, gave enhanced GCR fluxes in the Earth's atmosphere but did not influence climate in the Greenland area [21]. Of these objections, only argument (4) suggests that such a mechanism is not effective, whereas arguments (1)–(3) all indicate that the evidence in its favour is inadequate (but cannot be used to argue that it is not active). In relation to (4), there is some evidence that the failure to see an effect of the Laschamp event [253] may have been a local characteristic of the climate in the Greenland area [108]. Other studies give indications of an influence of the geomagnetic field on pre-industrial climate. Recent reports of associations between the main geomagnetic field and climatic changes [254–258] would be very significant, if confirmed. These changes have also been linked to latitudinal motions of the intertropical convergence zone [254, 259] and effects on civilizations that had a critical dependence on rainfall [255, 259, 260–262]. Nevertheless, objection (4) remains a key debate.

Harrison and Stephenson [263] found evidence for a GCR effect on diffuse fraction measurements at a variety of UK meteorological stations. As these are homogeneous sequences

of simple measurements, this does counter objection (2) to some extent; however, the effect was small and no allowance is made for the effect of the variable aerosol optical depth. The best chance of answering objection (1) is the CLOUD experiment at CERN [264], which has just begun to studying the “ion-aerosol clear-air” mechanism. However, Pierce and Adams [265] have estimated that this mechanism is 2 orders of magnitude too small to explain the reported effects. Other proposed mechanisms involving the atmospheric electric field [266] have been proposed [267–270].

In addition to the solar cycle variation in GCRs, there are sudden decreases in GCR fluxes (Forbush decreases) and these have been reported as giving responses in ground-based cloud data [271] and in satellite cloud cover data [272] using “compositing” analysis (also called “superposed epoch” and “Chree” analysis). The problem with these studies (particularly if the satellite dataset are employed) is that there are very few large Forbush decreases and the results appear to be dominated by one or two very large events. The delay of the putative effect is also a puzzle. Nevertheless, it has been independently reported that 3% of cloud variability on short timescales may be associated with GCRs [273]. The potential importance of this effect is that there are long-term changes in the open solar flux [12] that yield the long-term changes in GCRs [82-84], which could in turn introduce long-term changes in climate if the mechanism is sufficiently effective [85].

### **Solar energetic particles and ozone**

SEPs are directed towards Earth poles by the geomagnetic field where they generate nitrates on hitting Earth’s atmosphere as demonstrated, for example, in observations by Mlynchak et al. [274]. These nitrates are seen to migrate downwards over time [275, 276], resulting in catalytic destruction of stratospheric ozone [277]. Large SEP events generate considerable transient polar ozone depletions, which persist in winter until UV irradiance of the polar stratosphere resumes [278-281]. Recently, Seppälä et al. [282] reported changes in polar winter surface temperatures, which they associate with large SEP events, based on the modelling predictions of such effects by Rozanov et al. [283].

## **Are the GMAST Data Correct?**

There are difficulties in combining the available data into a single homogeneous GMAST anomaly time series. Different approaches are taken and different data used. For example, the way that regions of missing data are handled varies—GISS [284] interpolates into areas of missing data, whereas HadCRUT3v [285] does not. Nevertheless, as shown in figure 2, the GISS and HadCRUT3v reconstructions agree rather well and both show a recent plateau in GMAST anomaly, such that the HadCRUT3v value is still below 1998 levels although this is not true of GISS.

There are, however, potential issues that could influence both reconstructions. For example, Thompson et al. [286] report that sea-surface temperature measurement biases may have contributed a downward step in the GMAST of about  $0.3^{\circ}\text{C}$  in the middle of the 20<sup>th</sup> century. Correcting this would probably improve the agreement in figure (2) with the GCM model fit shown, but initial indications are that this correction would also lead to a lower solar contribution being derived by detection-attribution studies. In other words, if Thompson et al. are correct, the amplification of the solar forcing (with a beta factor  $> 1$ ) in some detection-attribution studies would be an example of data “snooping” because it relied on an artefact in the data.

Lockwood [9] carried out a simple multivariate fit analysis that fits the plateau in the HadCRUT3v GMAST well. In this fit, the plateau arises mainly because of the lack of El-Niño events since the major 1998 event, with a small contribution from the solar decline. This fit demonstrates that this feature could be readily explained as the combined effect of known influences. (Note that this statement can be no more definitive than this because of the limitations inherent in the multivariate fits, as discussed earlier). The plateau is also nothing unusual, compared to past variations around the upward trend [287, 288, 61].

