

Solar influence on global and regional climates

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Published Version

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(2012) Solar influence on global and regional climates.
Surveys in Geophysics, 33 (3-4). pp. 503-534. ISSN 1573-
0956 doi: 10.1007/s10712-012-9181-3 Available at
<https://centaur.reading.ac.uk/28365/>

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Published version at: <http://dx.doi.org/10.1007/s10712-012-9181-3>

To link to this article DOI: <http://dx.doi.org/10.1007/s10712-012-9181-3>

Publisher: Springer

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Mike Lockwood

Surveys in Geophysics

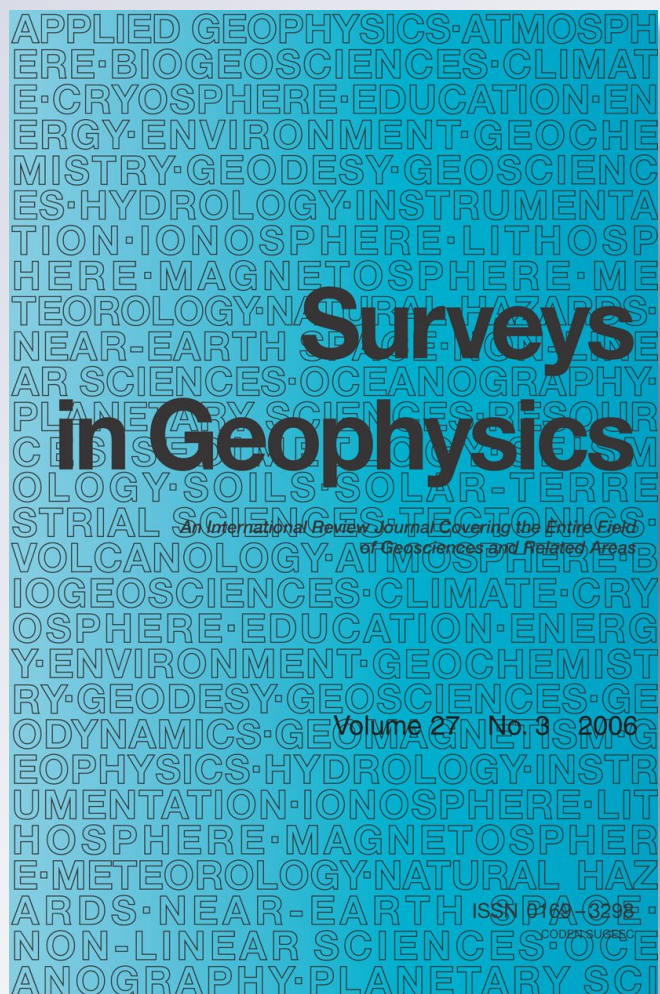
An International Review Journal

Covering the Entire Field of Geosciences
and Related Areas

ISSN 0169-3298

Surv Geophys

DOI 10.1007/s10712-012-9181-3



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Solar Influence on Global and Regional Climates

Mike Lockwood

Received: 5 October 2011 / Accepted: 1 February 2012

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Abstract The literature relevant to how solar variability influences climate is vast—but much has been based on inadequate statistics and non-robust procedures. The common pitfalls are outlined in this review. The best estimates of the solar influence on the global mean air surface temperature show relatively small effects, compared with the response to anthropogenic changes (and broadly in line with their respective radiative forcings). However, the situation is more interesting when one looks at regional and season variations around the global means. In particular, recent research indicates that winters in Eurasia may have some dependence on the Sun, with more cold winters occurring when the solar activity is low. Advances in modelling “top-down” mechanisms, whereby stratospheric changes influence the underlying troposphere, offer promising explanations of the observed phenomena. In contrast, the suggested modulation of low-altitude clouds by galactic cosmic rays provides an increasingly inadequate explanation of observations.

Keywords Solar variability · Global climate change · Regional climate change · Blocking events · Maunder minimum · Total solar irradiance · UV spectral irradiance · Galactic cosmic rays · Open solar flux · Stratosphere–troposphere coupling

1 Introduction

Solar electromagnetic radiation powers Earth’s climate system and, consequently, it is often naïvely thought that changes in this solar output must be responsible for changes in Earth’s climate. However, the huge thermal time constant of the outer part of the Sun limits the variability in its surface temperature, and hence its total power output, which is

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dominated by visible and infrared emissions from the solar surface (the photosphere) (see review by Lockwood 2004). As a result, changes in solar power output on decadal, centennial and millennial timescales are limited to small changes in effective surface temperature (associated with magnetic fields) and potential, although as yet undetected, solar radius variations (see reviews by Solanki et al. 2005; Lockwood 2010). Larger percentage variations are seen in solar UV emissions (Lean et al. 1997) which arise from the lower solar atmosphere (the chromosphere) (Loukitcheva et al. 2009) and which influence the stratosphere in Earth's middle atmosphere between about 10 and 50 km (see review by Gray et al. 2010). Even more variable are solar X-rays and extreme ultraviolet (EUV) emissions that originate in the upper solar atmosphere (the corona) and dominate the behaviour of Earth's uppermost atmosphere (the thermosphere, above about 90-km altitude) (Le et al. 2011). In addition to these electromagnetic outputs, the Sun modulates energetic charged particle fluxes incident upon the Earth. Solar energetic particles (SEP) are emitted by solar flares and from the shock fronts that form ahead of super-sonic (and super-Alfvénic) ejections of material from the corona (Schwenn 2006). SEPs are incident upon Earth's atmosphere in polar regions where they enhance the destruction of stratospheric ozone (Jackman et al. 2006; 2008). 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 shielding solar magnetic field into interplanetary space results in the Sun modulating the number of GCRs reaching Earth (see, for example, review by Potgieter 2008). Air ions generated by GCRs enable Earth's global electric (thunderstorm) circuit (Rycroft et al. 2008), and it has been proposed that they also modulate the formation of low-altitude clouds (Svensmark and Friis-Christensen 1997). The Sun also emits a continuous stream of low-energy charged particles called the solar wind (e.g., Marsch 2006). A small fraction of the solar wind energy incident on Earth is extracted by the geomagnetic field and deposited in the thermosphere at high latitudes (Cowley 1991; Thayer and Semeter 2004). This deposition changes the behaviour of the thermosphere globally (e.g., Fuller-Rowell et al. 2007), but this is an extremely low-density atmospheric layer, and there are no robust observations, nor any confirmed theory, that suggests these thermospheric variations are transmitted through the middle atmosphere to the troposphere below.

Both electromagnetic and charged particle emissions from the Sun are known to vary over the decadal-scale solar magnetic activity cycle, as do GCR fluxes (see review by Lockwood 2004). But any effects on climate are much more significant for any variations over longer timescales. This review discusses and evaluates potential effects on Earth's climate of variations in these solar emissions. "Top-down" mechanisms involve solar UV irradiance (or perhaps energetic particles) modulating stratospheric temperatures and winds which, in turn, may influence the underlying troposphere where Earth's climate and weather reside. These contrast with "bottom-up" effects in which the total solar irradiance (TSI, dominated by the visible and near-IR) variations cause surface temperature changes and upward coupling to the troposphere.

2 Historical Perspective

It is interesting to ponder what the author citation h-index of the astronomer Sir Frederick William Herschel (1738–1822) would be. Certainly, his 1801 paper (Herschel 1801), in which he speculated on a connection between sunspots and regional climate (for which he used the market price of wheat as a quantifiable proxy), 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. Indeed, Herschel himself notes limitations to his speculation that many subsequent studies of solar influence on climate have failed to adequately consider. Common pitfalls include the following:

1. The potential for selection effects mean that one must ask, “Would a reported correlation coefficient be as high if an equivalent data set were substituted?” (For example, in Herschel’s case, was the behaviour of the price of barley similar to that of wheat? If not, why not?) Selection effects can often arise (unintentionally or otherwise) from the use of restricted data intervals and/or the choice of which parameters to compare. Selection effects are the major reason why the specific issues (2)–(5) below are particular problems.
2. Sunspots are only indirectly related to the solar outputs that are relevant to climate. (Herschel attempts to build an argument about enhanced emission from sunspots which we now know to be incorrect).
3. The lack of suitable measurements of Earth’s global climate on long timescales leads to the use of indirect proxies (Herschel used the price of wheat), and there are many other factors, unrelated to climate, which can influence such proxies.
4. The climate data used have often been for a limited season (in Herschel’s case, this is effectively the growing season of wheat) which may not adequately reflect changes in the annual mean data.
5. The climate data used have often been regional, and not global (Herschel used the price of wheat in the UK and not on the global market); regional climates show large variations around the global mean.
6. The data sets are not homogeneous, and measurement series often contain instrumental drifts and discrete jumps. (Herschel notes this in respect of the sunspot data available to him).
7. Correlations can occur by chance, and the probability of this happening must be evaluated, allowing for the persistence in the data time series and the number of free parameters. Hence, the significance of any correlation must be determined (by comparison with a suitable noise model). In addition, tests are needed to prevent “data snooping”, that is, exploiting a feature in the data that turns out to be a statistical or instrumental artefact. To ensure that wrong conclusions are not drawn from statistical coincidences, clear null hypotheses must be formulated and proper statistical tests performed (Yiou et al. 2010; Legras et al. 2010; Love et al. 2011).
8. Solar variability effects are convolved with other influences on climate (volcanoes, aerosols, land-use changes and greenhouse gases). For example, Herschel neglected the effects of volcanic eruptions that occurred during the interval that he studied.
9. The effects of internal climate variability have often been overlooked or underestimated. There are internal oscillations (particularly associated with the oceans on decadal timescales), and a common error is to “overfit” the data, thereby wrongly ascribing variations to an external solar origin. 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 or a harmonic combination of various multiyear cycles (Drijfhout et al. 1999; Moore et al. 2006).

