WHAT DO COSMOGENIC ISOTOPES TELL US ABOUT PAST SOLAR FORCING OF CLIMATE?

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Abstract. In paleoclimate studies, cosmogenic isotopes are frequently used as proxy indicators of past variations in solar irradiance on centennial and millennial timescales. These isotopes are spallation products of galactic cosmic rays (GCRs) impacting Earth's atmosphere, which are deposited and stored in terrestrial reservoirs such as ice sheets, ocean sediments and tree trunks. On timescales shorter than the variations in the geomagnetic field, they are modulated by the heliosphere and thus they are, strictly speaking, an index of heliospheric variability rather than one of solar variability. Strong evidence of climate variations associated with the production (as opposed to the deposition) of these isotopes is emerging. This raises a vital question: do cosmic rays have a direct influence on climate or are they a good proxy indicator for another factor that does (such as the total or spectral solar irradiance)? The former possibility raises further questions about the possible growth of air ions generated by cosmic rays into cloud condensation nuclei and/or the modulation of the global thunderstorm electric circuit. The latter possibility requires new understanding about the required relationship between the heliospheric magnetic fields that scatter cosmic rays and the photospheric magnetic fields which modulate solar irradiance.

Keywords: galactic cosmic rays, total solar irradiance, cosmogenic isotopes, paleoclimate changes

1. Introduction

Paleoclimate studies frequently use cosmogenic isotope abundances as indicators of past total solar irradiance (TSI) variations (see review in this volume by Beer *et al.* (2006). In Section 2 we focus on three examples by Bond *et al.* (2001), Neff *et al.* (2001) and Wang *et al.* (2005b). In these studies it is either explicitly or implicitly assumed that the inferred deposition rates of the isotopes are strongly related to either TSI or spectral solar irradiance. As discussed in the reviews by Fröhlich (2006) and Rottman (2006) in this volume, we now have solar irradiance observations covering three decades. Figure 1 shows that an anticorrelation is observed between TSI and galactic cosmic ray (GCR) fluxes (Lockwood, 2002a; Muscheler *et al.*, 2003). However, because of the large thermal capacity of the oceans, these potential decadal-scale variations in climate forcing will be heavily damped in Earth's climate response, and any century-scale changes would be much more significant (Wigley and Raper, 2005). Because we have only a partial understanding of the

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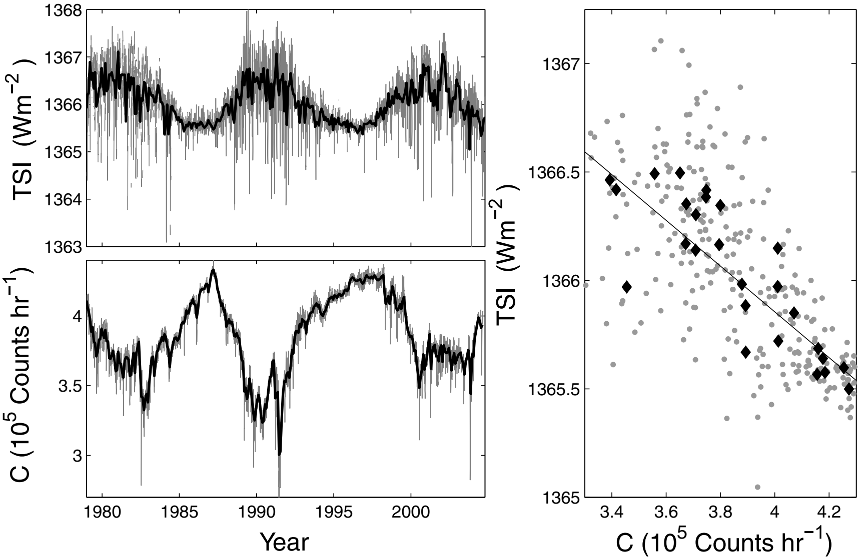