## **Future Directions**

From solar-induced variations of cosmogenic isotopes over the past  $10^4$  years, Lockwood [61] has deduced there is an 8% chance that the Sun will return to Maunder minimum conditions within 50 years. Feulner and Rahmstorf [289] used a coupled model to predict that this will offset anthropogenically rising global mean temperatures by no more than  $0.3^{\circ}\text{C}$  in the year 2100, relative to what would happen if the solar output remained constant. Similarly Lean and

Rind [290] found that the solar decline would delay reaching a given temperature level by no more than a decade. Thus these predictions show that continued solar decline will do little to alleviate global warming. However, the decline will do much to end the debate about the fraction of global warming that can be attributed to solar change. For the first time since anthropogenic climate change became rapid, solar and anthropogenic trends are now in opposite directions. Non-robust fits (of low statistical significance, suffering from data snooping and selection effects, and which have not isolated internal variability) will fail sooner rather than later because of the change in solar behaviour. Thus the next few years will provide much better estimates of the solar contribution. Concerning the global temperature rise, there is every indication that these new estimates will, if anything, be smaller than previous estimates. On the other hand, there are indications that some regional climates are much more susceptible to solar changes than others. Understanding and differentiating “top down” and “bottom up” solar forcings will be key because these will have very different effects on the spatial patterns of the responses. Key advances in this area will be made in modelling, with higher resolution in time and space, better understanding of numerical noise and of the relationship of natural climate variability to that in the model behaviour, fewer parameterisations, better definition of the inputs forcings, and inclusion of more biological responses alongside the physical and chemical. However, these developments will take time and in many cases mitigation and adaptation decisions may have to be taken based on the most successful of the current model simulations.

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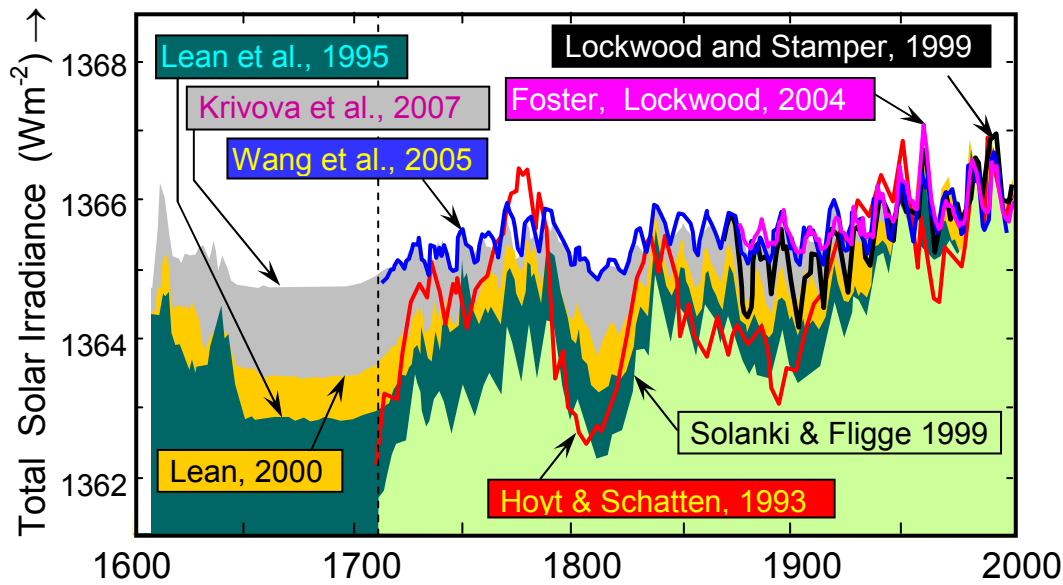
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**Figure 1.** Reconstructions of past variations in TSI using different solar proxies. The Hoyt and Schatten (1993) [291] estimates are based on solar cycle length,  $L$ . Solanki and Fligge (1999) [292] used the annual sunspot number,  $R$  (available back to 1713, the dotted line). Lean et al. (1995) [293] and Lean (2000a) [60] used a combination of the group sunspot number  $R_G$  (available back to 1611), and its 11-year running mean. In these early reconstructions, the amplitude of the slowly-varying component was derived by comparison of the modern-day Sun and Maunder-minimum Sun to distributions of the luminosity of cyclic and non-cyclic Sun-like stars. Lockwood and Stamper (1999) [44] used the observed correlation between the variations of TSI and the open solar flux on decadal timescales [45]. Wang et al. (2005) [51] used a solar magnetic flux transport model constrained to fit the observed open solar flux variation [42, 12]. Foster (2004) [294] and Lockwood (2004) [90] used Greenwich sunspot observations (available back to 1874). Krivova et al. (2007) [55] used  $R_G$  and the open solar flux variation.