10. Even a statistically significant correlation or detected periodic signal does not establish causality, neither do lags nor phase relationships for coupled systems involving stationary oscillations.
11. Lastly one must ask, “Is there a realistic mechanism or series of mechanisms that could have given rise to the correlation?” (Herschel’s proposal invoked a chain of interactions, encompassing 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 modest, by modern standards, at 14; however, his most influential paper (Eddy 1976) has been cited 954 times (citation analysis using Web of Science, October 2011). This famous paper particularly focussed on European temperature records and the period of extremely low solar activity (when almost no sunspots were observed) known as the Maunder Minimum (circa 1645–1715). This topic is discussed further in Sect. 6 of the present review.

The academic reputation of the field of Sun-climate relations is poor because many 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 putative solar effects as an excuse for inaction on anthropogenic warming. In particular, figures and statistics with known errors, limitations and inaccuracies are repeatedly reproduced on the Internet and in the media (as discussed, for example, by Damon and Laut 2004), and publications are reported in a massively selective manner. 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 Jager (2008), Gray et al. (2010) and Lockwood (2004, 2010, 2012).

3 Solar Variability and Global Climate Response Timescales

Solar outputs reaching Earth undergo periodic variations over a range of timescales. These include the 27-day variation due to solar rotation, annual variations due to the ellipticity of Earth’s orbit, the decadal-scale solar magnetic (sunspot) cycle 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 and, in reality, the role of the oceans means that a spectrum of response times is to be expected. Knutti et al. (2008) 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 (Hansen et al. 1985), but an effective timescale of 5–20 years has been predicted by Dickinson and Schaudt (1998). The climate response modelling of Rind et al. (1999) and analysis of pre-industrial data by Waple et al. (2002) and Weber (2005) yield response times of up to 10 years. Held et al. (2010) use both an

energy balance model (EBM) and a coupled atmosphere–ocean General Circulation Model (GCM) to investigate the implications of two time constants—a rapid response on a timescale of about 5 years and a slower “recalcitrant” response on a timescale of several hundred years. They show that the rapid response is currently dominant, but the longer timescale would become important if greenhouse gas emissions were to be stabilised. All these time constants mean 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 are damped is still a matter of debate. Some studies find that the GMAST response to recent solar cycles may be 0.1 K or larger (White et al. 1997; Douglass and Clader 2002; Camp and Tung 2007; Lean and Rind 2009). However, some of the apparent responses found in regression studies of empirical data may not, in reality, be due to real associations and causality. This is because of one or more of the potential pitfalls discussed in Sect. 1 (such as overfitting so that internal variability is ascribed to external forcing, degeneracy between different forcing factors, understated uncertainties in regression coefficients and in the response to forcing). That this can be the case has been demonstrated clearly using model simulations (Ingram 2006; Benestad and Schmidt 2009; Stott and Jones 2009).

4 Global Climate Response

This section considers the multidecadal trends (e.g., Brönnimann et al. 2007) rather than the great many reports of putative solar-cycle variations observed in the troposphere (e.g., Camp and Tung 2007; Coughlin 2004; Gleisner et al. 2005). One reason why the global climate response timescales have recently become a consideration is the realisation that, since 1985, all the relevant solar outputs have been changing in the opposite direction to those needed to explain the rise in GMAST (Lockwood and Fröhlich 2007). Thus, for solar activity to contribute to recent warming, there must be a long GMAST response time constant. For example, Scafetta and West (2007) and Scafetta (2009) have employed multiregression fits of GMAST data that involve a short-timescale response (to allow the observed weak solar-cycle variations to be reproduced) plus a long-time-constant response. This is different from the Held et al. (2010) study discussed in the last section because the longer time-constant response dominates. Multiple regression analysis of this kind has been used several times previously (e.g., Santer et al. 2001; Lean 2006; Lockwood 2008), but can be misleading if inter-correlations exist between the data series that are input into the study or if genuine factors are omitted. In addition, naïve regression analyses may also be misleading due to convoluted nonlinear response associated with feedback processes, the use of non-optimal regression techniques or the presence of internal system variability (Benestad and Schmidt 2009). In general, all forcings need to be considered for the attribution of climate change and the effects of degeneracy between solar and volcanic forcings over recent centuries are a particular concern because major eruptions tend to occur at an average rate near one per solar cycle and even have a periodicity close to the 88 years of the solar Gliessberg cycle (Qu et al. 2011) and because bursts of volcanic eruptions and a lack of eruptions can cause long-term cooling and warming, respectively. Hence, such analyses need to be interpreted with a great deal of caution and judgement with regard to the choice of input variables and as to whether the conclusions are sensible. There are other potential pitfalls. For example, there is a strong possibility that the fits of Scafetta and West (2007) and Scafetta (2009) suffer from a “data snooping” problem as they are strongly dependent on a feature in the TSI data composite that they employed

which has been argued to be a calibration error (Lockwood and Fröhlich 2008). Benestad and Schmidt (2009) present a full critique of the robustness of the fits; however, here, we simply look whether their implications are sensible or not. Scafetta and West (2007) and Scafetta (2009) find that solar change contributed over 60% of the temperature rise (i.e. more than 0.5°C) since pre-industrial times, and it is instructive to ask, “How does this agree with the changes in the various radiative forcings?”

Our best estimates of ΔS , the change in the average TSI between the Maunder Minimum and recent decades, have decreased over recent years (see review by Gray et al. 2010). Initially, ΔS was estimated from surveys of “Sun-like” stars (Baliunas and Jastrow 1990; Zhang et al. 1994), but results of more extensive surveys did not confirm the key result, nor did they support its application to our Sun (Hall and Lockwood 2004; Giampapa 2004). Subsequently, smaller ΔS estimates have been derived using sunspot numbers and the open magnetic flux of the Sun, which can be derived from historic geomagnetic data (see review by Lockwood 2004). These studies find ΔS to be comparable to the amplitude of recent solar cycles (i.e. 0.1%) (see Gray et al. 2010 and references therein) and such estimates are currently employed, for example, in the 2007 IPCC report. The more recent estimates of the change in TSI equate to a change in radiative forcing of $\Delta f_S = \Delta S(1 - A)/4$. Earth’s albedo, A , is particularly poorly known (Charlson et al. 2005; Pallé et al. 2009) but using a best estimate of $A \approx 0.3$ (Loeb et al. 2009) gives $\Delta f_S \approx 0.24 \text{ W m}^{-2}$. Two recent papers disagree with this consensus value, but do not agree on even the sign of the adjustment needed. Schrijver et al. (2011) argue that the consensus Δf_S is overestimated, whereas Shapiro et al. (2011) suggest it should be increased by a factor of at least 4, to a value near 1 W m^{-2} . Where these two papers differ is in their treatment of the “quiet” Sun between groups of sunspots (“active regions”), and Lockwood (2011b) argues that neither makes a compelling case for an adjustment to the consensus value at the present time.

From flask measurements and ice-core data, we can compute the radiative forcing caused by the observed rises in well-mixed trace (i.e. excluding water vapour) greenhouse gas (GHG) abundances over the same interval (Forster et al. 2007). The abundance of carbon dioxide has risen from 280 ppmv in pre-industrial times to 362.5 ppmv in 2000, which corresponds to $+1.56 \text{ W m}^{-2}$. The corresponding radiative forcing contributions for other trace GHG are the following: $+0.47 \text{ W m}^{-2}$ for CH_4 , $+0.28 \text{ W m}^{-2}$ for CFCs/HCFs/halons, and $+0.14 \text{ W m}^{-2}$ for NO_x . This gives a total radiative forcing by trace GHG of $\Delta f_G = 2.45 \text{ W m}^{-2}$, which is ten times larger than our best estimate of the solar forcing Δf_S . Note that this estimate of Δf_G is known with considerable certainty from the analysis of absorption spectra. Persistent reports, mainly in the media and on the Internet, that absorption lines are saturated (such that adding more GHG does not cause any radiative forcing change) ignore a huge body of research that extends back to the 1950s and are demonstrably false when one considers the whole IR spectrum (Shine et al. 1995). Energy balance shows that, for steady state, the observed GMAST rise since the Maunder Minimum would correspond to a total forcing, including feedbacks (which include water vapour effects), of $\Delta f = 5.15 \text{ W m}^{-2}$ (Lockwood 2010). The uncertainty on this estimate is of order $\pm 0.5 \text{ W m}^{-2}$, dominated by the uncertainty in the pre-industrial temperature, with a small contribution from the uncertainty in the power stored in the deep oceans.

