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Testing the proposed causal link between cosmic rays and cloud cover

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Abstract
A decrease in the globally averaged low level cloud cover, deduced from the ISCCP infrared data, as the cosmic ray intensity decreased during the solar cycle 22 was observed by two groups. The groups went on to hypothesize that the decrease in ionization due to cosmic rays causes the decrease in cloud cover, thereby explaining a large part of the currently observed global warming. We have examined this hypothesis to look for evidence to corroborate it. None has been found and so our conclusions are to doubt it. From the absence of corroborative evidence, we estimate that less than 23%, at the 95% confidence level, of the 11 year cycle change in the globally averaged cloud cover observed in solar cycle 22 is due to the change in the rate of ionization from the solar modulation of cosmic rays.

Keywords: clouds, cosmic rays, global warming

1. Introduction

In [1, 2] a correlation was demonstrated for 'low clouds' (<3.2 km in altitude) between the changes in the globally averaged 'low cloud cover (LCC) anomaly' and the changes in the cosmic ray (CR) count rate (e.g. see figure 1 of [2]). Here 'LCC anomaly' means the difference between the mean monthly LCC and the time averaged value for the month. The LCC anomaly was derived by these groups from the satellite data provided by the International Satellite Cloud Climatology Project (ISCCP) from the monthly averaged D2 analysis using the infrared data [3]. It was implied by both groups that a decrease in CR intensity causes a decrease in LCC. Since this may not be the case if both effects are correlated to a third variable, it is prudent to look for further evidence of such a causal connection. Such a causal connection would have vast importance since, according to [1, 2, 4], it could be the main cause of the presently observed global warming. The proposed mechanism for this depends on the observation of an increase in solar activity over the last century [5]. An increase in solar activity causes a net decrease in CR intensity which, according to the causal connection proposed in [1, 2, 4], causes a decrease in LCC. This, in turn, leads to increased warming of the Earth's surface by the Sun. The effects of solar changes on the increases in the global mean surface air temperature have been discussed more fully in [6] and are reviewed in [7].

The International Panel on Climate Change (IPCC) has not considered this effect as significant [8] since the origin of the correlation observed in [1, 2] has been questioned [9]. The grounds for this doubt are that the ISCCP infrared data give different results from the day time low cloud data and also that the correlation after 1994 is of poor quality. The correlation was also questioned since a similar one was observed over the USA but with the opposite sign [10] to that seen in [1, 2]. These doubts should be weighed against the following. Firstly, in the daytime LCC shown in figure 1b of [9] there is structure at the maximum of the solar activity, albeit with a poorer correlation than the infra red data with the CR modulation. Secondly, there is no inconsistency between the surface data over the USA seen in [10] and the ISCCP infra red data since the latter also show an anti-correlation over the USA (see figure 2a in [2], which we also confirm). Thirdly, a correlation between the CR rate and cloud cover was also observed in [11] where cloud cover was determined in a completely different way from that adopted in [1, 2, 4]. Fourthly, a latitude dependence between the calculated ion concentration from CR at altitude 3 km and the low cloud amount was reported in selected local regions where the correlation coefficient between the two distributions is high [12]. Fifthly, whilst after 1994 there is a poor correlation at high Earth latitudes, we see a possible correlation in the tropical regions (see below) and it is well known that sequential solar cycles behave differently from each other due to the reversal of the solar magnetic field. The IPCC labels the level of scientific understanding of the observed correlation as 'very low'. Given these facts the correlation observed in [1, 2] needs to be studied further. Here we adopt the approach of looking for other possible manifestations of the causal connection, assuming that it exists, in order to corroborate the effect or otherwise.

The implication of the causal connection proposed in [1, 2] is that LCC is influenced by the rate of ion production in the atmosphere. In this paper, we have examined various incidences of ionizing radiation changes in the atmosphere from cosmic rays to look for consequential changes in LCC which would result if the causal connection existed. We have looked for changes in LCC from changes in the CR intensity due to solar activity as the geomagnetic latitude increases i.e. as the vertical rigidity cut off (VRCO) decreases. We have also looked at the effects on LCC of the known sporadic changes in the CR intensity. These cases, where there is a change in the ionization rate, have been examined to see if a corresponding change in cloud cover occurs, as would be expected from the causal connection hypothesized in [1, 2]. Throughout we use the same ISCCP D2 data sample as in [1, 2] unless otherwise stated.

