LONG-TERM VARIATIONS IN COSMIC RAY FLUXES AND TOTAL SOLAR IRRADIANCE AND THEIR POSSIBLE INFLUENCE ON GLOBAL CLIMATE CHANGE

*M. Lockwood *)*
Space Science and Technology Department, Rutherford Appleton Laboratory, Oxfordshire, UK

Abstract
Studies of how geomagnetic activity is excited by the solar wind flow have allowed quantification of the open magnetic flux of the Sun, revealing it to have more than doubled during the 20th century. This flux fills the heliosphere out to the termination shock and shields Earth from galactic cosmic rays: thus, were air ions produced by cosmic rays to facilitate the formation of clouds in any way, this magnetic field would modulate terrestrial cloud cover. We here confirm there is a strong and statistically significant anticorrelation between the heliospheric field and the global coverage of low-altitude (<3.2 km) clouds and discuss the implications for extrapolating cloud-cover estimates back in time. We also show that the correlation between clouds and cosmic rays and the anticorrelation between clouds and total solar irradiance (TSI) are very similar in their strength and significance, making distinction between potential TSI and cosmic ray effects difficult to achieve.

1. INTRODUCTION

The aa index of geomagnetic activity was devised by *Mayaud* in 1972 and, on annual timescales at least, successfully quantifies global geomagnetic activity from just two, antipodal observatories [1]. The importance of this index lies in the fact that it is a homogenous data series that extends back to 1868. *Lockwood et al.* have recently used the aa data to infer long-term changes in the open flux of the Sun that threads the coronal source surface and is dragged into the heliosphere by the solar wind flow [2]. The method they devised was an inversion of the analysis of *Stamper et al.* [3] who used data from solar cycles 20, 21 and 22, for which regular spacecraft measurements of the near-Earth heliosphere are available. The method was refined by *Lockwood and Stamper* [4] who used only cycles 21 and 22 to determine the required coefficients and held back the heliospheric field measurements from cycle 20 as an independent test of the method. The RMS differences between the inferred and observed radial components of the heliospheric field B_r for the test cycle 20 were actually smaller than for the fitted cycles 21 and 22. Further confirmation of the method comes from the very high and highly significant anticorrelation between the inferred open solar flux and the counts detected by various neutron monitors due to cosmic ray bombardment of the atmosphere [5]: 80% of the variation of the cosmic ray flux could be associated with the heliospheric field strength. A number of different processes contribute to the shielding of cosmic rays [6], but scattering by irregularities in the heliospheric field is a dominant effect [7], such that the shielding is dependent on the open solar flux. Included in the remaining 20% that is not explained by the variation in open solar flux, is the known effect of solar cycle number on cosmic ray fluxes at Earth. This is expected theoretically as a consequence of the gradient and curvature drifts associated with large-scale heliospheric structure [6]. The effect reverses with the polarity of the polar solar field, roughly 1 year after the

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*) Also at Department of Physics and Astronomy, Southampton University, Southampton, UK.

peak of each cycle, and is apparent at the data, predominantly at solar minimum when the heliospheric field is weakest [7, 8, 9].

The method used to derive the heliospheric field is based on the theory of solar wind – magnetosphere coupling by *Vasyluinas et al.* [10], and thus by extrapolating back in time to before cycle 21 we are assuming that no there is no additional unknown factor, not included in this theory, the behaviour of which is different on decadal and century timescales. Given the correlation obtained for cycles 21 and 22 is 0.97, to be relevant this factor would need to have introduced variability before the start of cycle 21, but not subsequently. An important point in this respect is that the correlation between the open solar flux inferred from geomagnetic activity and cosmic ray neutron products was equally high and significant for solar cycles 19, 20, 21 and 22. Thus the method has been confirmed by independent data from cycles 19 and 20 – despite the fact that cycle 19 was the largest solar activity cycle ever observed and that cycle 20 was surprisingly weak.

The key finding from the method is that the heliospheric field, averaged over full solar cycles, increased by 140% over the 20th century [2]. Extrapolating using the correlations with the cosmic ray fluxes discussed above, yields that the flux of primary cosmic rays was some 15% higher on average in 1900 than at present for energies above 3 GeV and 4% higher for >13GeV [5]. Support for this inferred drift comes from the abundance of the ^{10}Be found, for example, in the Dye-3 Greenland ice core [11, 12]. This is formed as a spallation product when cosmic rays impact O and N in the atmosphere, and is then deposited in the ice sheet by precipitation. The dependence of precipitation on climatic conditions introduces scatter, nevertheless a clear anticorrelation with the inferred open solar flux is found [5]. In addition, the variation of ^{14}C found, for example, in tree rings is consistent with the change seen in ^{10}Be [13]. The complication for both these isotopes is that the abundances detected are subject to climate change. However, the effect is very different in the two cases: ^{10}Be is precipitated into ice sheets, a process that introduces lag and a dependence on climate, whereas ^{14}C is directly absorbed in gaseous state but has reservoirs in the biomass and oceans, exchange with which masks the true cosmogenic production rate and is expected to vary with climate. However, the similarity of the inferred century-scale changes in ^{10}Be and ^{14}C production rates strongly implies that the cause is a variation in cosmic rays and not climatic.