Thus, to explain the warming with GHG forcing alone requires feedbacks to account for a forcing of $\Delta f - \Delta f_G \approx 2.67 \text{ W m}^{-2}$, that is, a (positive) feedback factor of $a_G = \Delta f / \Delta f_G \approx 2.1$. To explain 60% of the warming with solar forcing requires a feedback factor of $a_S = 0.6 \times \Delta f / \Delta f_S \approx 12.8$ and a feedback factor of $a_G = 0.4 \times \Delta f / \Delta f_G \approx 0.8$ for greenhouse gases. In other words, the fit of Scafetta (2009) requires a huge positive

feedback for the solar forcing but a negative feedback for the greenhouse forcing. Thus, this fit raises much bigger problems than it solves and makes no sense physically.

But not all multiple regression fits suffer from such problems. Figures 1 and 2 show the results of a fit to recent GMAST data (1954–2011) using the method of Lockwood (2008). Like that by Scafetta (2009), this fit allows for the climate response times (in this case by passing each input variation through a filter with a response time constant which is iterated in the fit); however, it differs in that it uses different input variations. In fact, the best-fit response time for each input was found to be near 1 year and constraining all inputs to the same response time generated an almost identical fit with fewer free parameters. The galactic cosmic ray flux is used to quantify the solar input as the data sequence is longer and more stably calibrated than the available TSI record, and there is a good (anti)correlation between the two (see Fig. 3). In addition, the El-Niño Southern oscillation (ENSO) can be regarded as an energy input into the surface layer that is quantified by the N3.4 index (based on the sea surface temperature in the equatorial Pacific). Figure 1 shows excellent agreement between observed and fitted variations for 1953–2011, and Fig. 2 shows that the dominant component of the fitted variation is anthropogenic and the solar contribution is small (and actually downward on average for this interval). The fit residuals shown in the bottom panel of Fig. 1 are attributed to internal variability. For this fit, we find that the contributions to the GMAST rise are in almost the same ratios as the radiative forcing changes over the interval. This means that the feedback factors required are approximately the same for all forcings (so $a_S \approx a_G \approx 2$). This multiple regression fit is subject to the same set of caveats as all others (i.e. selection effects of the choice of inputs, inter-correlations between inputs, nonlinear responses and overfitting of internal variability). However, it does demonstrate that a simple combination of known inputs can explain the observed GMAST variation (incidentally including any recent apparent

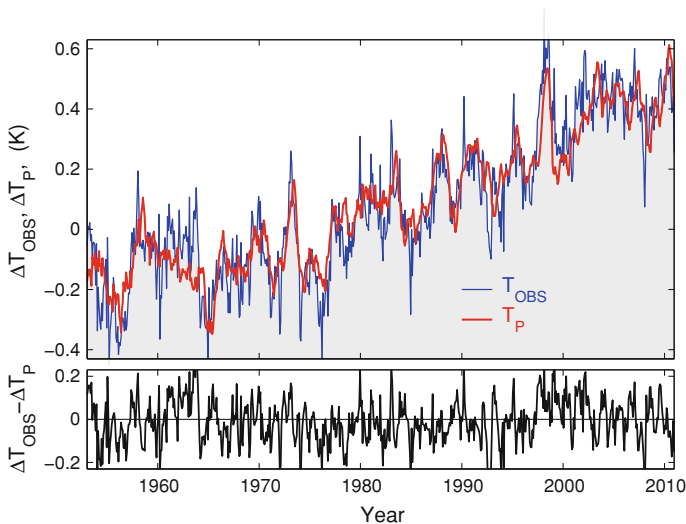


Fig. 1 Top observed (T_{OBS} , blue) and fitted (T_{P} , red) global mean air surface temperature (GMAST) variations for 1953–2011. The monthly observations are the HADCrut3v database (Brohan et al. 2006), and the fit is carried out using the procedure of Lockwood (2008) that allows for climate response times. Bottom the variation of the fit residuals ($T_{\text{OBS}} - T_{\text{P}}$)

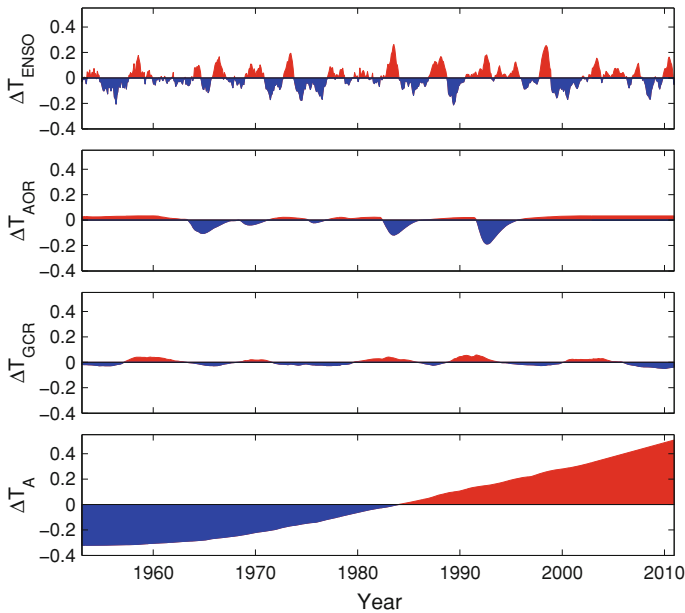


Fig. 2 The contributions to the fitted variation T_P in Fig. 1. Each panel uses the same y-axis scale to allow comparison (above/below average values are shown in red/blue), and each input parameter has been smoothed/lagged using its best-fit response time parameter. Fits are achieved with the Nelder-Mead search method. From top to bottom ENSO (input quantified by the N3.4 ENSO index), volcanoes (quantified by the global mean atmospheric optical depth, AOD); solar (quantified by GCR fluxes observed by neutron monitors), and anthropogenic (quantified by the GISS model E forcings for well-mixed trace greenhouse gases, land-use changes and man-made tropospheric aerosols). For comparison, the RMS fit residual $\langle (T_{OBS} - T_P)^2 \rangle^{1/2}$ is 0.10°C (see Fig. 1b)

plateau) very well indeed and in a way that is consistent with the known radiative forcing changes. Notice that this analysis has not made use of any numerical climate model results.

To be fully rigorous, one has to move to “detection–attribution” studies, in which the effect of varying an input to a general circulation ocean–atmosphere climate model (GCM) must be detected above the internal variability of the climate system, as modelled by the GCM. Results do depend on which GCM is used, although there is also now considerable degree of agreement between the different models and, indeed, with the results shown in Fig. 2. A comprehensive review of detection–attribution methods and results is given as part of the IPCC 4th Fourth Assessment Report (Hegerl et al. 2007). Some key conclusions in this context are that (a) the combined effects of solar and volcanic forcings has resulted in a net cooling over recent decades; (b) models simulate much less warming over the 20th century in response to solar forcing alone than for greenhouse gas forcing alone (Cubasch et al. 1997; Broccoli et al. 2003; Meehl et al. 2003, 2004; Tett et al. 1999, 2002); (c) in combination, the greenhouse effect on surface temperatures is dominant over the solar effect (Stone et al. 2007a, b), although there is some debate about the precise contributions (Stott et al. 2003); and (d) the changes in the altitude profiles also reveal a dominant greenhouse gas effect (Jones et al. 2003).