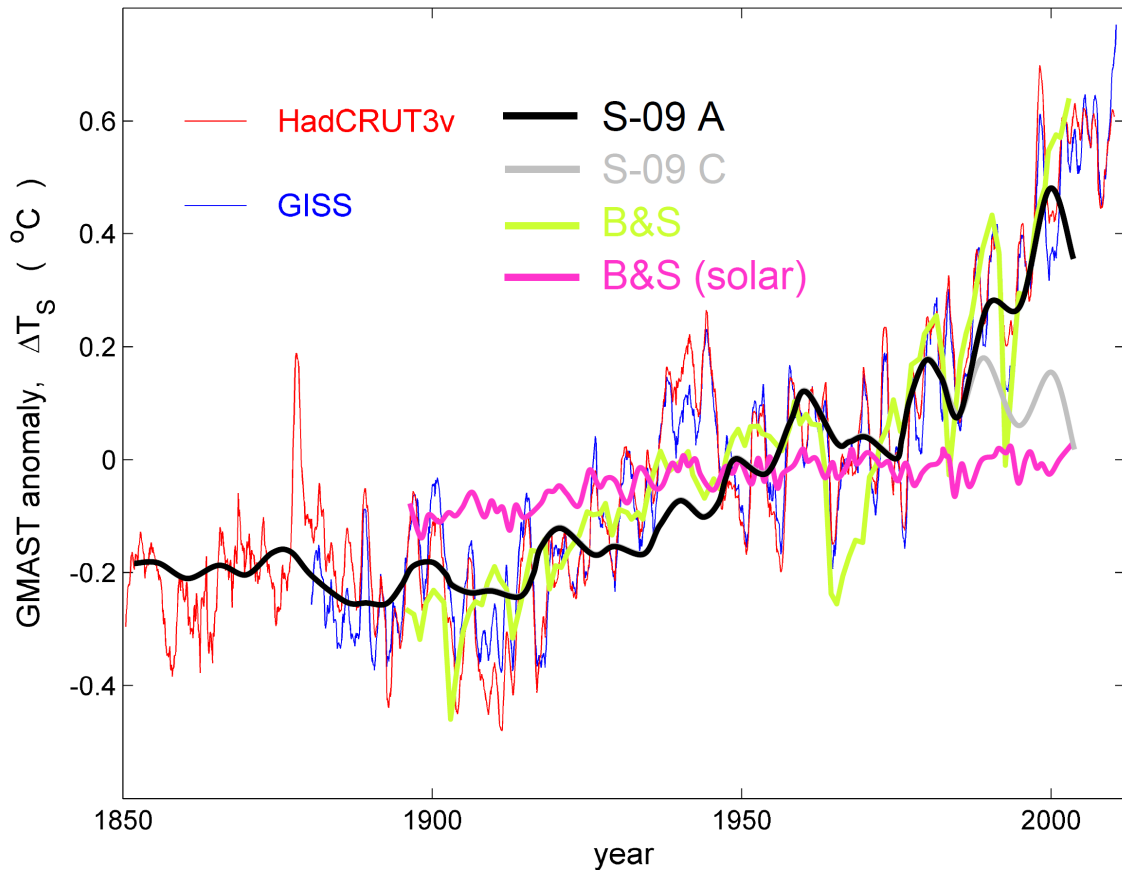


Figure 2. Estimates in the literature of the contributions of solar change to observed global temperature rise vary widely. The blue line shows the global mean surface temperature (GMAST) anomaly compiled from observations by NASA/GISS [284], the red line the equivalent HadCRUT3v compilation by UEA and the UK Meteorological Office [285]. (Both GISS and HadCRUT3v have here been re-normalised to a reference period of 1900-2000). The black and grey lines are estimates of the solar contribution from multivariate fits by Scafetta [141]: these employ only solar forcing and use as input the TSI reconstruction of Krivova et al. (2007) [55] (see figure 1), splined to different data composites of modern-day TSI measurements. The black curve (S-09A) is consistent with the ACRIM data composite whereas S-09C (in grey) is consistent with the PMOD data composite. The green line is the fit by Benestad and Schmidt [10] from full GCM modelling of all known climate forcings, the solar contribution to which is shown in mauve. The main issue is not so much the closeness of fit, it is the robustness and appropriateness of the procedures used, as discussed in the text. Only robust procedures have predictive power which is the key test of all science. Note the effect of extreme sensitivity of the solar-only multivariate fit to small features and hence the potential for “data snooping”: the fit to the data after 1990 of the S-09A curve relies on the ACRIM composite which differs from the PMOD by what many believe to be a single (and rather small) erroneous calibration skip during the so-called “ACRIM gap” (see Lockwood and Fröhlich, 2007 [11]). Using the PMOD composite (S-09C), the limitations of the multivariate