Svensmark and Friis-Christensen [14], *Svensmark* [15] and *Marsh and Svensmark* [16] have discussed a correlation between cosmic ray fluxes and global cloud cover on Earth. The correlation is best with higher energy cosmic ray fluxes and low-altitude cloud cover.

The present paper contains three studies. Given that the open solar flux quantifies 80% of the cosmic ray variation, section 2 looks at the direct correlation between open solar flux and cloud cover. We then use the long-term variation in the open flux derived from the aa index to look at the possible change in global cloud cover since 1900, assuming the correlation were real and not influenced by any other factors. One possibility for such a factor is the total solar irradiance (TSI) of the Sun, which is now known to show a solar cycle variation [17, 18, 19] and which also shows an upward drift over the 20th century in a variety of reconstructions that employ proxy data [4, 20, 21, 22]. The open solar flux, for the interval of the global cloud cover data at least, is well correlated with the TSI [4, 23]. This correlation was originally found in annual mean data and before observations for the rising phase of solar cycle 23 became available [4]. However, recent work [23] has shown that the correlation, although somewhat lower in monthly averages (correlation coefficient, r = 0.61), is highly significant (>99.99%), and has been maintained in solar cycle 23. Section 3 compares the correlations between cosmic rays and cloud cover and TSI and cloud cover. Section 3 also considers the effect of temporal smoothing on the significance of these correlations.

2. CLOUD COVER AND OPEN SOLAR FLUX

Figure 1 shows the time series of monthly means for 1984-1994 of the strength of the heliospheric field near Earth ($|B|$), the aa index and the percentage change in global cloud cover from the average, $<C>$ (inverted here for comparison with the other two). The cloud cover data are from the infrared (10-12 μm) "D2" set compiled and inter-calibrated by the International Satellite Cloud Climate Project (ISCCP) [25], they are for cloud-top pressures exceeding 680 hPa, and thus correspond to altitudes below about 3.2 km. The heliospheric field data are monthly averages of the hourly means of the interplanetary magnetic field (IMF) observed from a variety of near-Earth satellites (a continuation of the "Omnitape" data [26]). The relationship of this near-Earth field strength to the open solar flux has recently been evaluated [27]: in monthly averaged data it gives an estimate of the total open solar flux that has no systematic error and an uncertainty of about ±20%, dominated by the variable open magnetic flux that threads the heliospheric current sheet sunward of the Earth. This magnetic flux averages to near zero in annual data and the total uncertainty is reduced to is reduced to about ±10%, dominated by the uncertainty introduced by the small latitudinal gradients in the heliospheric field.

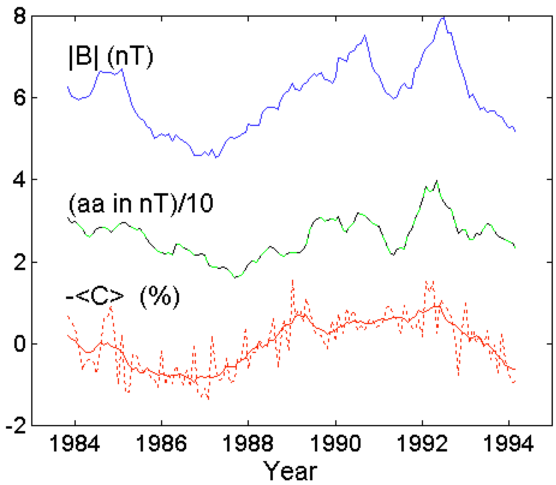

Figure 1. Monthly means of : (a) the magnitude of the heliospheric field near Earth ($|B|$, blue line) ; (b) the aa index (green and black line); and (c) $-<C>$, where C is the percentage change in global cloud cover from the overall average for 1984-1994. (The red dashed lines are monthly means of $-<C>$ and the red solid line is a 12-month smoothed running mean of the monthly data).

2.1 Correlation Analysis

The correlogram for annual means of $<C>$ and $|B|$ is shown in figure 2. We can regard the heliospheric field as the input to the system, and the global cloud cover, via the modulation of cosmic rays and any effect they have on clouds, as the output. The Wiener-Lee theorem states that the cross-correlation function (ccf) of the input and the output is the convolution of the autocorrelation function (acf) of the input and the response function of the system, F_R. Figure 2 shows that a square wave pulse form of F_R at lags between 0 and –1 year produces a good match to the observed ccf. This gives a mean lag in the response of the clouds of 6 months, similar to that found for the ^{10}Be isotope variation [5]. The origin of this lag is not clear. We would expect some delay because of the time taken for the solar wind to carry changes in the heliospheric field near Earth to the outer heliosphere and the heliospheric termination shock. However, this would be of order 3 months at most [28, 29]. When considering this lag, and the magnitude of the peak anticorrelation at it, we must remember that figure 2 uses annual means. Figure 3 shows the results of the same analysis using the monthly data.