Figure 1. The anticorrelation of GCR fluxes with the total solar irradiance (TSI) since 1978. *Left-hand panels:* the variations of (top) the PMOD TSI composite (Fröhlich, 2006) and (bottom) the GCR counts, C, detected by the neutron monitor at Climax. In both cases, the grey line gives the daily values, and the black line the monthly means. It can be seen that the agreement is poor on a daily basis because of the effect of individual sunspot groups on TSI. *Right-hand panel:* Scatter plot of TSI as a function of C. The grey points show monthly means, the black diamonds the annual means. The best-fit linear regression to the annual data is also plotted. The correlation coefficients (and significance levels) are -0.68 (99.99%) and -0.85 (91.5%) for, respectively, monthly and annual data.

physics of the centennial and millennial changes in TSI and cosmic rays, we cannot be sure that the correlation seen on decadal timescales will also apply on century timescales. Reconstructions of TSI over the past 3 centuries do show strong similarities with records of cosmogenic isotope abundances (Lean *et al.*, 1995). However, the physics behind this connection is far from clear and quantitative scaling of TSI from cosmogenic isotope records is not yet possible. The common denominator between the two is the solar magnetic field, the TSI being determined by the field in the photosphere (see review in this volume by Solanki, 2006) and GCR fluxes and cosmogenic isotopes being modulated by the "open" field which passes through the solar corona and fills the heliosphere (see review in this volume by Heber *et al.*, 2006). However, the open solar flux is only small fraction (a few percent) of the photospheric flux and it is not immediately apparent why the former should be a reliable indicator of the latter. Furthermore, TSI variations depend not only on the total photospheric flux, but also on the distribution of flux tube sizes (see review by Lockwood, 2004).

The alternative hypothesis, discussed in Section 3, is that cosmic rays have a direct effect on climate, for example via a proposed influence on cloud formation or via modulation of the global electric circuit.

This paper addresses the issues surrounding this central question of the relationship of cosmogenic isotopes to TSI and climate, after first reviewing some of the evidence for a link between them in Section 2.

2. Paleoclimate Evidence for Solar Variability Effects on Climate

In recent years, a body of evidence has emerged that solar variations have had a clear effect on climate throughout the Holocene, the warm period that has prevailed throughout the past ten thousand years. These studies have been made in many parts of the world and employ a wider variety of paleoclimate indicators (Davis and Shafer, 1992; Jirikowic *et al.*, 1993; Davis, 1994; Van Geel *et al.*, 1998; Yu and Ito, 1999; Bond *et al.*, 2001; Neff *et al.*, 2001; Sarnthein *et al.*, 2003; Hu *et al.*, 2003; Prasad *et al.*, 2004; Wei and Wang, 2004; Christla *et al.*, 2004; Wang *et al.*, 2005b; Maasch *et al.*, 2005; Mayewski *et al.*, 2005). Here we discuss just three of the many examples.

The average abundance of ice-rafted debris has been measured in cores of ocean-bed sediment throughout the middle and North Atlantic. These glasses, grains and crystals are gouged out in known glaciers, from which they are 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 "ice-rafted debris" are very sensitive indicators of currents, winds and temperatures in the North Atlantic and reveal high, and highly significant, correlations with both the ^{10}Be and ^{14}C cosmogenic isotopes (Bond *et al.*, 2001).

A second example of such paleoclimate evidence has been obtained from the oxygen isotope ratio δ^{18}O, as measured in stalagmites in Oman (see Figure 2). This has been found to show an exceptional correspondence with the cosmogenic isotopes on timescales between decades and several thousand years (Neff *et al.*, 2001). U-Th (Uranium-Thorium series) dating is used on the stalagmite and the limits to allowed temporal "wiggle-matching" are set by experimental uncertainties and have been rigorously adhered to. The δ^{18}O is, in this case, a proxy for local rainfall and reveal enhanced rainfall caused by small northward migrations of the inter-tropical convergence zone. Large effects are seen because the latitudinal gradient around the site is large. These correlations are between cosmogenic isotopes and local climate indicators. However, Wang *et al.* (2005b) have recently repeated this analysis and found the same result on the edge of the monsoon belt in China. Therefore there is strong evidence for global shifts in the latitude of the monsoon belt associated with cosmic ray variations.