Coupled ocean–atmosphere climate models (GCMs) have developed rapidly over the last 2 decades, and this has altered the details of the attribution of solar effects. In general, the derived solar-induced changes in GMAST have been small, even for the larger drifts in solar

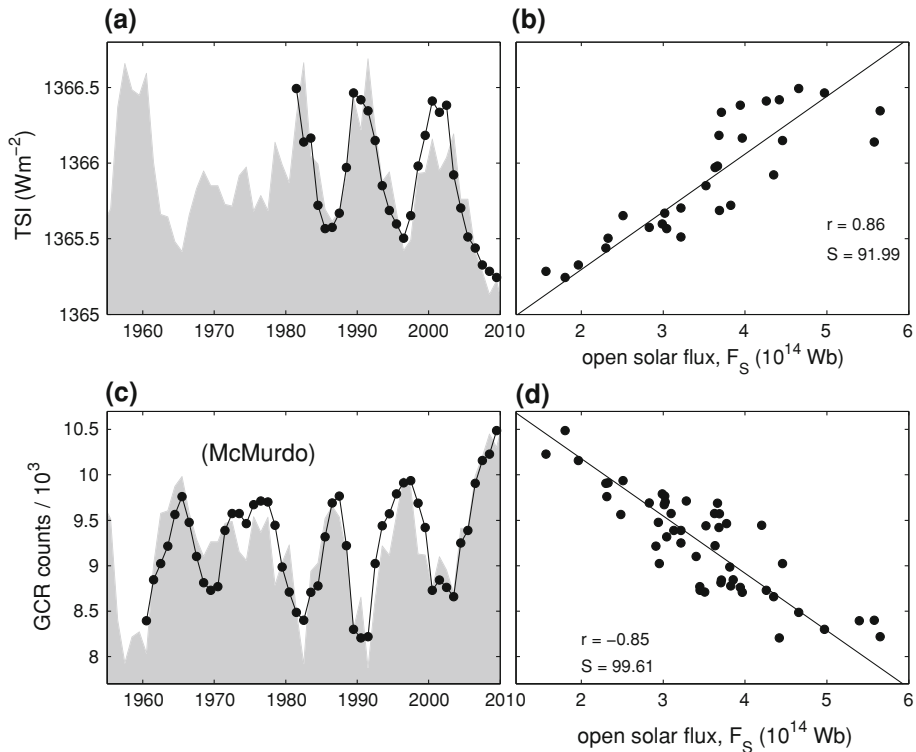


Fig. 3 The relationships between annual means of the open solar magnetic flux, F_S , and (top) the total solar irradiance, TSI (here quantified using the PMOD composite: Fröhlich 2009) and (bottom) the galactic cosmic ray (GCR) flux (here quantified using the counts detected by the McMurdo neutron monitor in Antarctica). The left-hand panels show the time series, and in both cases, the best-fit linear regression of F_S is shown by the area shaded grey. The right-hand plots show the scatter plots with the best-fit linear regression line. The correlation coefficients r and their significances S (compared against the AR (1) noise model) are given (from Lockwood et al. 2010a)

radiative forcing predicted by the early TSI reconstructions (Wigley and Raper 1990). Full comparisons are not possible because the TSI reconstructions have evolved at the same time as the complexity and resolution of the models has increased. As expected, weaker solar effects are found for the smaller ΔS inherent in the more recent TSI reconstructions (compare, for example, Wigley and Raper 1990 with Zorita et al. 2004 and/or Stendel et al. 2006). Examples of recent GCM experiments giving a relatively large “bottom-up” solar effect have been presented by Rind et al. (2008). The input solar forcing change between the Maunder Minimum and the present day used was 0.68 W m^{-2} (more than twice the consensus Δf_S discussed earlier) with an input of 1.9 W m^{-2} from total anthropogenic forcing, including Δf_G . This solar forcing is well outside the range of $0.06\text{--}0.30 \text{ W m}^{-2}$ quoted by Hegerl et al. (2007), and the Rind et al. experiments generally gave a relatively large solar contribution (near 30%) to the total GMAST rise (the total GMAST rise also being larger than is observed). The tropical response, in particular, was much greater than observed, consistent with an excessive TSI change input to the experiments.

Rind et al. (2008) 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, driven by a greater equator to pole temperature gradient, were found to extend down into the troposphere and in some experiments the jet stream weakened and moved polewards. 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. (2003, 2008, 2009) includes ocean–atmosphere coupling and with the stratosphere and suggests potential resonant connections between UV solar forcing and the ENSO oscillation, as also discussed by Emile-Geay et al. (2007) and White and Liu (2008a, b).

5 Paleoclimate Studies and Solar Proxies

For paleoclimate studies, it is important to bear in mind all the potential pitfalls listed in Sect. 2 of this review. However, there is an additional problem to consider with the data sequences, which is not a factor for direct observations, namely dating (van Geel and Mook 1989). Because record dates are uncertain, “wiggle matching” is often used (Kilian et al. 1995; Blaauw et al. 2003). Even if this is done with great care, such that the date of any one data point is not changed by more than the accurately computed dating uncertainty, there is inevitably a selection effect at work. This is because the adjustments are always made to improve correlations and not to degrade them. For this reason, there is a marked tendency for some correlations to degrade as the accuracy of the dating is improved.

An additional factor to bear in mind is that solar variability in paleoclimate studies is quantified using the abundance of cosmogenic isotopes, usually ^{14}C and ^{10}Be , found in terrestrial reservoirs. ^{10}Be is a spallation product of galactic cosmic rays hitting atmospheric O, N and Ar atoms; ^{14}C is produced by thermal neutrons, generated by cosmic rays, interacting with N. About two-thirds of the ^{10}Be are 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. The deposition into any one reservoir is influenced, to some extent, by climate conditions (e.g., Vonmoos et al. 2006; Field et al. 2006; Aldahan et al. 2008; Heikkilä et al. 2008). On the other hand, the ^{14}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}C and ice sheets in the case of ^{10}Be) are vastly different for these two major cosmogenic isotopes. We can discount the possibility that matching variations in the isotope abundances in their respective reservoirs are similarly influenced by climate during their terrestrial life history, because the transport and deposition of each are so different. After allowance has been made to both series for the effect of geomagnetic field changes, the correlation between decadal means over the past millennium of the abundance of ^{10}Be and the production rate of ^{14}C is 0.81 (with the ^{10}Be leading, as expected, by about 10 years and a significance level exceeding 99%) (Bard et al. 1997). This correlation also applies to the more recent data. For example, the solar modulation potentials (see review by Usoskin 2008) for 1600–1960 derived from ^{10}Be and ^{14}C (as presented by Lockwood et al. 2011b) yield a correlation coefficient of 0.83. The ^{14}C data are the means from tree cores in many parts of the world, but the ^{10}Be data are from two just ice cores, one from Antarctica and another from Greenland. However, the

influence of regional deposition variations on the ^{10}Be abundance is known to be small because the correlation with ^{14}C is high. Thus, it is concluded that the correlations that are found for both isotopes are associated with the one common denominator in their production, namely the incident cosmic ray flux.

The abundances of these isotopes are routinely used in paleoclimate studies as a proxy indicator of solar irradiance (Bard et al. 2000). Lockwood (2006) showed that the relationship between production of the ^{10}Be cosmogenic isotope and TSI is monotonic but may not be linear, depending on the effect of unknowns in the long-term quiet Sun irradiance behaviour. The flux of the GCRs that generate the cosmogenic isotopes is modulated by three following influences (Beer 2006): (1) the interstellar flux of GCRs incident on the heliosphere; (2) the shielding by the heliosphere; and (3) the shielding by the geomagnetic field. The spatial distribution of the interstellar GCR fluxes in our galaxy is on a sufficiently large scale compared to distances moved by our solar system through the galaxy, which means that we can neglect variations on timescales of Myr and smaller. The geomagnetic field shield has varied on timescales of 10 kyr. This variation has, in the main, been gradual during the Holocene, 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. To allow studies of the remaining effect, solar variability, studies have corrected the cosmogenic isotope record to allow for the secular geomagnetic variations (e.g., Steinhilber et al. 2008, 2009).

Figure 3 investigates the relationship of GCRs and total solar radiance in modern data. The magnetic flux that leaves the top of solar atmosphere (the “open solar flux”, F_S) is the source of magnetic field in the heliosphere, and it is irregularities in this heliospheric field which scatter GCRs and shield them away from Earth. As a result, there is a good inverse relationship between F_S and the flux of GCRs (Rouillard and Lockwood 2004), which is demonstrated by the lower panel in Fig. 3. The upper part of Fig. 3 looks at the relationship between F_S and the total solar irradiance, TSI. This relationship is more indirect than that with GCR flux in that F_S is a small, and potentially variable, fraction of the field that threads the photosphere and thereby modulates the visible/IR emission of Sun (via the darkening effects of sunspots and the brightening effect of smaller magnetic flux tubes called faculae: Solanki et al. 2005; Wenzler et al. 2006). F_S correlates well with TSI over the solar cycle (Lockwood and Stamper 1999; Lockwood 2002), and recent studies indicate that observed TSI does also reflect some of the longer-term drift in F_S (Fröhlich 2009). Modelling of the long-term variations (since the Maunder Minimum) in F_S and TSI (Vieira et al. 2011; Wang et al. 2005) provides support for the broad correlation between the two.