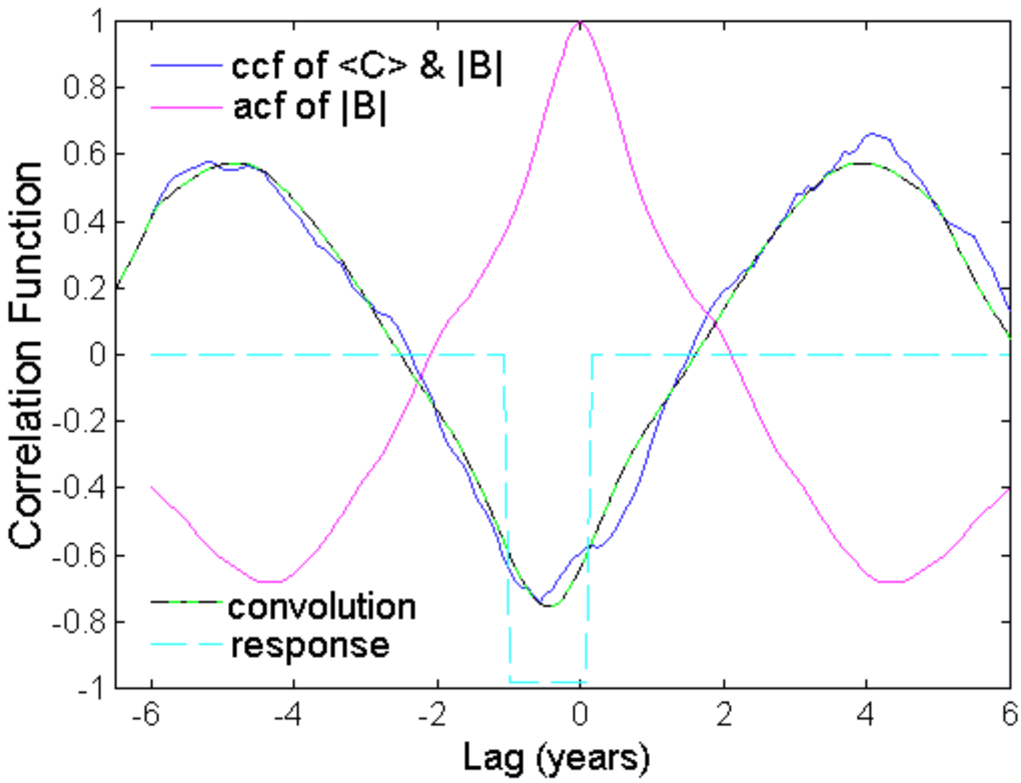

Figure 2. Correlogram for annual means of low-altitude cloud cover <*C*> and IMF strength |*B*|: (blue) the cross-correlation function (ccf) of <*C*> and |*B*| ; (mauve), the autocorrelation function (acf) of |*B*| ; (cyan dashed) the best-fit response function, F_R; (green-and-black) the convolution of F_R with the acf of |*B*|. All are shown as a function of lag, with positive values defines as <*C*> leading |*B*|. Data are for 1983 to 1994.

It can be seen that a good match to ccf is again achieved. The peak anticorrelation is at a lag of –1 month, more consistent with a solar wind propagation delay. The peak is $r = -0.53$, a weaker correlation coefficient than in Figure 2, but a statistically much more significant result because there is much less "persistence" or "conservation" in the unsmoothed data. We can quantify the significance using the Student's t-test, by making a correction to the number of degrees of freedom to allow for persistence [30]:

$$N_e = N\,(1 - a_1)/(1 + a_1)\,, \qquad t = |r|\,\{(N_e - 2)/(1 - r)\}^{1/2}\,, \qquad (1)$$

where N is the number of samples, N_e is the effective number of samples, and a_1 is the mean autocorrelation at lag 1 of the input and the output. The acf at lag 1 for <*C*> and |*B*| is 0.65 and 0.40 for monthly data, giving $a_1 = 0.505$, the t statistic derived from (1) then yields a significance of 99.98% (i.e. the probability that this correlation is a chance occurrence is just 2×10^{-4}).

2.2 Extrapolation back in Time

Data on the IMF magnitude |*B*| only extends back to 1963 [26]. However, we can go further back in time if we use the coronal source flux, F_s, which has been estimated from the aa index [2] and is related to |*B*| by:

$$F_s = (1/2).\,4\pi R_1^2\,|B_r| = 2\pi R_1^2\,|B|\,\cos(\gamma) \qquad (2)$$

where R_1 is 1AU (the mean Earth-Sun distance), B_r is the radial component of the IMF and γ is the IMF garden hose angle at Earth [2, 23]: on annual timescales γ is almost constant [2, 3] and thus $|B|$ and F_s are approximately linearly related.