Importantly, these correlations are found for both the ^{14}C and ^{10}Be isotopes. Both are spallation products of GCRs hitting atmospheric O, N and Ar atoms. However, there the similarities end because their transport and deposition into the reservoir where they are detected (ancient tree trunks for ^{14}C and ice sheets or

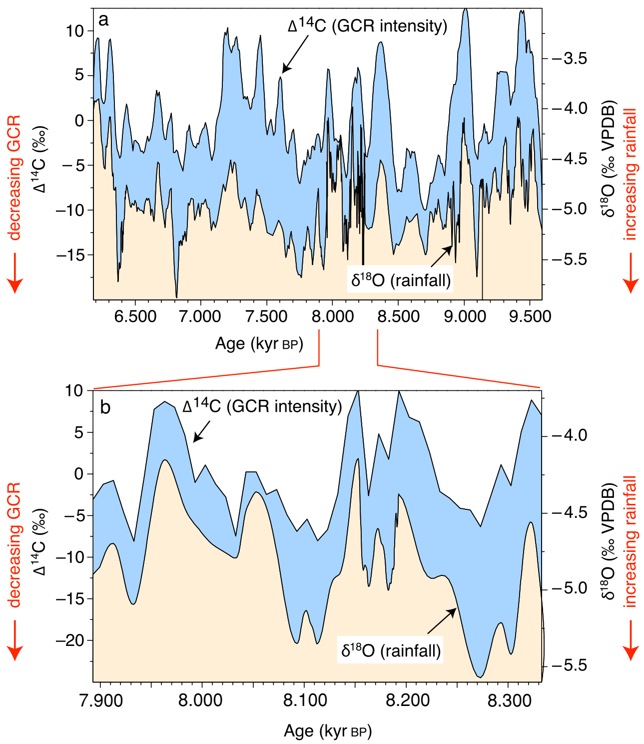

Figure 2. Comparison of $\delta^{18}O$, an indicator of local rainfall, from stalagmite analysis of a cave in Oman and $\Delta^{14}C$ from global tree ring data. The bottom panel shows a higher time-resolution analysis allowed by a period of rapid stalagmite growth. The correlation is seen to apply on timescales between decades and several thousand years (Neff *et al.*, 2001).

ocean sediments in the case of ^{10}Be) are vastly different in the two cases. We can discount the possibility that the isotope abundances in their respective reservoirs are similarly influenced by climate during their terrestrial life-history because the transport and deposition of each is so vastly different. Thus we can conclude that the correlation is found for both isotopes because of the one common denominator in their production, namely the incident GCR flux.

The flux of the GCRs that generate the cosmogenic isotopes is modulated by three influences (Beer *et al.*, 2006): (1) the interstellar flux of GCRs incident on the heliosphere; (2) the GCR shielding by the heliosphere; and (3) the GCR shielding by the geomagnetic field. The spatial scale of interstellar GCR flux variation in our galaxy is sufficiently large compared to distances moved by our solar system through the galaxy, that we can neglect incident GCR 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 (Tric, 1992; Baumgartner *et al.*, 1998), 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 BP (Laj *et al.*, 2001). These events complicate the cosmogenic isotope record (Bhattacharyya and Mitra, 1997; Damon *et al.*, 1978) but are not consistent with the variations seen on timescales of order 1 kyr and less seen, for example by Bond *et al.* (2001), Neff *et al.* (2001) and Wang *et al.* (2005b). This being the case, most of the variations on these timescales arise from heliospheric shielding.

With these considerations, the correlations between these cosmogenic isotopes and paleoclimate indicators allow just two possible classes of explanation:

A. Air ions produced by GCRs have a direct effect on climate.
B. The GCR flux is anticorrelated with another factor that influences climate to the extent that it is a good proxy for that factor.