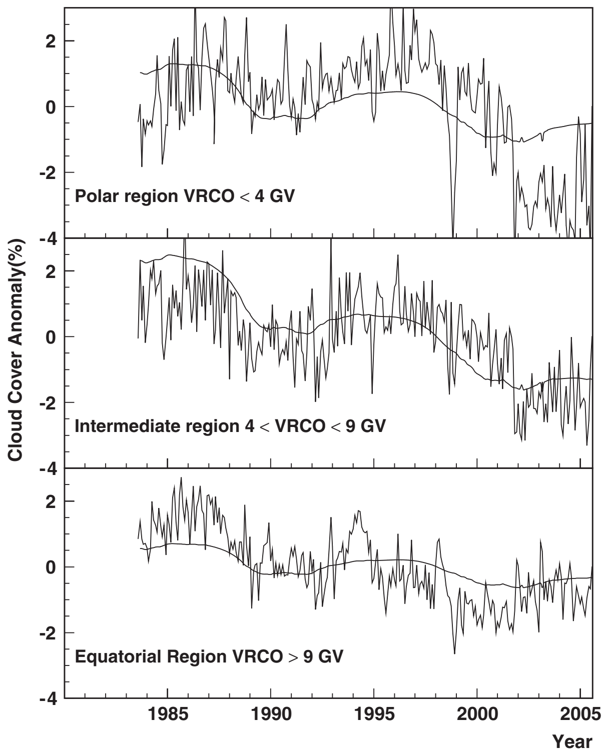

Figure 1. The LCC anomaly as a function of time for various ranges of vertical cut off rigidity (VRCO). The smooth curve shows a fit of the monthly mean of the daily sun spot number (SSN) with an assumed linearly falling systematic change. The SSN is anti-correlated with the CR count rate with a lead time of some months.

2. The correlation between cosmic rays (CR) and low cloud cover (LCC)

Figure 1 shows the LCC anomaly determined from the ISCCP infra red data as a function of time averaged over the Earth, in three separate regions. The smooth curves in figure 1 show the best fits of the LCC anomaly to the mean daily sun spot (SS) number (inverted) superimposed on an assumed linear change with time in the LCC anomaly. Such a change may be real or it could be due to an artefact of the satellite instrumentation as discussed in [13]. The fit was made using the CERN library fitting programme MINUIT [14] to minimize the value of χ^2 between the measurements and the curve. The errors on the data points were taken from the mean square deviations of independent pairs of neighbouring points. The free parameters in the fit were the slope and intercept of the assumed smooth linear systematic change in the LCC, a multiplicative constant for the monthly averaged daily American sunspot number (SSN) [15] and a time shift for the delay between the onset of the *dip* in the LCC and the increase in the SSN. The multiplicative constant represents the amplitude of the dip in the LCC per unit change in SSN. We take this amplitude as the magnitude of 'the effect'. The fits were rather poor (see figure 1) with values of χ^2 per degree of freedom of from 1.5 to 2.5. However, fits between 1985 and 1996 (solar cycle 22) were better than this, allowing the amplitude of the dip to be determined in this time range. The modulation of the cosmic ray intensity is strongly anti-correlated with the variation in the SSN. The time shift between the onset of the dip and the change in the SSN will be used in the manner to be described later.

The observed dip in figure 1 is similar to that seen in [1, 2] between the years 1985 and 1995. However, the dip in LCC seen in solar cycle 22 (peaking in 1990) is not evident in solar cycle 23 (peaking in 2000) except, surprisingly, in the equatorial region where the solar modulation is least.