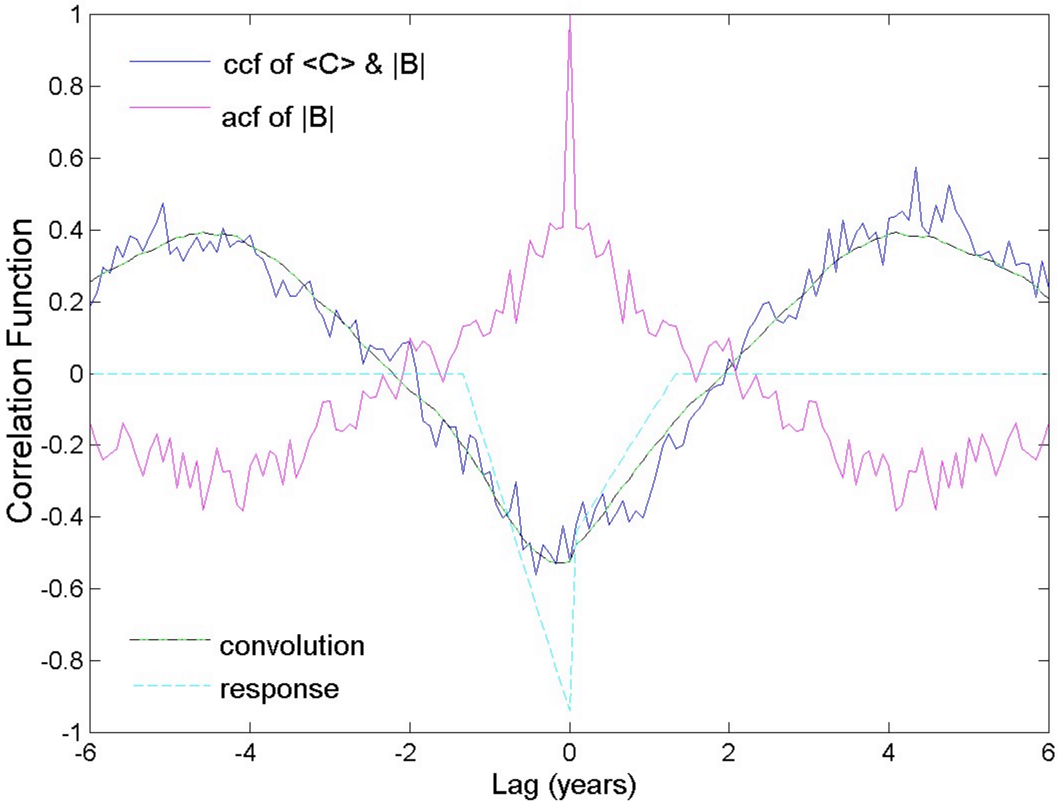

Figure 3. Same as Figure 2, but for monthly mean data

The uncertainties inherent in the use of equation (2) have recently been analysed in detail and are of order ±20% in monthly data and ±10% in annual data [23]. The implications for the past behaviour of global cloud cover depend on whether the relationship implied by the above correlation is linear or not. Figure 4 shows the scatter plot for the annual means of <*C*> and F_s. It can be seen that a linear regression (black line) gives a reasonable fit to the data (correlation coefficient, r = -0.932), but a square-law fit (blue line) is slightly better (r = -0.957).

Using the Fisher-Z test [23], we find that there is no statistical significance to the difference between these two correlations. However, figure 4 does stress how dependent the assumed functional form of the regression is, if we use it to extrapolate cloud cover to a period of very low open solar flux. This is apparent in figure 5, which plots the inferred cloud cover found from the two regressions shown in figure 4, applied to the full sequence of F_s values derived from the aa data [2]. The linear fit predicts that the minimum in F_s at 1900 would correspond to an average cloud cover that was roughly 1% higher then than at the present time: for the square-law fit, this figure is about 3%. Figure 5 shows the recent time series of the data and the two extrapolations: it can be seen that extension of the D2 dataset to cover 1994-1999 should resolve between these two proposed functional forms for the extrapolation.