The most controversial suggestion under category A, is that cosmic rays directly modulate the formation of clouds. However, this is not the only possibility because GCRs are the source of electrical conductivity in the sub-ionospheric gap and thus are vital to the global thunderstorm electric circuit, which also may have a solar cycle variation (Schlegel *et al.*, 2001). The most likely factors for which GCRs could be a proxy (category B) are the total solar irradiance or the UV spectral irradiance. Note that paleoclimate studies usually (explicitly or implicitly) assume a category B explanation.

3. Direct Cosmic-Ray Effects: Clouds and the Global Electric Circuit

The most controversial suggestion for a direct effect of cosmic rays on climate is that they directly modulate the formation of clouds (Friis-Christensen and Svensmark, 1997; Svensmark, 1998; Marsh and Svensmark, 2000, 2003; Udelhofen and Cess, 2001; Kristjánsson and Kristiansen, 2000; Carslaw *et al.*, 2002; Arnold and Neubert, 2002). This idea was first proposed by analogy to cloud chamber particle detectors – an analogy that is not valid because natural atmospheric supersaturations are much smaller than those needed to make a cloud chamber work. The idea has been revived by observed correlations over recent solar cycles between GCRs counts and the global composite of satellite cloud cover observations compiled by the International Satellite Cloud Climatology Project, ISCCP (Rossow *et al.*, 1996). Udelhofen and Cess (2001) found a solar cycle signal in ground-based data from 90 weather stations across the North American Continent. Instrument relocation and changes mean that a long-term drift in these ground-based data cannot be determined, but de-trended data show a clear and persistent solar cycle variation in coastal cloud cover in data that extends back to 1900. The best correlations between GCRs and global cloud cover have been obtained by Marsh and Svensmark (2000) from the infrared observations of clouds (10–12 μm) that make up the "D2" set compiled by ISCCP: these authors find that it is primarily liquid, maritime clouds, away from regions of an El Niño (ENSO) event, that correlate well with GCR fluxes. Other authors argue that the results are still influenced by ENSO events (Farrar, 2000). Correlations on shorter timescales due to Forbush decreases in GCR fluxes, have been reported in localised datasets by Veretenenko and Pudovkin (1997).

The arguments against such direct cosmic ray-cloud connection have been:

1. Given the atmospheric supersaturations, there is no known mechanism that can cause the effect.
2. The inter-calibrations involved in the composite ISCCP dataset render it unsuitable for this type of analysis.
3. The data sequences are too short and so the significance of the correlations is low or marginal.
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 (Beer, 2001).

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 but cannot be used as arguments that it is not active. In relation to 4, there is some evidence that the failure to see an effect of the Laschamp event may have been a local characteristic of the climate in the Greenland area (Christla *et al.*, 2004). Nevertheless, objection 4 remains the key debate.

Concerning the potential mechanisms (objection 1), there are now some viable proposals. Air ions are produced in the atmosphere, broadly in proportion to the flux of incident GCRs (Aplin *et al.*, 2005) and there are plausible mechanisms now known, by which these can grow into cloud condensation nuclei (CCNs) at natural atmospheric supersaturations (Carslaw *et al.*, 2002). These include the growth of air ions into aerosols (Yu and Turco, 2000; Eichkorn *et al.*, 2002) and the effects of atmospheric electric fields on the microphysical connection between aerosols and clouds (Tinsley *et al.*, 2000; Tripathi and Harrison, 2002). Given these mechanism appear to be viable, the major debate now is if such an effect would be significant compared to the many other sources of CCNs (Carslaw *et al.*, 2002).

In relation to objections 2 and 3, recent studies using longer series of homogeneous data are providing new and strong evidence that there could indeed be a direct cosmic ray-cloud effect in certain regions (Harrison and Stephenson, 2005). Specifically, the "diffuse fraction" (the ratio of the intensity of daylight under direct illumination and in the shadow of an obscuring shield) is a simple and repeatable measure of local cloudiness and aerosols that has been made at many weather stations for many years. Figure 3 summarises some of these results from stations in the UK. Part (a) shows that the diffuse fraction is 2% lower on the 14% of days when the Climax GCR count is less than 3.6×10^5 hr^{-1}, compared to the days when it exceeds this threshold. This result is found at all the stations studied and is highly statistically significant (usually at or exceeding the 99.9% level) in almost all cases. Note that it is possible, or even probable, that the effect is only for stations in clean, maritime air (Wilding and Harrison, 2005) and appears to be less significant in regions of high rainfall.