The globally averaged decrease in LCC during solar cycle 22 (averaging the dips in figure 1) is $1.28 \pm 0.14\%$. The globally averaged total LCC amount is 28% giving a change in LCC during the dip of $\Delta LCC/LCC = 4.6 \pm 0.5\%$. The globally averaged peak to peak modulation in the CR neutron monitor count rate is computed to be $11 \pm 1\%$ of the total. The neutron modulation was determined from a study of the data from 35 neutron monitors around the globe [16][3] using similar methods to those described in [17]. A fit to the measurements of the peak to peak modulation versus SSN gives $\Delta N/N = 1.15 \times 10^{-3}$–$0.061 \times 10^{-3}\ V$ per SSN, where V is the VRCO. The muon modulation is a factor 3 lower than this [18] due to the higher primary energy needed to produce muons. Ionization is also produced from the electromagnetic component of CR whose long term modulation has not been measured. This will depend on π^0

[3] We thank Takashi Watanabe for providing us with the data from the neutron monitors.

production from CR primary interactions which will have a threshold energy intermediate between those for muons and neutrons. We therefore assume that the total globally averaged solar modulation of the cosmic ray ionization rate is the average of those for muons and neutrons i.e. $7 \pm 3\%$, where the uncertainty bridges the gap from muons to neutrons. The solar modulation of the globally averaged ionization rate, q, will be reduced to $\Delta q/q = 6 \pm 3\%$ by the dilution of the ionization over land (29% of the Earth's surface) by radioactivity which will produce an ionization rate of a similar magnitude to that from CR at low cloud altitude [19]. The fractional change in the LCC is therefore related to the rate of ionization change due to solar modulation by

$$\frac{\Delta \mathrm{LCC}}{\mathrm{LCC}} = 0.77 \pm 0.38 \frac{\Delta q}{q} \qquad (1)$$

implying that LCC $\propto q^{\xi}$ with $\xi = 0.77 \pm 0.38$, where the error is dominated by the uncertainty in $\Delta q/q$. This is compatible, within the error, with a $q^{0.5}$ behaviour. Such behaviour is expected, at least in clean air, if LCC $\propto n$, where n is the small ion concentration which is expected to be limited mainly by recombination [20].

To study the detailed shape of the correlation shown in figure 1 the globally averaged LCC amount is plotted directly against the Climax neutron counter monitor rate, N_{C}, in figure 2. The good correlation is evident. Fits of the form

$$\mathrm{LCC} = \beta + \gamma N_{\mathrm{C}}^{\alpha} \qquad (2)$$

have been made. Here the first parameter, β, can be interpreted as a measure of the LCC amount attributable to non-ionizing sources and the second term to ionizing sources. If the part of the LCC amount which depends on ionization is proportional to the small ion concentration, n, and $n \propto q^{\xi}$, the parameter α is related to ξ by $\alpha = a_1 a_2 \xi$, where $a_1 = (\delta q/q)/(\delta N/N)$ and $a_2 = (\delta N/N)/(\delta N_{\mathrm{C}}/N_{\mathrm{C}})$.[4] We take $\delta q/q = 6 \pm 3\%$, the globally averaged solar modulation $\delta N/N = 11 \pm 1\%$ (as discussed above) and the solar modulation measured for the Climax detector to be $\delta N_{\mathrm{C}}/N_{\mathrm{C}} = 19\%$, so that $a_1 a_2 = 0.32 \pm 0.16$.

The data in figure 2 are insufficient to determine precisely the parameters, α, β and γ separately. Fits with different combinations of the parameters are equally good as measured by the χ^2. However, the value of χ^2 rapidly becomes unacceptable when β is increased to a value corresponding to more than 70% of the cloud arising from non-ionizing sources, i.e. a fraction of at least 30% comes from ionization. The following argument also shows that the latter fraction must be large. The smooth curve in figure 2 shows the fit with $\beta = 0$ which gives $\alpha = 0.17$ with a $\chi^2 = 148.9$ for 146 degrees of freedom and a correlation coefficient of 0.54. The values of the parameters α, β and γ are strongly correlated such that increasing values of α are associated with increasing values of β and decreasing values of γ. The fits with $\alpha > 0.16$, corresponding to $\xi > 0.5$, give positive values of β while fits with $\alpha < 0.16$, corresponding to values of $\xi < 0.5$, give negative values of β which are unphysical. Assuming that it is implausible that the LCC amount generated by ionization varies faster than linearly with q, i.e. $\xi < 1$, then α must be less than 0.48, taking $\delta q/q$ at its upper limit of 9%. Such a value of α gives a fit with $\beta = 20\%$, implying that the fraction of the LCC generated by sources other than ionization is less than $20/28 = 0.7$ i.e. a minimum fraction of 0.3 of the LCC amount is generated by ionization. At $\xi = 0.5$ the value of β is compatible with zero. Hence assuming ξ lies in the range 0.5–1.0 the fraction of the LCC generated by ionization lies somewhere between 1 and 0.3, respectively.