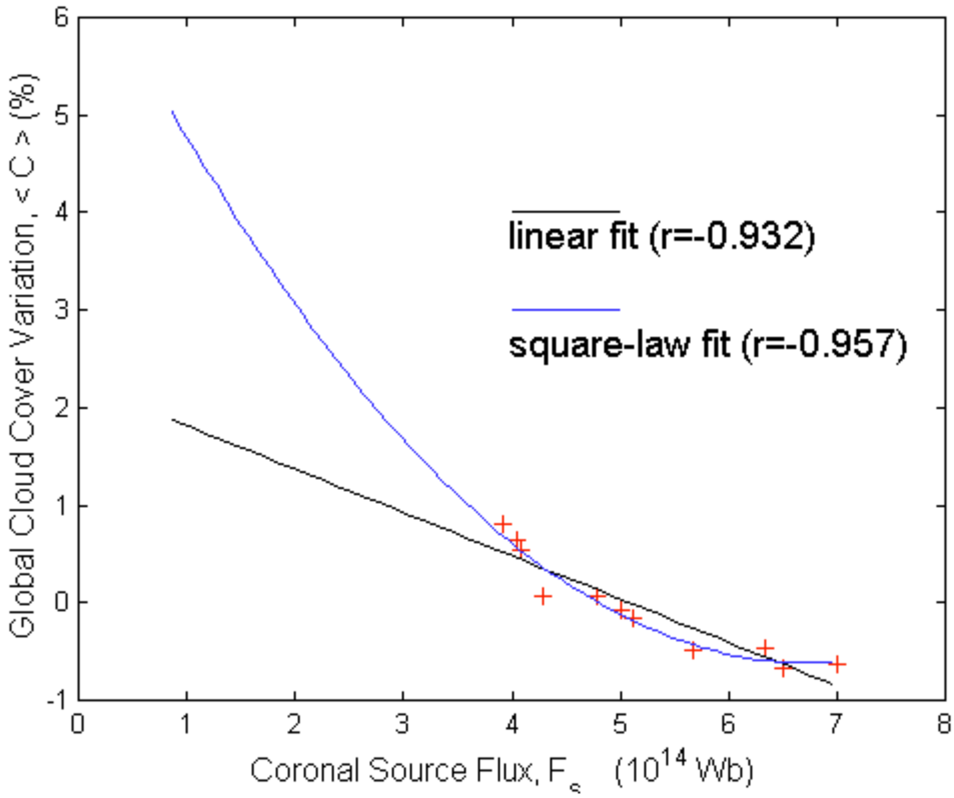

Figure 4. Annual means the global low-altitude cloud cover <*C*> as a function of the coronal source flux derived from the aa index, F_s. The red crosses are the data, the black line a linear regression fit and the blue line a square-law fit.

Thus the data strongly imply that global cloud cover was higher around 1900 than it is now. However, before we can say this with certainty and quantify the factor involved, we need to understand the physical and chemical mechanisms of the interaction and so we can understand the regression fit and know which is the most appropriate functional form to use.

3. CLOUD COVER AND TOTAL SOLAR IRRADIANCE

The correlation of global, low-altitude cloud cover is significantly higher for cosmic rays than for the 10.7 cm radio flux from the Sun [14, 15, 16]. However, at this wavelength, the solar emission is far from representative of the IR, optical, and UV emissions that dominate energy input into the terrestrial climate system (rather, F10.7 is very closely related to sunspot activity and is most relevant to Earth's upper atmosphere, the thermosphere). A sequence of total solar irradiance (TSI) values covering more than 2 solar cycles has been compiled by Fröhlich and co-workers [18, 19]. This compilation requires careful intercalibration of the various space-based radiometers used and allowance for their degradations with time and exposure. The data reveal a solar cycle variation with TSI being of order 0.1% greater at sunspot maximum than at sunspot minimum. Figures 7 and 8 show the scatter plots of the integrated, global, low-altitude cloud cover <*C*> with the Huancauyo/Hawaii cosmic ray counts (>13 GeV) and with the TSI, respectively. The red and green lines are the respective best least-squares linear regression fits: in both cases the data used are monthly means.

The peak correlation coefficients for the data shown in figures 7 and 8 were both obtained for zero lag between the data series and were -0.741 and +0.654 (for TSI and cosmic rays, respectively). Using the Students t-test discussed above, these correlations are significant at the 99.8% and 99.6% levels. Although the correlation is marginally higher for TSI than for the cosmic rays, the Fisher-Z test [23] tells us that the difference between these two correlations is not significant (the significance level being only 30.1%, i.e. the probability that the difference arose by chance is 0.699).

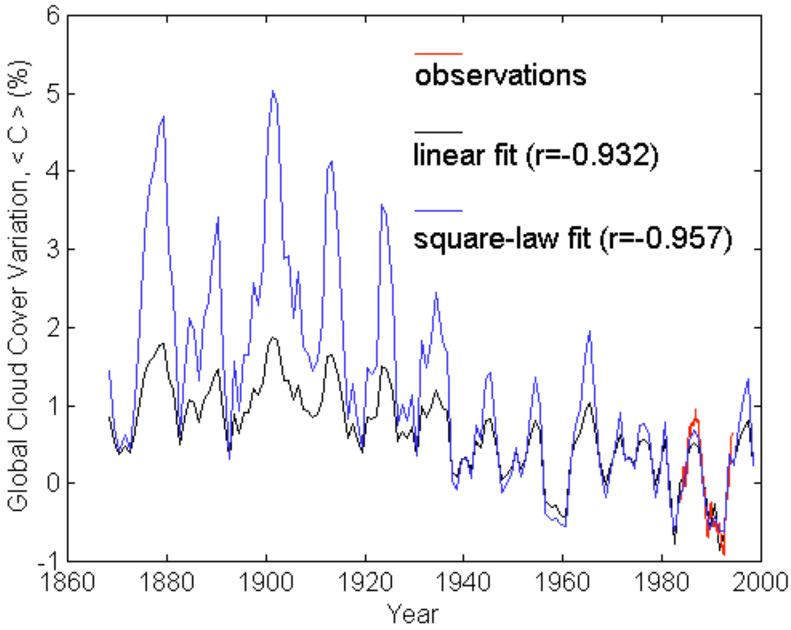

Figure 5. Extrapolated low-altitude global cloud cover estimates for 1868-1998: (black) from a linear fit to observation; and (blue) from a square-law loss. The observed data are shown in red.