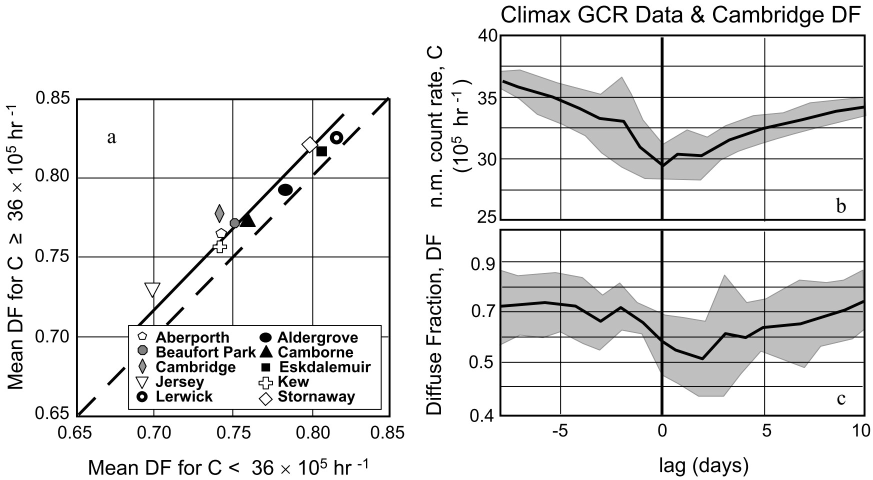

Figure 3. The effect of GCR fluxes on the diffuse fraction (*DF*) observed at a variety of weather stations in the UK. The data are compared to the counts, C, from the neutron monitor at Climax, Colorado (detecting cosmic rays of rigidity exceeding 3 GV). *Left-hand panel:* (a) The mean diffuse fraction on days when C exceeds 3.6×10^5 hr^{-1} as a function of the corresponding value at the same station when C is less than this threshold. In all cases, *DF* is lower for the days with lower C: the black line shows a 2% decrease. The stations used are: Aberporth (data available from 1957–2000; probability that the difference of *DF* arrived by chance, $p < 0.1\%$); Aldergrove (1976–2000, $p = 8\%$); Beaufort Park (1865–2000, $p < 0.1\%$); Camborne (1981–2000, $p = 1\%$); Cambridge (1957–1971, $p < 0.1\%$); Eskdalemuir (1957–2000, $p = 20\%$); Jersey (1968–1994, $p < 0.1\%$); Kew (1947–1980, $p < 2\%$); Lerwick (1952–2000, $p = 0.6\%$); and Stornaway (1982–2000, $p < 0.1\%$). *Right-hand panels:* An example of a superposed epoch analysis of Forbush decreases (in this case for the Cambridge station) showing mean values as a function of the time relative to the time of the minimum C in the event. The black lines in panels (b) and (c) show, respectively, the mean variation in C and the corresponding variation in mean *DF*. In both cases the 95% confidence limits are shown by the grey band (Harrison and Stephenson, 2005).

The studies reviewed above appear to show a solar influence on cloud cover. However, even if these prove to be robust, we must be cautious in ascribing this variation purely to the direct effect of cosmic rays. Some (but by no means all) GCM climate simulations have revealed an effect of TSI variations on cloudiness (see review by Haigh, 2003), via the distribution of atmospheric heating and its effect on winds and circulations, and TSI is well (anticorrelated) with GCR fluxes. Lockwood (2001b, 2002b) showed that the peak correlation coefficient on decadal timescales for the global cloud cover anomaly was +0.654 with the GCR data but was −0.741 with the TSI (see also Kristjánsson *et al.*, 2002). These correlations are significant at the 99.8% and 99.6% levels, respectively. Although the correlation is marginally higher for TSI than for the GCRs, application of the Fisher-Z test shows that the difference between these two correlations is not significant (the significance level of the difference being only 30%, i.e., the probability that the difference arose by chance is 0.7).