[4] It can be seen that $\delta q/q = a_1 a_2 \delta N_{\mathrm{C}}/N_{\mathrm{C}}$ which on integration gives $q \propto N_{\mathrm{C}}^{a_1 a_2}$ i.e. $q^{\xi} \propto N_{\mathrm{C}}^{a_1 a_2 \xi}$.

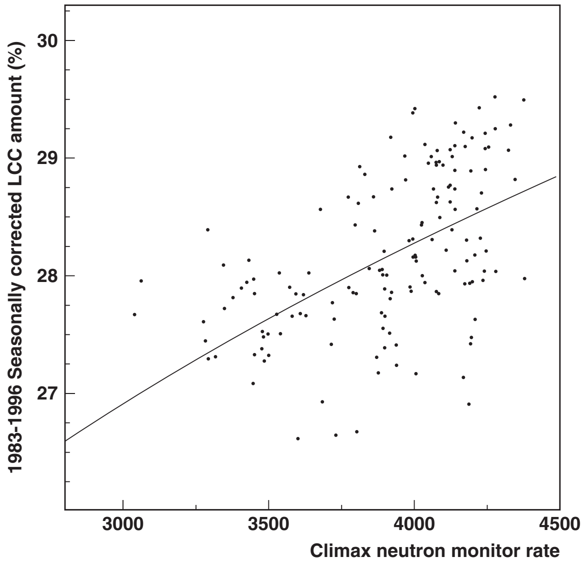

Figure 2. The seasonally corrected LCC amount as a function of the Climax neutron monitor count rate (both monthly averaged) during solar cycle 22 (1983–1996). The seasonally corrected LCC amount was obtained by adding the globally averaged LCC to the monthly globally averaged anomalies. The smooth curve shows the fit described in the text.

In summary, assuming that the correlation shown in figures 1 and 2 is not accidental a very large fraction of the LCC must be generated by ionization. We now attempt to corroborate this assumption and this necessary deduction.

3. Latitude dependence of 'the effect'

It is well known that the magnitude of the CR time variation, due to the 11 year solar cycle, varies with latitude. More accurately, it is a function of the VRCO, the reason being that the geomagnetic field deflects away more low energy particles as the geomagnetic equator (highest VRCO) is approached. Since the CR flux increases rapidly as the primary energy decreases, the solar modulation becomes less severe as the VRCO increases towards the geomagnetic equator. Hence, if the causal connection between the CR ionization rate and LCC proposed in [1, 2] exists with the necessary large fraction of the LCC produced by ionization demonstrated above, one would expect larger changes in LCC at low values of VRCO than at high values. Furthermore it is known that there is a delay of some months between the decrease in the CR intensity and the increase in the sun spot (SS) number with the even numbered solar cycles showing smaller delays than the odd numbered[5]. Note that the CR count rate is anti-correlated to the SS number.

The observed dip in figure 1 is similar to that seen in [1, 2] between the years 1985 and 1995. However, the expected rise in amplitude of this dip with decreasing VRCO is not apparent. To investigate the effect of the VRCO further and to check that the above result was not due to a latitude dependent efficiency of the cloud production mechanism, the LCC was determined in three strips of latitude for the Northern and Southern hemispheres of the Earth separately. The amplitude of the dip in solar cycle 22 was measured from the fit for each, as a function of VRCO. The dip was visible in every subdivision. Figure 3 (upper panel) confirms that the amplitude of the dip appears to be rather constant with VRCO rather than increasing with the observed increase in CR modulation determined as described above. Furthermore there is no discernible difference between the Northern (where oceans are less dominant) and Southern hemispheres (where oceans are more dominant). Figure 3 (lower panel) shows that the measured value of the delay between the onset of the dip and the change in SS number fluctuates randomly rather than concentrates around a fixed delay (expected to be −3 months for the CR increase in solar cycle 22). Each latitude band has a median value compatible with zero with an overall mean of -0.9 ± 1.6 months, where the error is the standard error determined from the root mean square (RMS) deviation of the measurements from the mean. This is compatible with the onset of the increase in SS number but somewhat earlier than the arrival time of the CR increase (−3 months). Hence there is a somewhat better time correlation between the start of the dip and onset of the increase in the SS number than with the change in the CR rate, although the error is too large to be conclusive.