fit begin to become apparent after around 1985 (with the oppositely-directed solar and GMAST trends noted by Lockwood and Fröhlich [11]). The fits of Scafetta [141] continue up to 2002: the subsequent exceptionally low solar minimum reveals that even curve S-09A will have a downward trend after 1997 and it too fails to reproduce the most recent GMAST data [61].

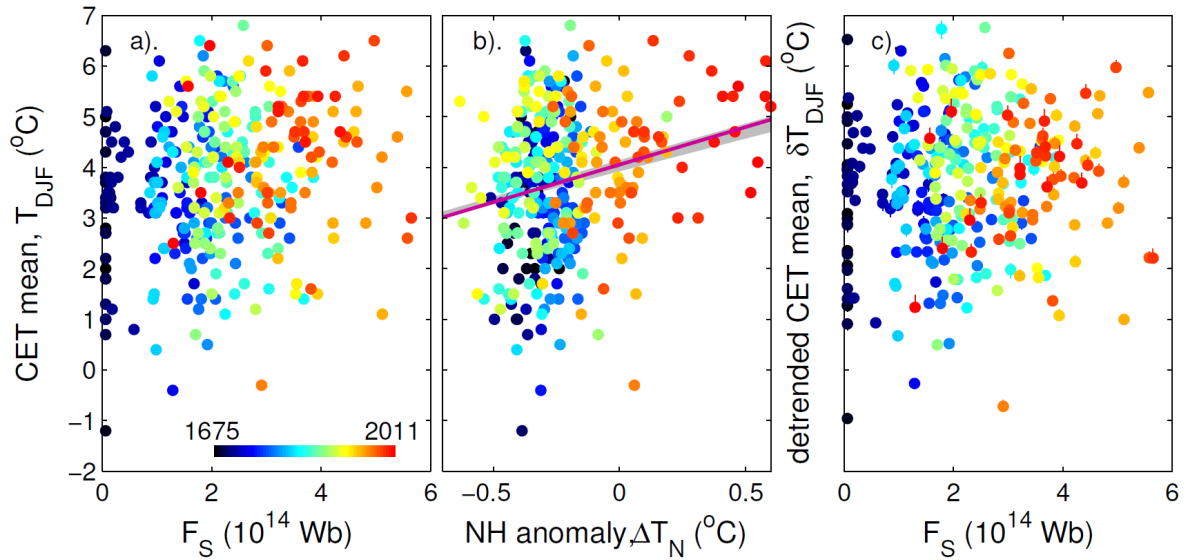


Figure 3. Scatter plots of mean winter Central England Temperature (CET),  $T_{\text{DJF}}$ , as a function of (a) open solar flux,  $F_S$  and (b) the hemispheric mean surface temperature anomaly  $\Delta T_N$  (extended to before 1850 using the median of a basket of proxy reconstructions). Points are coloured according to the date using the scale shown in (a). The line in (b) is the ordinary least squares linear regression fit and the grey area bounds the uncertainty range set by the use of proxy reconstructions for  $\Delta T_N$  prior to 1850. The correlation coefficients for (a) and (b) are low at 0.23 and 0.25 (significant at the 99.1% and 99.6% levels). In the case of (b) this demonstrates the great variability of a regional/seasonal temperature around a global-scale mean. (c) is the same as (a), for the detrended winter CET data  $\delta T_{\text{DJF}}$ , where the detrending allows for the hemispheric change  $\Delta T_N$  and uses the regression line shown in (b). Part (c) shows that, even after allowing for the hemispheric trend, most of the coldest winters in central England occur at low solar activity, as quantified by  $F_S$ . Lockwood et al. [192] test this against the null hypothesis that  $F_S$  has no effect on winter CET values and show that this tendency is statistically significant at around the 95% level.