The production of cloud condensation nuclei by cosmic rays is not the only possibility in category A, because GCRs are the source of electrical conductivity in the sub-ionospheric gap and thus are vital to the global electric thunderstorm circuit (Markson, 1981; Bering *et al.*, 1998; Harrison, 2002a). Atmospheric electric field changes are linked to changes in global temperature, as they modulate global changes in air ion concentrations (Aplin *et al.*, 2005) and, potentially, non-thunderstorm clouds. Thunderclouds charge by collisions between ice and water moving vertically at different velocities in convective activity: in most cases, the top of the cloud becomes positively charged, the base negatively charged. Current flows from the ground to the cloud in the form of lightning and up from the cloud to the horizontally-conducting ionosphere above about 80 km. The latter is made possible by the conductivity in the sub-ionospheric gap due to the air ions produced by GCRs and give rise to optical signatures such as Sprites, Elves, and Blue Jets. In this way, thunderstorms charge the ionosphere up to a positive potential of order 300 kV. Away from the thunderclouds that power the circuit, return downward current is driven by the ionospheric potential and is made possible by the GCR-induced conductivity and, at the lowest altitudes, ionisation caused by the release of radioactive gases from the ground. The fair-weather electric field corresponds to this return current and has been shown to have fallen by about 3% per decade over the 20th century at a number of sites (Harrison, 2002b, 2004; Märcz and Harrison, 2005). Given that lightening is known to be influenced by GCRs and the solar cycle (Schlegel *et al.*, 2001; Arnold and Neubert, 2002), this may be consistent with long-term modulation of sub-ionospheric conductivity caused by a predicted drop in GCRs fluxes associated with an observed rise in the heliospheric field (Carslaw *et al.*, 2002). To complicate the picture even further, changes in atmospheric electricity may be a factor in a direct effect of GCRs on clouds (Tinsley *et al.*, 2000; Tripathi and Harrison, 2002).

4. The Connection Between Cosmic Rays and TSI on Centennial Time Scales

Lockwood *et al.* (1999) devised a method for deriving the open solar flux F_S since 1868 using the *aa* geomagnetic index. They found that F_S had approximately doubled over the twentieth century. This F_S value is very well anticorrelated with both GCR fluxes and the abundance of the ^{10}Be cosmogenic isotope (Lockwood, 2001a). This variation has been reproduced by a continuity model (see the review in this volume by Solanki, 2006) and by numerical models of magnetic flux transport over the Sun (Wang *et al.*, 2005a; Schrijver *et al.*, 2002).

As discussed in the review in this volume by Heber *et al.* (2006), full understanding of GCR shielding is complex. However, the simple anti-correlations found by Lockwood (2001a) show that much of the variation (specifically, about 75%) of the GCR flux at Earth was explained by the open flux. Bonino *et al.* (2001) fitted the modulation parameter M with a quadratic expression in F_S and so were able to estimate the variation in the GCR spectrum from the variation in the open flux. Similarly, Usoskin *et al.* (2002) used a power-law variation of M with F_S. The modulation parameter (Cini-Castagnoli and Lal, 1980) is a simple way of describing heliospheric GCR shielding, based on the so-called "force-free" approximation. Whilst it is not going to describe all features of all GCR masses, charge states and energies in all parts of the heliosphere, it has had good success in describing the variation of the spectrum and flux of proton GCRs at Earth over recent solar cycles (Bonino *et al.*, 2001; Masarik and Beer, 1999; Usoskin *et al.*, 2002).