However, it should be noted that GCR fluxes and cosmogenic isotopes are not just indicators of TSI. Much of the magnetic field that modulates TSI as it passes through the photosphere also modulates solar UV emissions as it passes through the chromosphere. The UV part of the solar spectrum is much more variable than TSI and modulates ozone abundance, temperatures and winds in Earth’s stratosphere (see review by Gray et al. 2010). Composites of observed UV spectral solar irradiance (SSI) had shown little variation in the spectral shape, such that at all wavelengths they exhibit similar temporal variations to TSI (Lean et al. 1997), and this has been reflected in centennial reconstructions of SSI (Lean 2000; Krivova et al. 2009). However, recent observations of the descent into the current “unusual” (for the space age) solar minimum (Lockwood 2010) cast doubt on this as they show more variability in the UV and considerable change in spectral shape (Harder et al. 2009). This implies that at the wavelengths responsible for stratospheric modulation, centennial variation may be greater than previously thought. These new data are from the SORCE satellite and are supported by observed changes in ozone abundance

(Haigh et al. 2010). If confirmed, this is a considerable change in our understanding in spectral irradiance variability as it means that TSI change is predominantly caused by UV changes and that the changes at IR/Visible wavelengths are actually in the opposite direction to those in the UV and TSI. This contrasts sharply with previous models in which the waveform of temporal variations was taken to be similar at all wavelengths (Lean 2000; DeLand and Cebula 2008; Krivova et al. 2009). At present, there is no consensus as to how these new results should be used and incorporated into models. Schmidt et al. (2011) argue that as the SORCE data come from one instrument (the Spectral Irradiance Monitor, SIM) and are for a limited period (the declining phase of cycle 23) it is premature to act upon them. However, it should be noted that the prior data were also limited in temporal and wavelength coverage, and there are doubts about their accuracy at some wavelengths (DeLand and Cebula 2008). Unfortunately, the wavelength band in which inter-calibrations can be carried out is very limited (Lockwood 2011a), and a homogenised data sequence of spectral irradiance will have to rely heavily on modelling (Krivova et al. 2011), at least until new space-based instrumentation can be commissioned. At the time of writing, the latest data from SIM (<http://lasp.colorado.edu/sorce/data/>) during the rising phase of solar cycle 24 show a reverse of the changes seen in the declining phase of cycle 23, despite the low activity levels of the new cycle (Owens et al. 2011). This implies that long-term calibration drift is not the cause of the radically different trends in the SIM data. SRPM (Solar Radiation Physical Modelling) analysis combines information of the features in the solar chromosphere with physics-based solar atmospheric spectral models to compute the emergent intensity spectrum, and initial work suggests that it is able to reproduce trends observed by SIM and that solar active regions are not the only cause of the observed variations (i.e. changes in the quiet-Sun internetwork/network radiance are involved).

The trends suggest that the open solar flux F_S may also be related to long-term variations in solar UV emissions (Lockwood et al. 2010b), and hence cosmogenic isotopes may be a proxy indicator of UV effects. In addition, cosmogenic isotopes would, of course, be a direct indicator of any cloud modulation by GCRs, where such a mechanism to be active, and F_S is highly anti-correlated with GCR fluxes (Rouillard and Lockwood 2004). Recent results relating to the GCR-cloud mechanism are discussed in Sect. 8.

This review focuses on recent work that uses the open solar flux F_S to quantify solar activity. From the discussion above, F_S can reveal effects associated with changes in TSI, UV spectral irradiance, GCRs or even SEP fluxes. In addition, F_S is highly correlated with mean geomagnetic activity levels (indeed it is reconstructed before the start of space observations using geomagnetic data, Lockwood et al. 2009; Lockwood and Owens 2011) and so is likely to be linked to reports of climate effects associated with geomagnetic activity (e.g., Seppälä et al. 2009; Bochníček and Hejda 2005; Thejll et al. 2003).

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 carried out in many parts of the world and employ a huge variety of paleoclimate proxies. They will not be discussed here, and the reader is referred to the recent review by Lockwood (2012). The most interesting of these studies employed terrestrial data that are indicators of more than just local climate and/or where matching signals are seen at geographically separated sites. Some studies have used proxy data from very large numbers of sites to reconstruct temperature maps, cross-calibrating with early observational data (e.g., Mann et al. 2009). Nevertheless, a key point to note is that most paleoclimate evidence is local, or at best regional, and not global in scope.

Section 4 discussed how solar influence on climate on a global scale has been relatively minor and how studies that arrive at a different conclusion have been flawed and not

robust. Section 6 reviews the growing evidence in modern data for solar influences on some regional and seasonal climates.

6 Regional Climate Effects

Using both a climate model and empirical reconstructions, Shindell et al. (2001a, b) found that even though solar-induced GMAST changes are small (below about 0.3°C), regional temperature changes associated with solar variability can be quite large. In their model, these occur primarily through a forced shift towards the low index state of the North Atlantic oscillation (NAO) as solar irradiance decreases. This leads to lower temperatures over the northern hemisphere continents, especially in winter ($1\text{--}2^{\circ}\text{C}$), in agreement with historical records and proxy paleoclimate data for surface temperatures.

For post-industrial measurements, North and Stevens (1998) applied optimal signal detection theory to data from 36 regions around globe but found the solar signal was small and not highly significant. On the other hand, multivariate fits by Lean and Rind (2008) and Lean (2010) do find strong solar responses in certain regions. Figure 4 shows the multiple regression maps to modern AST (Air Surface Temperature) data by Lean (2010). These are derived in a similar way, and using the same inputs, as the fits to global means of AST (i.e. the GMAST) shown in Figs. 1 and 2. The maps in Fig. 4 are for annual mean data. The top panel shows that the response to a strong El-Niño event is, obviously, dominated by the equatorial Pacific, but there is also strong North Pacific cooling and continental North American warming. The second panel shows that a large equatorial volcanic eruption produces widespread cooling from 40°S to 70°N , especially in North America and the North Atlantic Ocean, but strengthened westerly winds, and a more positive phase of the NAO produces warming in the northern Eurasian continent. The bottom panel shows that the response to anthropogenic effects is widespread and particularly strong in the northern hemisphere at middle to high latitudes, as predicted by GCMs (e.g., Stott et al. 2000). The third panel shows that the response to solar variability is strongest at middle latitudes (near 40°) in both the northern and southern hemispheres, in the vicinity of the interface of the Hadley and Polar cells (Gleisner and Thejll 2003; Haigh 2003). We would expect climate to respond to solar variability with distinct seasonality because the lower latitudinal gradient of solar energy in summer means that dynamical processes are then not as strong. Remember that, as for all such multiple regression fits, the procedure may have overfitted decadal-scale internal oscillations with the input solar variation and so may have overestimated the response. The most noticeable feature is that the northern hemisphere response is much greater than the southern, with a strong longitudinal variation such that the biggest effect is over Europe and western Asia (referred to hereafter as Eurasia). Statistically significant signatures of multidecadal solar activity changes in atmospheric temperatures in Eurasia have recently been reported by Kossobokov et al. (2010) and Le Mouél et al. (2008, 2009, 2010) but Yiou et al. (2010) and Legras et al. (2010) argue that they do not survive proper null-hypothesis testing.

Climate fluctuations for different regions tend to cancel, giving global means that are much less variable than regional ones and which more clearly reveal trends. Figure 5 stresses how different the behaviour of a regional/seasonal climate in Europe can be from the global or hemispheric means. The plot uses winter (December–January–February, DJF) 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 (Manley 1974; Parker et al. 1992). The CET measurements cover a spatial scale of order