Neither the amplitude variation with VRCO nor the arrival times shown in figure 3 corroborate the claim of a full causal connection between CR ionization rate and the LCC anomaly. We proceed to set a limit on any contribution from a partial correlation.

We attempt to quantify the part of the dip related to changes in the CR ionization rate and that related to other sources which are independent of the ionization rate, as follows. The change in LCC during the solar cycle, ΔLCC, can be decomposed into a part which is dependent on the change in the ionization rate $\Delta\mathrm{LCC_I}$ and a part due to other mechanisms correlated with solar activity but not directly due to ionization, $\Delta\mathrm{LCC_S}$, i.e. $\Delta\mathrm{LCC} = \Delta\mathrm{LCC_I} + \Delta\mathrm{LCC_S}$. Differentiation shows that $\Delta\mathrm{LCC_I} = \kappa \mathrm{d}N/N$. where $\kappa = N\mathrm{d}g(N)/\mathrm{d}N$ with $g(N)$ the functional dependence of the LCC on the ionization rate as measured by the neutron monitor rate, N. The function $N\mathrm{d}g(N)/\mathrm{d}N$ is slowly varying with N for reasonable functions, $g(N)$, over the range of changes of $\delta N/N$ during the solar cycle, so that κ is approximately constant. For example, if LCC $\propto n \propto q^{\xi} \propto N^{a\xi}$ where $a = (\delta q/q)/(\delta N/N) \sim 0.5$ (see above) and $\xi \sim 0.5$, κ will change by ∼5% as $\delta N/N$ changes from 0 to 0.2. From this it can be seen that the dip depth may be expressed as

$$\Delta\mathrm{LCC} = \Delta\mathrm{LCC_S} + \kappa\delta N/N \quad (3)$$

where κ can be treated as a constant.

We use this to identify the part of the distribution in the upper panel of figure 3 which correlates with the CR modulation. A fit was performed of the shape of the neutron modulation variation (the correlated part) and a constant term (the uncorrelated part) to the measurements. The fit gave the fraction of the distribution correlated with the neutron modulation to be 0.02 ± 0.13 i.e. compatible with zero with a value of $\chi^2 = 17.8$ for 16 degrees of freedom. From this it is deduced that less than 23% of the distribution, at the 95% confidence level, belongs to the part correlated with the CR modulation and more than 77% belongs to the other sources correlated to solar activity but not directly to the change in ionization rate. These limits are incompatible with a large part of the change in the LCC during solar cycle 22 being produced by a change in ionization and so they do not corroborate the hypothesis of such a change proposed in [1, 2]. The correlation seen in figures 1 and 2, if real, must be due to an effect, other than ionization, which is correlated with solar activity.

This upper limit represents a limit on the fraction of the globally averaged dip in the LCC seen in solar cycle 22 which is caused by CR ionization. There could be local changes from this ionization such as those reported in [12] which, from the