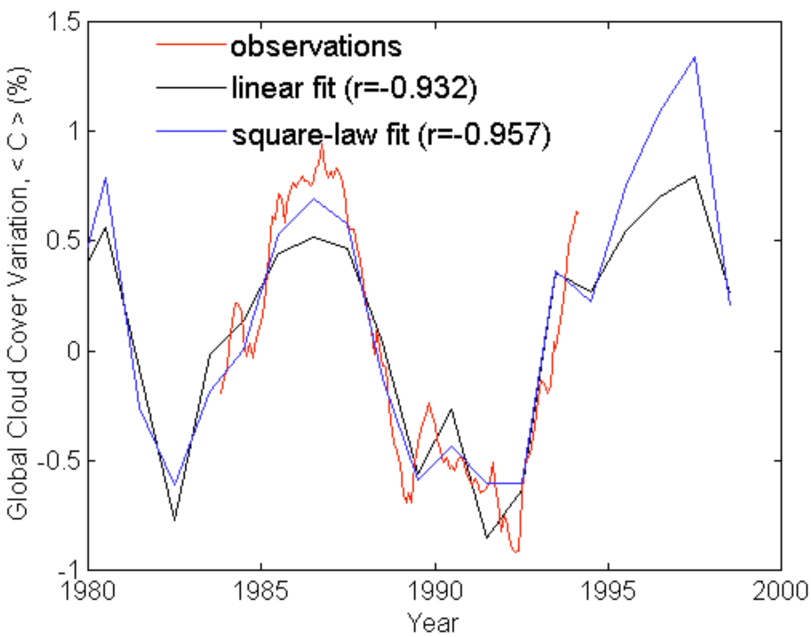

Figure 6. Detail from Figure 5 for 1980-2000.

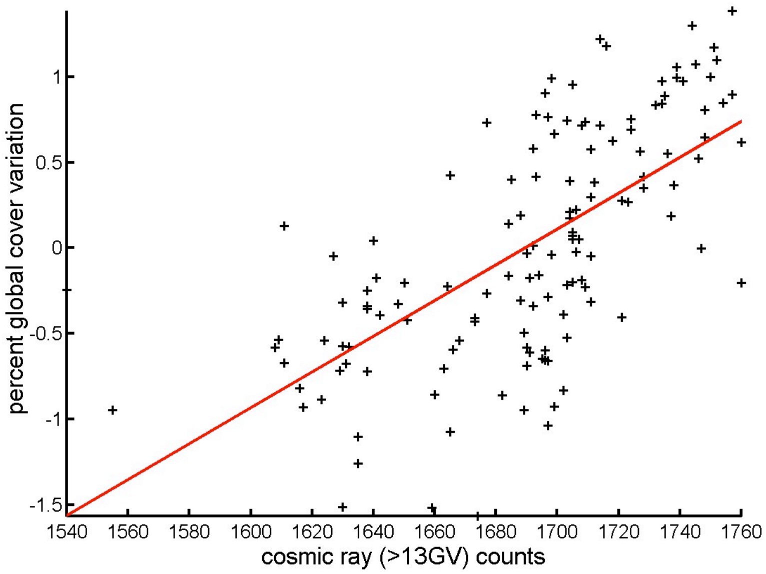

Figure 7. Scatter plot of monthly means of global cloud cover <*C*> against simultaneous monthly means of counts from the Huancayuo/Hawaii neutron monitor (that detects cosmic rays of energy > 13GeV). The red line is the best-fit linear regression.

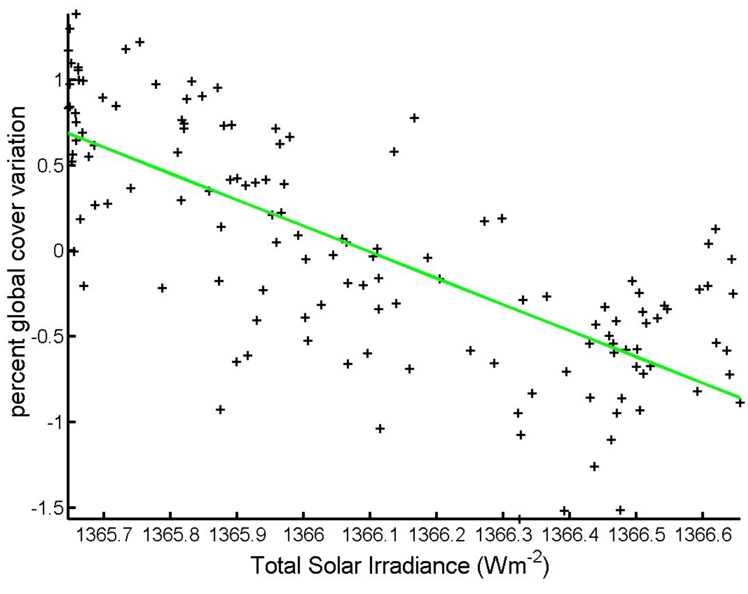

Figure 8. Scatter plot of monthly means of <*C*> against simultaneous monthly means of the total solar irradiance. The green line is the best-fit linear regression.

Figure 9 shows the time series of monthly means for the <*C*>, TSI and cosmic ray data. The TSI data and cosmic ray counts have been scaled onto the same scale as <*C*> using the linear regression lines shown in figures (8) and (7), respectively.