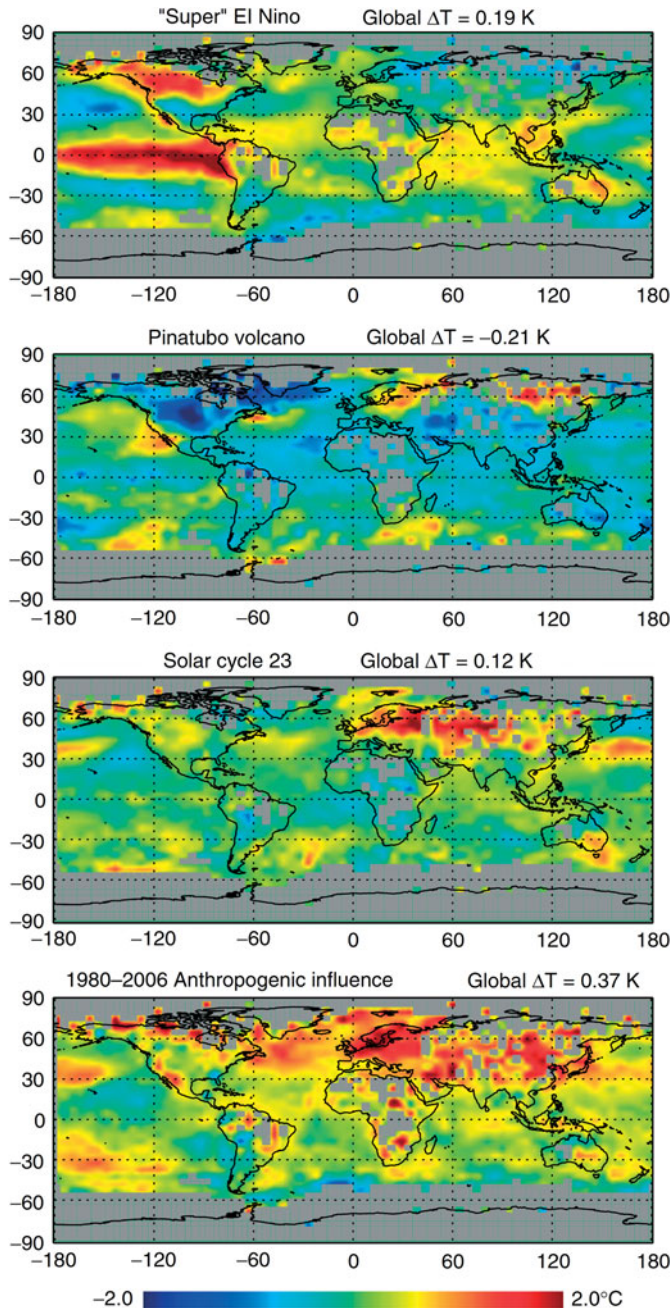


Fig. 4 Maps of the global responses to given features in the input data series in Fig. 2 from multiple regression analysis, which give a GMAST contribution of ΔT which is given at the top of each panel: (from top to bottom) **a** the “super-El-Niño” event of 1998, **b** the Pinatubo volcanic eruption, **c** solar cycle 23 and **d** the net anthropogenic forcing over the period 1980–2006. These are very similar in form to the maps of the regression coefficients of GMAST presented by Lean and Rind (2008) for the annual time series data shown in Fig. 2 (after Lean 2010)

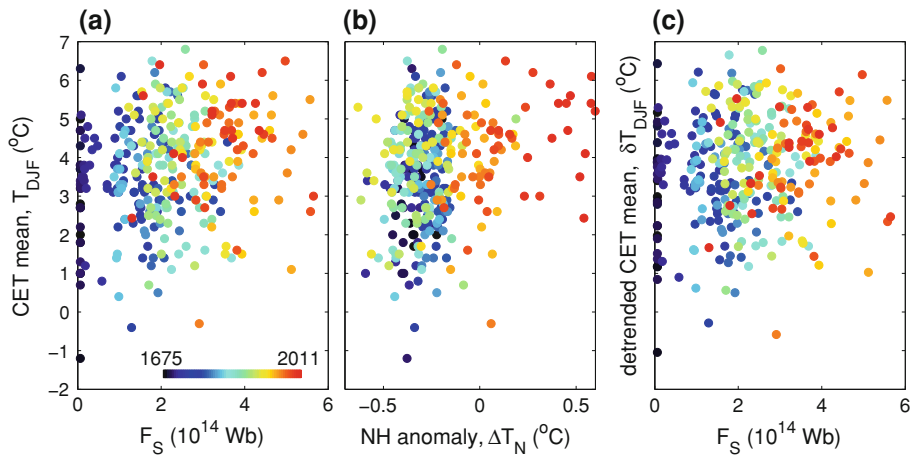


Fig. 5 Scatter plots of mean winter Central England temperature (CET), T_{DJF} , as a function of **a** open solar flux, F_S and **b** the hemispheric mean surface temperature anomaly ΔT_N (the HADCRUT3v reconstruction is here extended to before 1850 using the median of a basket of proxy paleoclimate 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 range of the proxy reconstructions for ΔT_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 using the AR (1) noise model). 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 δT_{DJF} , where the detrending allows for the hemispheric change ΔT_N and uses the regression line shown in **b**. **c** shows that, even after allowing for the hemispheric trend, most of the coldest winters in central England occur at lower solar activity, as quantified by F_S . Lockwood et al. (2010a) 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. Several tests were carried out on the differences between distributions of F_S above and below various thresholds in δT_{DJF} . These were then repeated for the differences between distributions of δT_{DJF} above and below various thresholds in F_S

300 km which makes it a “small regional” climate indicator. In winter, the NAO, and associated changes in thermal advection, contribute to a large fraction of the observed variability of CET (Karoly and Stott 2006). Comparison of parts (a) with (b) of Fig. 5 shows that T_{DJF} correlates with both open solar flux F_S and the hemispheric mean surface temperature ΔT_N . However, the correlation is very weak in both cases. Lockwood et al. (2010a) 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 solar irradiances are thought to be low and GCR fluxes are high). This can be seen by the lack of points in the bottom-right corner of Fig. 5c which was found to be significant at more than the 95% level using 6 different tests against the null hypothesis. Figure 6 shows that both surface temperature and surface pressure in winter (DJF means) in ERA-40+ re-analysis data for 1957–2001 show a clear influence of F_S (Woollings et al. 2010b). Figure 6a shows that difference in the means for low solar activity (lower tercile of the F_S distribution) minus that for high solar activity (the upper tercile of that distribution). Temperatures are lower in Eurasia by up to 4°K, but note that they are higher in Greenland by up to 3°K. Figure 6b shows the corresponding plot, sorted using the NAO index. In fact, the temperature drops in central Europe are not as large for the NAO sort, being up to about 2°K. The significances of the differences exceed 95% over a more extensive area in Eurasia for the solar than the NAO pattern. It is also interesting to

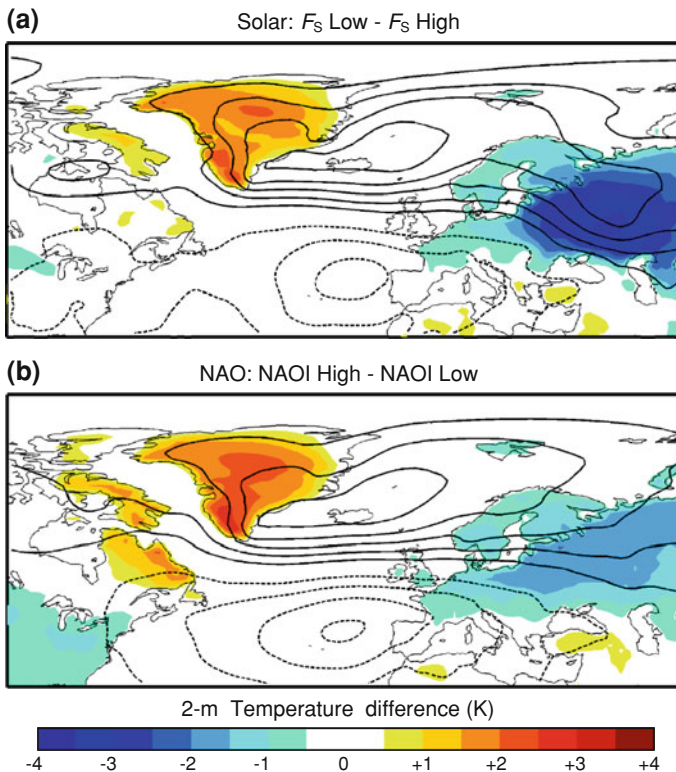


Fig. 6 **a** Composite difference maps of winter (DJF) means of mean surface level pressure (MSLP, contours 1 hPa apart) and 2-m temperature (colour map) between low- and high-solar conditions defined by the lower and upper terciles of the open solar flux, F_s . **b** Scaled anomalies associated with the NAO for comparison, in this case the two subsets are for the lower and upper terciles of the NAO index. Data are from the European Centre for Medium-range Weather Forecasting ERA-40 reanalysis data set (Uppala et al. 2005) extended to cover 44 complete winters (1957/1958 to 2000/2001) using operational data (from Woollings et al. 2010b). A bootstrap test was employed, resampling the sets of winters in order to estimate the sampling uncertainty, to test whether the solar pattern in **a** was different from that associated with the NAO in **b**: this found that the two patterns are significantly different at the 93% level

note that the perturbation circulation pattern for the solar effect is similar to, but still significantly (>93%) different from, that for the NAO, reaching further to the East.