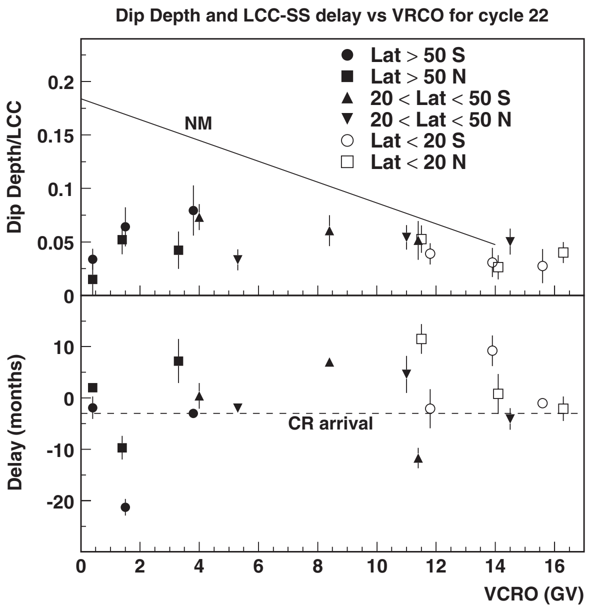

Figure 3. The observed modulation of the LCC (upper panel) as measured from the fit to solar cycle 22 only (see figure 1). The 'modulations' are expressed by the dip amplitude at the time of the solar maximum (1991) divided by the mean LCC. The smooth curve labelled NM shows a fit to the fractional modulation, $\mathrm{d}N/N$, measured from neutron monitors around the World (see text). The lower panel shows the fitted delay between the onset of the dip and that of the SS number in months. The dashed line shows the expected delay if a correlation existed between the changes in CR and CC. The measured delay between the CR decrease and increase in SSN is 3 months in cycle 22. NB positive delay means CC precedes the increase in SSN.

[5] We are grateful to A Erlykin and K Kudela for the measurement of the CR-SS delay.

above upper limit, must contribute less than a fraction of 23% to the globally averaged dip.

4. Sporadic changes in cosmic ray activity

Rapid changes in CR intensity occur from time to time. These take the form of large intensity increases, so called ground level events (GLE), or smaller decreases in intensity (Forbush decreases) [21]. Such changes of intensity usually last for periods from a few hours to days and sometimes longer in the case of Forbush events. A survey has been given in [22]. These changes present an opportunity to test for LCC–CR correlations since if the causal connection proposed in [1, 2] exists one would expect to see changes in the LCC at the times of these events. The causal connection implies an increase (decrease) in LCC following a GLE (Forbush decrease) and we assume that such changes occur in times shorter than days.

There were 3 very large GLEs during the time span of the ISCCP cloud data (1985–2005), each lasting several hours. The event on 29 September 1989 was clearly seen in both the CR neutron and muon monitors [23]. The peak intensity neutron monitor enhancement in this event was observed to change from four times the steady state value for neutron monitors with VRCO close to zero down to 1.17 times the steady state value at a VRCO of 11.5 GV while the muon monitors varied from 1.4 [23] to 1.08 times the steady state value in the same range of VRCO. The other two events (on 24 Oct 1989 and on 20 Jan 2005) had similarly large neutron monitor signals but they did not produce visible signals in the Nagoya muon monitor[6]. The global LCC averages as a function of time were reconstructed from the ISCCP D1 data, which are 3 h averages rather than the monthly averages of the D2 data, at times before and after each of the three GLEs. There were no visible anomalous changes in these global averages following each GLE where an increase of more than 2% would have appeared anomalous. It is difficult to make quantitative estimates of the expected changes in the LCC, according to the hypothesis of [1, 2], from such events since the amount of ionization produced by them is unknown. One can only conclude that the events do not provide corroborative evidence for the causal connection between cloud cover and ionization proposed in [1, 2, 4] even though the changes in the neutron monitor rate were very large.

The larger Forbush decreases during the time span of the ISCCP data (1984–2005) have been examined to see if they could be correlated with changes in the LCC. Most of these give relatively small changes in the CR intensity compared to the 11 year solar cycle modulation. Similar changes in the rates in the Nagoya muon detector (see footnote 6) were observed to those in a neutron monitor at the same VRCO. The globally averaged cloud cover change was taken as the difference between the LCC, using the ISCCP D2 data, in the month of the decrease and the average of the three preceding months. For some large shorter duration events the D1 data were used, taking the difference between the average LCC during 14 days before the event and seven days after. Figure 4 shows the change in the LCC anomaly for each Forbush decrease plotted against the change in the Oulu neutron monitor count rate averaged over the duration of the decrease. The data below an Oulu count rate change of 9%, which is roughly half the solar modulation during solar cycle 22, are too statistically imprecise to be conclusive. The statistical errors were determined from the RMS deviation of these points about the mean. However, the four points above a counting rate change of 9% have a mean LCC anomaly change of 0.68 ± 0.45%. This is compatible with the dashed line showing no correlation between the LCC and CR rate changes but it is 2.8 standard deviations above the value of −0.6% expected had there been a correlation similar to that seen in figure 2.