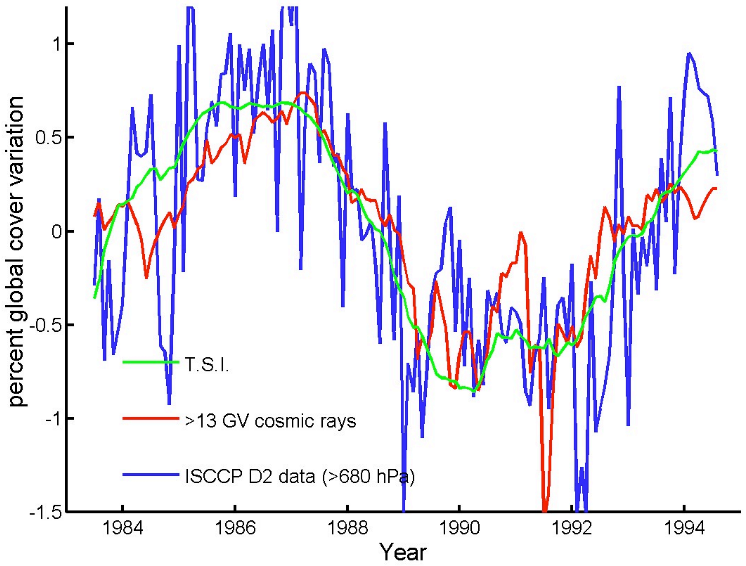

Figure 9. The variation for 1983-1995 of monthly means of : (blue) the global low-altitude cloud cover <*C*>; (green) the total solar irradiance (TSI); and (red) the >13 GeV comic ray flux. The TSI data and cosmic ray counts have been scaled using the linear regression lines shown in figures (8) and (7), respectively.

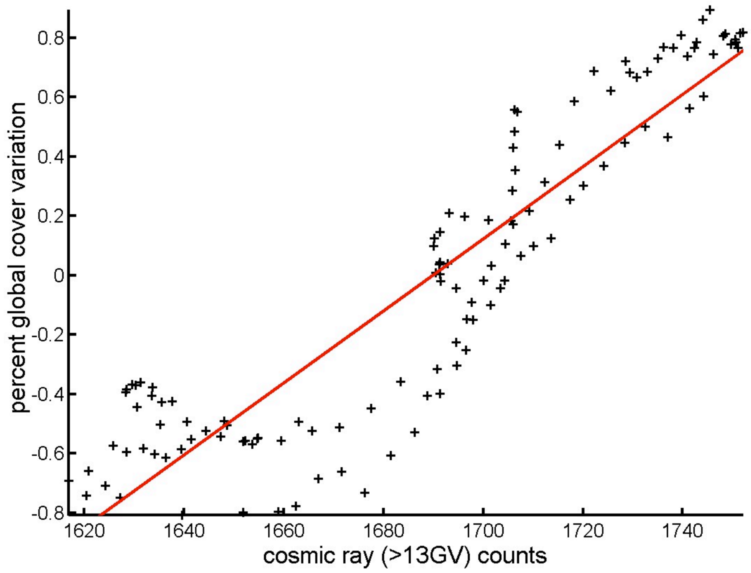

Figure 10. Same as figure 7, for 12-point running means of the monthly data

Figures 10, 11 and 12 correspond to 7, 8 and 9, respectively, but are for 12-point running means of the monthly data. It can be seen that the long-term variations are very similar in the data and the scatter in the scatter plots has been greatly reduced. For <*C*> and TSI, the lag of peak correlation is now at -1 month and the peak anticorrelation has been increased to –0.941 by the smoothing. For <*C*> and cosmic ray counts, the lag of peak correlation is still zero, but the peak correlation coefficient has been increased to +0.913. However, application of the significance test using the Students-t statistic and equation (1) shows that the significance of both these higher correlations has been reduced to zero by the smoothing. The effective number of independent samples N_e is reduced to a very small number because the acf at lag unity, a_1 , increases and approaches unity (see equation 1). This fact was noted by *Marsh and Svensmark* [16] for the correlation between <*C*> and cosmic rays, here we find the same to also be true for <*C*> and the TSI. Note that Marsh and Svensmark gained further evidence for the validity of the correlation with cosmic rays by looking at the global maps of the correlation and this should be repeated for TSI.