Early instrumental records from the Maunder Minimum indicate an increased frequency of easterly winds influencing the UK winter temperatures during exceptionally cold winters (Slonosky et al. 2001). This is consistent with the circulation perturbation in Fig. 6 and has also been deduced from indirect proxies (Luterbacher et al. 2001), including the spatial patterns of changes in recorded harvest dates (Wanner et al. 1995). This strongly 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 which 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. These changes are associated with a meander in the jet stream in the upper troposphere and lower stratosphere, such that its usual eastward (westerly)

flow becomes south-westward around the longitude of the event centre (Woollings et al. 2010a). 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 (Barriopedro et al. 2008). Note, however, that to the west of the event centre warm air is drawn up from the south-west and hence if the blocking event centre moves exceptionally far to the east temperatures in western Europe may rise rather than fall: the region where CET is measured is quite close to the average longitude of blocking event centres and, although it shows a net cooling effect for lower solar activity, this is much smaller than the effect found further to the east. This evidence suggests that solar-induced perturbations modulate the North Atlantic jet stream and hence the occurrence of blocking. 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 which have been found to respond to solar activity giving increased/decreased frequencies of easterly/westerly circulation patterns over Europe under low-solar activity conditions (Huth et al. 2006, 2008). Figure 7 (from Woollings et al. 2010b) studies changes in the occurrence of DJF blocking events, using the means of the blocking index of Berrisford et al. (2007) from the same data set as used in Fig. 6. The anomaly, compared to the overall mean, for the high (upper tercile) F_S subset is shown on the left and for low (lower tercile) F_S subset the right. For the high F_S winters, the blocking occurrence is up to 6% lower than the average, in a restricted region in the eastern North Atlantic and over North-Western Europe. On the other hand, for the low F_S winters, the same region shows the blocking occurrence is up to 8% higher. Monte-Carlo tests show these changes are significant at the 99% level. This modulation of the occurrence of winter blocking events is highly significant and provides a good explanation of the modulation of the surface temperatures and pressures seen in Fig. 6.

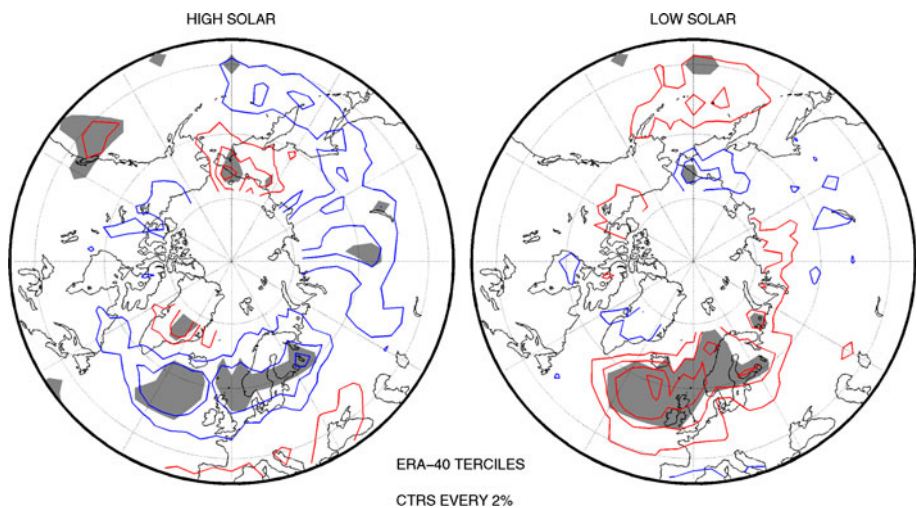


Fig. 7 Composite northern hemisphere anomalies, relative to the overall mean, of blocking episode frequency (defined using the blocking index of Berrisford et al. (2007) from the same data set as used in Fig. 6). Contours in the left and right hand panels show, respectively, the anomalies for the high- and low-solar activity winters, defined as the upper and lower terciles of the open solar flux, F_S , distribution. Contours are drawn every 2%, with positive/negative contours in red/blue, respectively, with the zero contour omitted. The grey area shows where the anomalies are significant at the 99% level, defined using a Monte-Carlo technique (from Woollings et al. 2010b)

Winter CET values are known to be strongly modulated by the NAO (Karoly and Stott 2006), 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 (Scaife et al. 2005). Furthermore, tropospheric blocking episodes are known to influence the stratosphere, and there have been strong suggestions that the coupling works both ways, such that they are also influenced by the stratosphere (Woollings et al. 2010a). In addition, various empirical studies have reported solar modulation of the NAO (Ruzmaikin and Feynman 2002; Thejll et al. 2003). The top-down mechanisms implied are discussed further in Sect. 7 and are likely to be connected to the centennial scale variations and phenomena seen in Europe during the Maunder Minimum. For example, the GCM runs experiments by Rind et al. (2008) produce a relative negative phase of the NAO during the Maunder Minimum which contributes to predicted lower European winter temperatures at that time.

Mann et al. (2009) studied regional climate on a global basis using paleoclimate data from tree trunks, ice sheets, corals and sediments from over 1,000 sites. They searched for solar influence on pre-industrial climate by comparing the difference between the “little ice age” pattern (which they define as 1400–1700 AD) and that for the “mediaeval maximum” (which they take to be 950–1250 AD): They find it shows a pattern that has some similarities to Fig. 4c. The reconstruction by Steinhilber et al. (2009) of TSI during the Holocene from cosmogenic isotopes gives a difference of 0.5 W m^{-2} between the means for these two intervals. However, the temporal variations deduced by Mann et al. do not agree particularly well with the Steinhilber et al. TSI reconstruction. For example, they do not show any feature at the time of the solar Maunder Minimum (circa 1645–1715 AD). Mann et al. argue that the spatial pattern is consistent with a relative positive/negative NAO-AO atmospheric circulation anomaly during the mediaeval maximum/little ice age, respectively, associated with annular bands of sea-level pressure anomalies that are positive/negative in the subtropics and mid-latitudes, and negative/positive at subpolar latitudes. This has been seen in model simulations as a dynamical response to imposed solar irradiance effects on ozone photochemistry (Shindell et al. 2001a, b).

Detection–attribution techniques have been applied on a regional and seasonal basis. Studies to date have generally found the solar contributions to be smaller than those of volcanoes and sulphate aerosols as well as smaller than the effects of greenhouse gas changes and land-use change. Hegerl et al. (2011) used a multifingerprint technique to detect a solar response in Europe, but in summer temperatures rather than the winter response discussed above. This was not robust to all tests and so remains speculative. It will be interesting to see whether these results change as models with better representation of the stratosphere are employed and when better characterisation of spectral solar irradiance becomes possible.

7 “Top-down” Solar Forcing

The dynamical coupling across the tropopause (Shepherd 2002) means that stratospheric forcing can influence the underlying troposphere (e.g., Hartley et al. 1998; Song and Robinson 2004; Matthes et al. 2006; Haigh and Blackburn 2006), and under some circumstances, robust tropospheric responses are indeed predicted by models. Observational studies show that stratospheric perturbations (e.g., stratospheric warmings) typically last at least a month, and on average, tropospheric effects are seen approximately 2 weeks later

(e.g., Baldwin and Dunkerton 2001). Note, however, that the strong, two-way coupling across the tropopause means that the appearance of the change first in the stratosphere is not necessarily an indication that the stratospheric changes are driving those in the troposphere. The latitudes of tropospheric jet streams have been shown to be sensitive to the solar forcing of stratospheric temperatures (Haigh 1994, 2003; Poore et al. 2004). This could occur through disturbances to the stratospheric polar vortex (Gray et al. 2004), which can propagate downwards to affect the tropospheric jets (Plumb and Semeniuk 2003) or through the effects of stratospheric temperature changes on stratospheric winds and the refraction of tropospheric eddies (Kushner and Polvani 2004; Simpson et al. 2009). Models (e.g., Shindell et al. 2001a, b) 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 (Perlwitz and Harnik 2003). 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. (2005) 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.

A wide variety of tropospheric responses has been suggested. Recent numerical modelling by Ineson et al. (2011) has simulated the effect of the large decline in the stratosphere-effective UV band inferred from the recent SIM/SORCE measurements by Harder et al. (2009) and Haigh et al. (2010). As discussed in Sect. 5, there is debate as to whether these observations exaggerate the variability of the UV irradiance but, on the other hand, the modelling maintains constant ozone concentrations, and this will underestimate the effect. The modelled response to the decreasing solar UV begins in the upper stratosphere and lower mesosphere, consistent with ERA-40+ reanalysis data. This signal is largest in the tropics (Frame and Gray 2010; Lockwood et al. 2010b) and so gives a relative decrease in the pole-to-equator temperature gradient for lower solar activity. This response is reproduced in the model and requires a weak easterly wind anomaly in the subtropical zonal mean circulation in the upper stratosphere. As predicted and inferred by Koder (2002) and Koder and Kuroda (2005), this anomaly amplifies as it propagates polewards and downwards during autumn and winter, giving a weaker polar vortex in December–January at solar minimum. Ineson et al. use the modelled Eliassen–Palm (EP) flux divergence to show that this downward propagation and amplification of the wind anomaly is associated with altered planetary wave activity.