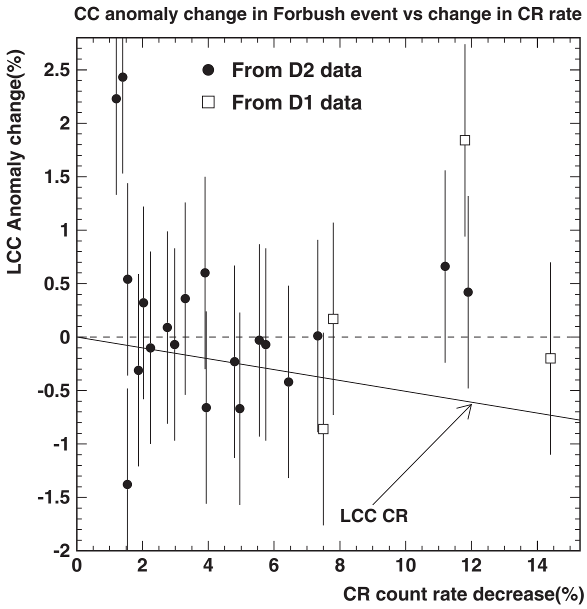

Figure 4. The measured change in the LCC plotted against the change in the Oulu neutron monitor count rate during the measurement time of 1 month for the D2 data (solid circles) and 1 week for the D1 data (open squares). The solid line shows the values expected from the smooth curve shown in figure 2. The Oulu count rate was observed to change by 17% due to the solar modulation during solar cycle 22.

A further attempt was made to correlate monthly fluctuations in the neutron monitor rates with those in the LCC. For each of the LCC and Climax neutron monitor monthly averages a linear extrapolation from seven of the measurements was made to the eighth. The fluctuation was then taken to be the difference between the eighth measurement and the extrapolated value. The regression line fitted to the plot of fluctuations in the LCC against the fluctuations in the Climax data had the form $\Delta\mathrm{LCC} = -0.0098 \pm 0.019\Delta N_\mathrm{C}/N_\mathrm{C}$, with correlation coefficient −0.03 indicating a poor correlation. Here $\Delta \mathrm{N_C}/N_\mathrm{C}$ in per cent is the fluctuation in the Climax count rate. If the dip in LCC shown in figure 1 is due to ionization from cosmic rays as hypothesized in [1, 2], the curve fitted to the data in figure 2 would predict that this line should have the form $\Delta\mathrm{LCC} = -0.048\Delta \mathrm{N_C}/N_\mathrm{C}$ i.e. a slope which is 2 standard deviations greater than that obtained from these fluctuations.

In conclusion, it is statistically improbable that the Forbush decreases are compatible with the hypothesis of a

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correlation between LCC and ionization as proposed in [1, 2]. Hence Forbush decreases do not provide evidence which can be used to corroborate such a hypothesis. There have been previous reports of observations of correlations between cloud cover and Forbush decreases [11, 24]. These seem to be incompatible with our observations although the statistical precision of the data is not powerful.

5. Conclusions

The dip in amplitude of 1.28% in the low altitude cloud cover noted in [1, 2] in solar cycle 22 (peaking in 1990) has also been seen in this analysis. This dip anti-correlates in shape with the observed mean daily sun spot number i.e. correlates with the change in cosmic ray intensity due to solar modulation. The dip is less evident in the following solar cycle 23 although it is possibly present in the tropical regions of the Earth. If the correlation noted in [1, 2] and its hypothesized causal connection between low cloud cover and ionization are real, it is shown that the magnitude of the effect implies that a large fraction of the low cloud cover is formed by ionization. However, no evidence could be found of changes in the cloud cover from known changes in the cosmic ray ionization rate.

In conclusion, no corroboration of the claim of a causal connection between the changes in ionization and low cloud cover, made in [1, 2], could be found in this investigation. From the distribution of the depth of the dip in solar cycle 22 with geomagnetic latitude (the VRCO) we find that, averaged over the whole Earth, less than 23% of the dip comes from the solar modulation of the cosmic ray intensity, at the 95% confidence level. This implies that, if the dip represents a real correlation, more than 77% of it is caused by a source other than ionization and this source must be correlated with solar activity.

Acknowledgments

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