The modulation parameter was also used by Masarik and Beer (1999) to predict the heliospheric modulation of cosmogenic isotope production, using GEANT high-energy particle simulations. These simulations also predict the counts observed by neutron monitors. Thus the above papers established a clear and quantitative connection between the open flux, F_S, the modulation parameter M, GCR counts seen by a neutron monitor (e.g., C for Climax) and the global mean production rate of the ^{10}Be cosmogenic isotope, $P[^{10}\text{Be}]$. (N.B. this connection was exploited by Usoskin *et al.*, 2003, and Solanki *et al.*, 2004, to estimate sunspot numbers over recent millennia using cosmogenic isotopes).

The triangular grey points in all panels of Figure 4 show annual means of the observed TSI since 1978 (the PMOD composite, Fröhlich, 2006), as a function of $P[^{10}\text{Be}]$, which has been scaled from the observed annual mean Climax n.m. count rate C (as shown in Figure 1) using the results of Masarik and Beer (1999).

Recently Foster (2004) and Lockwood (2004) have used a homogeneous composite of sunspot group data extending back to 1874 (derived from the Greenwich, Polokov and Mt Wilson datasets) to reconstruct the total solar irradiance. There is one key parameter which influences these reconstructions and which is unknown: that is the average quiet-Sun photospheric field (in pixels of a set size) at sunspot-minimum, $\langle B_r \rangle_{QS}$, during the Maunder minimum. (N.B. because these authors make use of relationships between the intensity and field seen by the MDI instrument on SoHO, they use MDI-sized pixels throughout). To make the reconstructions, the authors made three assumptions: assumption A is that $\langle B_r \rangle_{QS}$ in the Maunder minimum was the same as the present-day value; assumption B is that $\langle B_r \rangle_{QS}$ in the Maunder minimum was zero (a magnetically clean Sun at MDI resolution); and assumption C is that $\langle B_r \rangle_{QS}$ in the Maunder minimum was half the present-day value. Note that the resulting reconstruction A is very similar to that proposed by Foukal *et al.* (2004), whereas that for B is very similar to those by Lean (2000) and Lockwood and Stamper (1999). All three reconstructions have significantly less century-scale drift than that by Lean *et al.* (1995), which is frequently employed in General Circulation Model (GCM) simulations of climate change over the past century (see review by Lockwood, 2004).

The reconstructions also assumed that irradiance effects are entirely due to surface magnetic fields. Over recent cycles, the success of the SATIRE modelling