The number and fluence of solar energetic particle events (SEPs) also vary with the level of solar activity quantified by F_S (Barnard et al. 2011). 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 Mlynarczyk et al. (2003). These nitrates are seen to migrate downwards over time (Siskind et al. 2000; Funke et al. 2005), resulting in catalytic destruction of stratospheric ozone (Callis et al. 2000). Large SEP events generate considerable transient polar ozone depletions, which persist in winter until UV irradiance of the polar stratosphere resumes (Jackman et al. 2006, 2008; Randall et al. 2005, 2007). Recently, Seppälä et al. (2009) reported changes in polar surface temperatures which they associate with large SEP events. It should be noted that they used geomagnetic activity indices as indicators of the probability of SEP fluence, and these correlate highly with the open solar flux F_S . Thus, it is likely they are observing the same

phenomenon as reported by Lockwood et al. (2010a), Woollings et al. (2010b) and Bochníček and Hejda (2005) but are using an interpretation based on the model predictions of SEP effects by Rozanov et al. (2005, 2012). Similarly, the effect reported by Lu et al. (2008) which they attributed to the solar wind could well be via a correlation with open solar flux. In this context, it is interesting to note that the effects of SEPs may also be caused by other precipitating energetic particles, including GCRs or energetic electrons energised by the solar wind (see review by Rozanov et al. 2012, and references therein). Chemical and dynamical modelling of the effects of energetic particles has yielded a surface temperature perturbation pattern similar to that shown in Fig. 6 (Rozanov et al. 2012).

8 Cosmic Ray Modulation of Clouds

A long-standing suggestion is that cosmic rays can aid the formation of clouds (see reviews by Ney 1959; Carslaw et al. 2002; Kirkby 2007). This would be a highly significant effect because clouds modulate Earth's energy balance by changing the albedo A and by enhancing the infrared greenhouse trapping effect. The balance between these two competing effects is dependent on the cloud altitude: For low clouds the albedo effect dominates (such that more cloud is a cooling effect), whereas for high-altitude clouds the greenhouse trapping effect dominates (so that more cloud gives warming). A great many papers have been written about low-altitude global cloud cover arguing that it shows a solar-cycle variation, consistent with GCR modulation of the growth of cloud condensation nuclei (CCN) (Svensmark and Friis-Christensen 1997; Svensmark 2007; Marsh and Svensmark 2000, 2003, 2004). These studies have been based on the available satellite data after 1983, which give global coverage, and so still cover something less than three solar cycles. Other studies find no significant effect (Sloan and Wolfendale 2008; Kernthaler et al. 1999; Kristjánsson and Kristiansen 2000; Sun and Bradley 2002, 2004; Kulmala et al. 2010). A third set of studies find significant correlations but only in restricted regions (Erlykin et al. 2010; Kristjánsson et al. 2008), whereas a fourth set report a solar-cycle variation but find it to be more consistent with solar UV irradiance variability (de Jager and Usoskin 2006; Erlykin et al. 2010; Udelhofen and Cess 2001). Voiculescu et al. (2006) argue that both UV and GCRs have an effect. Harrison (2008) detected a weak 1.68-year oscillation in the long (1947–1990) 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 (Rouillard and Lockwood 2004). Hence, this supports a direct effect of GCRs rather than irradiance changes. It is expected that any effect would be more significant in clean maritime air where there is a shortage of CCNs for water vapour to condense on, and air ions generated by GCRs may be more significant factor (Kazil et al. 2006; Laken et al. 2009).

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 data set used render it unsuitable for this type of long-term variability analysis (e.g., Klein and Hartmann 1993). 3. The data sequences are too short and so the significance of the correlations is low. (For example, Sun and Bradley (2002, 2004) 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 (Nöel and Tarling, 1975) which at 40 kyr ago is the most recent and well

studied, gave enhanced GCR fluxes in the Earth's atmosphere but did not influence climate in the Greenland area (Beer 2006). Of these objections, only 4 argues that such a mechanism is not effective: 1–3 all argue that the evidence in its favour is inadequate. In relation to 4, there is some evidence that the failure to see an effect of the Laschamp event (Wagner et al. 2001) may have been a local characteristic of the climate in the Greenland area (Christla et al. 2004). 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 over the last three millennia (Haug et al. 2001; Gallet and Genevey 2007; Gallet et al. 2005, 2006; Courtillot et al. 2007) would be significant, if they survived robust null-hypothesis testing, because they would be via GCR effects and unrelated to solar irradiance changes. These changes have also been linked to latitudinal motions of the inter-tropical convergence zone (Haug et al. 2001). Harrison and Stephenson (2006) found evidence for a small GCR effect on diffuse fraction measurements at a variety of maritime UK meteorological stations (for 1951–2000) and Harrison et al. (2011) have found the base of some type of clouds is lowered by higher cosmic ray fluxes. As these are homogeneous sequences of simple measurements, this does counter objection (2) to some extent; however, the effect was small.

In addition to the solar-cycle variation in GCRs, there are sudden decreases in GCR fluxes over periods of a few days called Forbush decreases. These have been reported as giving responses in cloud data, both ground-based (Veretenenko and Pudovkin 1997) and from satellites (Svensmark et al. 2009), in “compositing” analyses (also called “superposed epoch” and “Chree” analysis). The problem with these studies (particularly if a satellite data set is employed) is that there are very few large Forbush decreases, and the results appear to be dominated by one or two events in the intervals of available satellite data. This means that statistical significance is very low. The long delay of the putative effect is also a major puzzle. Brown (2008) reports that 3% of cloud variability on short timescales could be associated with GCRs, whereas Calogovic et al. (2010) find no response at all. The potential importance of this effect is that there are long-term changes in the open solar flux F_S (Lockwood et al. 2009; Lockwood and Owens 2011) that yields the long-term changes in GCRs (McCracken and Beer 2007; Muscheler et al. 2007; Steinhilber et al. 2008) which could introduce long-term changes in climate if the mechanism was to be sufficiently effective.

The best chance of answering objection (1) is the CLOUD experiment at CERN (Duplissy et al. 2010), which has just begun to study the “ion-aerosol clear-air” mechanism. The first results have just been published (Kirkby et al. 2011). The results have some fascinating new insights into effects in the boundary layer, but do not say much about the growth of water droplets in low-altitude cloud in the troposphere. Through the influence of sulphuric acid, ionisation was shown to enhance the rate of water droplet growth at the temperatures characteristic of middle troposphere. However, the ion-induced aerosols only grew to about 2 nm, and to grow into droplets large enough to influence incoming or outgoing radiation to Earth, would be far too slow because there is not enough sulphuric acid in the atmosphere (Pierce and Adams 2009). As yet, the experiment is not reproducing the true mix of constituents in the mid-troposphere, so the results are highly provisional. Other proposed mechanisms involving the atmospheric electric field have been proposed (Harrison 2000) but have not yet been investigated.

The cloud-cosmic ray suggestion increasingly fails to match observations. The correlation between the solar-cycle variation and global cloud-cover estimates has degraded

rapidly in the more recent data (Gray et al. 2010). For each piece of evidence in its favour, an equal or greater number of studies fail to find the effect. Only studies finding rather subtle effects on cloud edges survive proper null-hypothesis testing. Lastly, we note that GCR-cloud effects would have shown up in the multivariate fits of GMAST shown in Figs. 1 and 2, which found only a weak solar response (indeed in these fits, the solar input was even quantified using GCR fluxes). In addition, even if the GCR-cloud mechanism was responsible for the effect that was seen, the global regression map (Fig. 4c) generates a major issue. Larger GCR fluxes would have been expected near the poles, where geomagnetic shielding of GCRs is weaker and with no longitudinal effects (with the possible exception of in the south Atlantic geomagnetic anomaly). Hence, additional effects, such as spatial variations in aerosols, would have to be invoked to explain maps such as shown in Fig. 4c.

9 The Future

We have no predictive models of the solar dynamo (see review by Weiss and Thompson 2009) and so can only make empirical analogue forecasts of future solar output changes. From solar-induced variations of cosmogenic isotopes over the past 10^4 years, Lockwood (2010) and Barnard et al. (2011) have deduced that there is an 8% chance that the Sun will return to Maunder Minimum conditions within 50 years. The recent evolution of solar cycle 24 indicates that the Sun may well be following such a trajectory (Owens et al. 2011). Feulner and Rahmstorf (2010) and Jones et al. (2012) have used GCMs and EBMs to predict that this will offset anthropogenically rising global temperatures by no more than about 0.2°C in the year 2100, relative to what would happen if the solar output remained constant. Similarly, Lean and Rind (2009) find that the solar decline would delay the arrival at a given temperature level by no more than about 5 years. Thus, these predictions show that continued solar decline will do little to alleviate anthropogenically driven global warming. However, the decline should do much to end the debate about the fraction of global warming that can be attributed to solar change. For the first time since about 1900, long-term solar and anthropogenic trends are now in opposite directions. Non-robust fits will fail sooner rather than later because of the change in solar behaviour. Thus, the next few years will give us much better estimates of the solar contribution to both global and regional climate change. For 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 will be more susceptible to solar changes (Lockwood et al. 2011a, b). Understanding spectral irradiance variability and differentiating “top-down” and “bottom-up” solar forcings will be needed as these will have very different effects on the spatial patterns of the responses and will behave differently in combination with other changes, such as sea ice loss. 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 mechanisms.

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