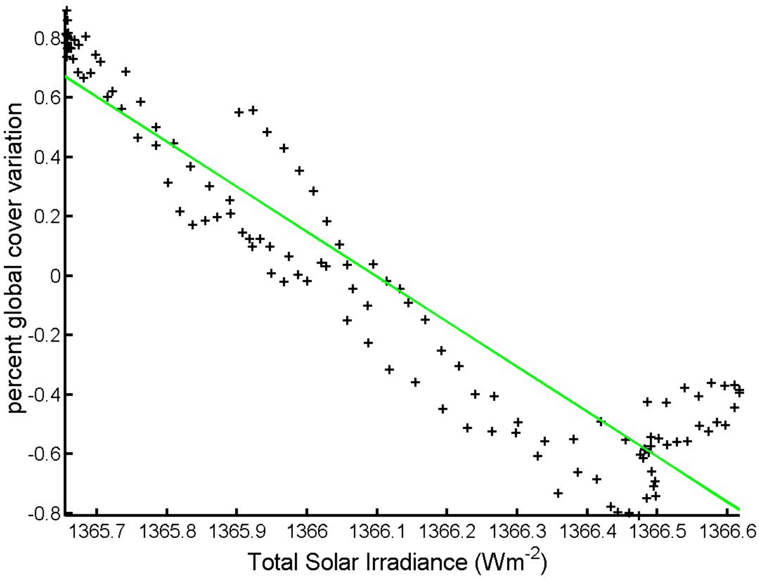

Figure 11. Same as figure 8, for 12-point running means of the monthly data

4. CONCLUSIONS AND DISCUSSION

The fraction of the globe covered by low-altitude clouds has shown a solar cycle variation in recent data [14, 15, 16]. With little more than one cycle of heterogeneous data, we cannot be sure that this is truly an oscillation that will continue to match the solar cycle variations so well. The temporal correlation between the low-altitude global cloud cover and cosmic ray counts is highly significant in monthly data. Introducing smoothing increases the correlation coefficient magnitude and makes the time-series plots appear to be in greater agreement, but also removes the statistical significance from the correlation.

An anti-correlation between the total solar irradiance (TSI) and global cloud cover is found to have the same strength and significance as the correlation with cosmic ray fluxes. Thus we cannot tell if it is more likely to be the cosmic rays or the TSI that are influencing cloud cover. In addition, because of the nature of all correlation studies, cannot we be sure that either TSI or cosmic rays have a causal effect on cloud cover. A parametric study using a global coupled ocean-atmosphere model is required to see if we would expect this anticorrelation between TSI and low-altitude cloud cover.

Whether caused by TSI or comic ray variations, the presence of a solar cycle signal in global cloud cover would effectively be an amplification of the solar effect on Earth's climate. Recent modelling using the UK Hadley Centre's HAD3CM global coupled ocean-atmosphere model has pointed towards the presence of such an amplification, both when fitting the 11-year solar cycle variation in the amplitude of the global spatial pattern of average tropospheric temperatures, and when fitting the 150-year drift in the global average surface temperature [M.R. Allen et al., Private communication, 2000]. In both cases an amplification factor of about 2.5 was needed to gain the best fit, compared to the value from radiative forcing arguments. To within the 90% confidence level, this factor varied between 1 and 6.

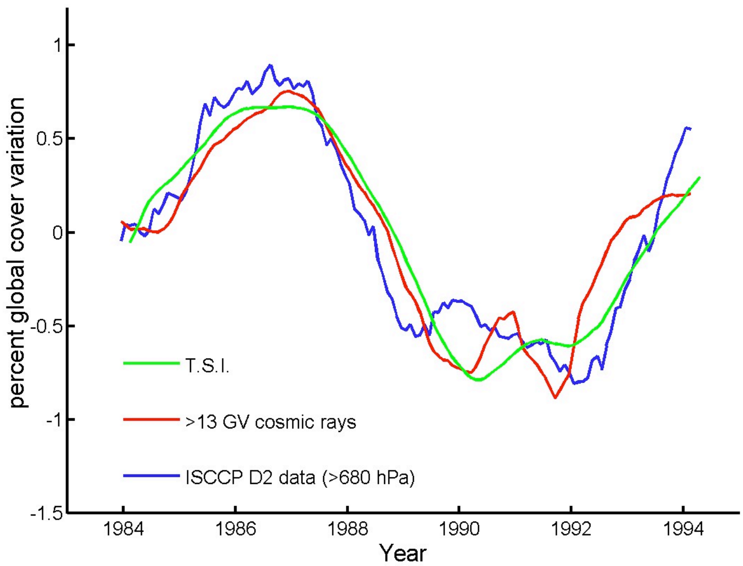

Figure 12. Same as figure 8, for 12-point running means of the monthly data

Somewhat surprisingly, this amplification of the solar influence calls for an amplification factor for the man-made influences that go into the model [M.R. Allen, private communication, 1999]. This amplification factor is much smaller than for the solar effect (of order 1.1). The key reason for this behaviour is that the main drift in the longer-term TSI variation took place between 1900-1950. This also happened to coincide with a period of reduced volcanic activity (a global cooling phenomenon). On the other hand, anthropogenic greenhouse gasses have had their dominant effect in the past 30 years. Underestimating the solar effect early in the 20^{th} century effectively causes the model to fit an anthropogenic effect that starts earlier but is less steep.

ACKNOWLEDGEMENTS

The author thanks Nigel Marsh and Henrik Svensmark for the provision of the D2 cloud cover data and the World Data Centre system for the cosmic ray, heliospheric and geomagnetic data. He is also grateful to Myles Allen, Nigel Marsh, Henrik Svensmark, Jasper Kirkby, and many other scientists for valuable discussions. This work was funded by the UK Particle Physics and Astronomy Research Council.

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