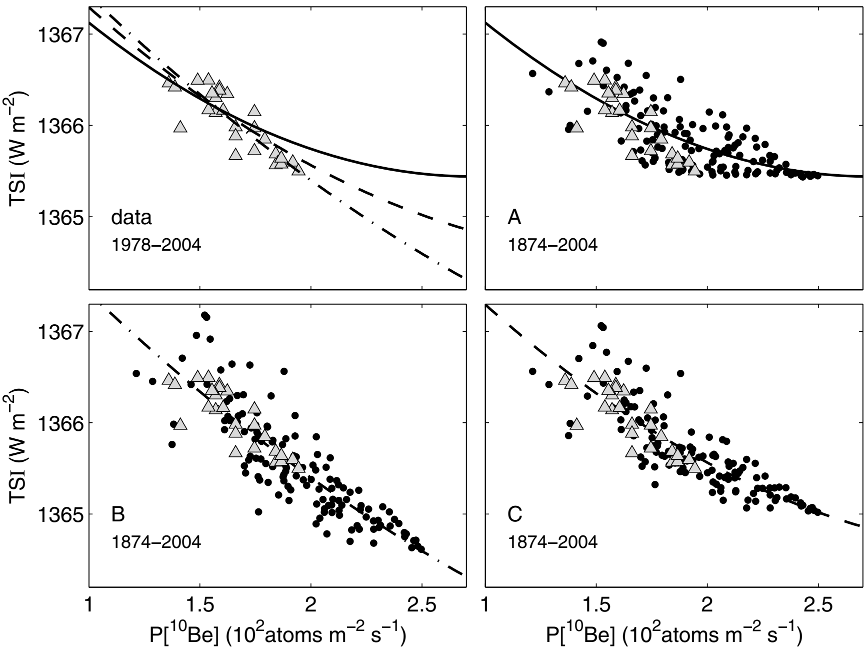

Figure 4. Scatter plots of annual means of the total solar irradiance I_{TS} against the production rate of the ^{10}Be isotope, $P[^{10}\text{Be}]$. *Top left:* the observed data since 1978: the PMOD TSI composite (Fröhlich, 2006) is plotted as a function of the flux of >3 GV GCRs (the data shown in Figure 1), scaled in terms of $P[^{10}\text{Be}]$ using the results of the GEANT simulations by Masarik and Beer (1999). These data are also shown as grey triangular points in the other panels. *The other 3 panels:* Black points show the annual I_{TS} values since 1874, reconstructed by Foster (2004) and Lockwood (2004) for assumptions A, B and C (see text for details), plotted against $P[^{10}\text{Be}]$ derived from the open flux $[F_S]_{aa}$ (Lockwood *et al.*, 1999). The lines give the best 2nd-order polynomial fits to the reconstructed data. All the polynomial fits are also reproduced in the first panel. From Lockwood *et al.* (2006).

(Solanki, 2006) means that "shadow" effects of fields deep in the convection zone are negligible. It is most likely that any such effects on century timescales would be associated with solar radius changes and these could add to the long-term drift in TSI.

The other three panels of Figure 4 (from Lockwood *et al.*, 2005) compare the reconstructed TSI for these three assumptions with the ^{10}Be production rate, $P[^{10}\text{Be}]$, which is here scaled from the open solar flux, as derived from the *aa* geomagnetic index, $[F_S]_{aa}$. In each case a best quadratic fit to the data is given, and all three fits are also shown in the top left panel (as solid, dot-dash, and dashed lines for assumptions A, B and C, respectively).

It can be seen that the predicted variation of TSI with $P[^{10}\text{Be}]$ is monotonic for all three assumptions. This means that cosmogenic isotopes can be used as a quantitative indicator of TSI, irrespective of the actual value of $\langle B_r \rangle_{QS}$ in the

Maunder minimum. However for more quantitative analysis, we do need an estimate of this value. All three assumptions are valid within the scatter of the points. However, at the lowest TSI a divergence between the best fit for assumption A and the data is becoming apparent. The variation is, in general, non-linear: the linear assumption used by Lockwood and Stamper (1999) being a good approximation only for assumption B. Given that cosmogenic isotopes continue to show a decadal oscillation in the Maunder minimum (Beer *et al.*, 1998) (implying some magnetic flux emergence, evolution and loss continued in the Maunder minimum), assumption B appears to be less likely than the other two.

5. Conclusions

Cosmogenic isotopes do tell us about past solar variations relevant to climate (Beer *et al.*, 2006). There are two potential relationships. Firstly, as we have gained a better understanding of the origin and evolution of open solar flux, a firm link between it and total and/or spectral solar irradiance is becoming apparent. Simulations reproduce this link but disagree on the scaling required (Solanki *et al.*, 2001; Wang *et al.*, 2005a). Lockwood *et al.* (2006) have shown that this scaling depends on the residual quiet-Sun photospheric magnetic flux in the Maunder minimum. With quantification of this value, the way is open for "quantitative palaeoclimatology" in which cosmogenic isotopes are used to quantify the solar irradiance input into GCMs which are then used in the forward modelling of proxies, for example predicting the ice rafted debris observed by Bond *et al.* (2001) or the stalagmite δ^{18}O observed by Neff *et al.* (2001) and Wang *et al.* (2005b).

The second relationship is the putative direct effect of cosmic rays on clouds and/or the global thunderstorm circuit. This effect remains highly controversial, but even the weak effect revealed by Harrison and Stephenson (2005) may be highly significant. This effect is seen in relation to short-term variations of GCRs (Forbush decreases, lasting only a few days) and Figure 1 shows that on these timescales the link between TSI and cosmic rays is almost non-existent. Thus these data do argue for a direct effect and not just via the anticorrelation of TSI with cosmic rays which is most apparent on timescales of a year or greater.

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