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Empirical evidence for a nonlinear effect of galactic cosmic rays on clouds

By R. Giles Harrison* and David B. Stephenson

Department of Meteorology, The University of Reading, PO Box 243, Earley Gate, Reading RG6 6BB, UK

Galactic cosmic ray (GCR) changes have been suggested to affect weather and climate, and new evidence is presented here directly linking GCRs with clouds. Clouds increase the diffuse solar radiation, measured continuously at UK surface meteorological sites since 1947. The ratio of diffuse to total solar radiation—the *diffuse fraction* (DF)—is used to infer cloud, and is compared with the daily mean neutron count rate measured at Climax, Colorado from 1951–2000, which provides a globally representative indicator of cosmic rays. Across the UK, on days of high cosmic ray flux (above 3600×10^2 neutron counts h^{-1}, which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by (19 ± 4) %, and (ii) the diffuse fraction increases by (2 ± 0.3) %. During sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction. The diffuse radiation changes are, therefore, unambiguously due to cosmic rays. Although the statistically significant non-linear cosmic ray effect is small, it will have a considerably larger aggregate effect on longer timescale (e.g. centennial) climate variations when day-to-day variability averages out.

Keywords: solar–terrestrial physics; atmospheric electricity; solar variability and climate

1. Introduction

In 1959, Edward Ney suggested that cosmic rays could affect the weather (Ney 1959), an idea revived by the positive correlation found between monthly galactic cosmic rays (GCR) and satellite-retrieved low cloud amount from 1983 to 1994 (Marsh & Svensmark 2000). Close associations have also been observed between cosmogenic isotopes and paleoclimate records, such as for the monsoon (Neff *et al.* 2001) and ocean temperatures (Bond *et al.* 2001). Cosmic rays are known to have variations on a wide range of timescales (Wolfendale 1963). An increase in cosmogenic isotope production occurred during the Maunder Minimum in solar activity (Beer 2000), and on longer times, there is some evidence for cosmic ray increases during passages of the galaxy's spiral arms (Shaviv 2002).

Cosmic rays produce molecular cluster ions throughout the atmosphere, down to the surface (e.g. Harrison & Carslaw 2003). By analogy with C. T. R. Wilson's cloud chamber, these might be expected to provide condensation nuclei on which cloud droplets form. This does not in fact occur, as natural atmospheric water

* Author for correspondence (r.g.harrison@reading.ac.uk).

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vapour supersaturations are many times smaller than those required in the cloud chamber, and are insufficient to permit condensation directly on cosmogenic ions (Mason 1971). Plausible indirect physical mechanisms have, however, been outlined recently, through which ions could influence clouds at natural atmospheric water supersaturations (Carslaw *et al.* 2002), such as through growth of cosmogenic ions to form aerosol (Yu & Turco 2001; Eichkorn *et al.* 2002; Wilding & Harrison 2005) and by electric charge effects on aerosol–cloud microphysics (Tinsley *et al.* 2000; Tripathi & Harrison 2002). Vertical motion of ions through cloud-forming regions occurs continuously due to the large potential difference between the ionosphere and the surface. The resulting vertical current density at the surface has been regularly observed in the UK (Harrison & Ingram 2005).

It is not known if these ion transport and ion growth mechanisms explain the cloud–cosmic ray correlation (Marsh & Svensmark 2000), which has also been interpreted as a cloud response to the 1986–1987 El Niño event (Farrar 2000). Analysis of longer time series of cosmic ray ion production and clouds in regions less influenced by El Niño can circumvent possible ambiguities in interpretation of satellite cloud retrieval, and provide new empirical evidence for a physical link between cosmic rays and clouds.

2. Diffuse solar radiation and neutron data

Cosmic rays have been routinely monitored since 1951, but regular observations of cloud using satellites began considerably later. Surface measurements of solar radiation, simultaneous with the cosmic ray data, offer an alternative to the satellite retrievals of cloud, as the diffuse component of the solar radiation at the surface, which arises from scattering of the solar beam by cloud (and aerosol), provides a measure of the cloud present. In the UK, hourly solar radiation data extend back to 1947 (Stagg 1950).

The fraction of diffuse radiation in the total radiation received at the surface varies from near zero, under aerosol-free cloudless conditions, to a maximum of one when the sky is fully overcast (e.g. Duchon & O'Malley 1999; Long & Ackerman 2000). The diffuse fraction (DF) is readily calculated from surface meteorological measurements of diffuse and total solar radiation. Such measurements can be obtained using a pair of thermopile pyranometer sensors, each of which has an electrical output proportional to the radiation received. One pyranometer is exposed to the full sky hemisphere for the total radiation and the other instrument is operated under a shade band. This obstructs the direct beam allowing only diffuse radiation to reach the sensor, although a correction is needed for the diffuse radiation intercepted by the shade band itself (Steven & Unsworth 1980). Such an instrument combination has been in operation at Reading since 1997 (Aplin & Harrison 2003). Figure 1 shows the DF measurements made at 09.00 UT daily at Whiteknights, Reading (51.442° N, 0.938° W) from 1997–2004, plotted against the traditional subjective determination of cloud amount made simultaneously by a human observer. Above a minimum value in clear skies due to aerosol, the DF is proportional to the cloud amount, reaching its maximum value when the sky is fully overcast or obscured by fog.

The daily mean DF from other UK solar radiation-recording meteorological sites is used here as a measure of cloud, and compared with a globally representative

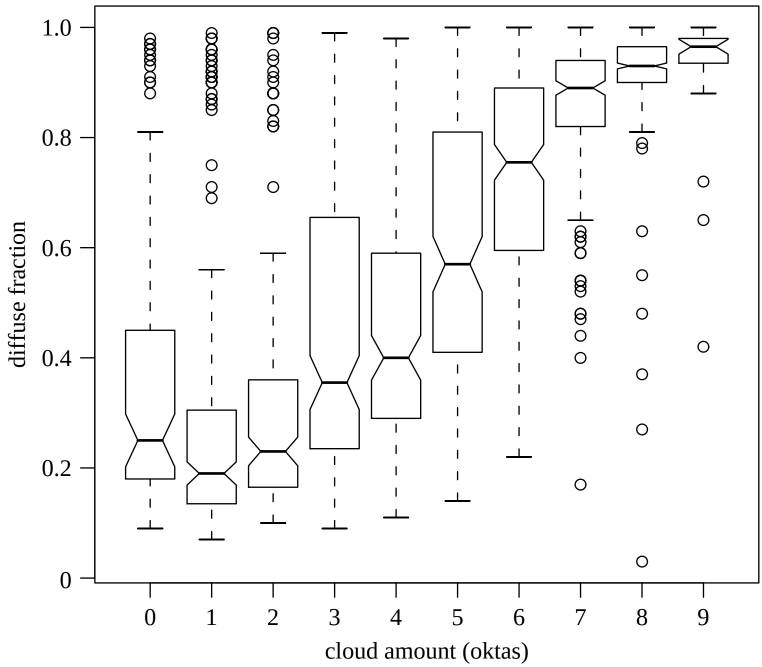

Figure 1. Diffuse fraction plotted against manually observed cloud amount in oktas (1 okta = one-eighth of the sky covered; 9 oktas represents obscuration of the sky due to fog) obtained at Reading at 0900UT, between 1 January 1997 and 31 December 2004, using a notched box plot. Notches indicate the 95% confidence limits on the medians: outliers are also shown. Each original DF value was calculated using 5 min averages of the diffuse and total irradiance from Kipp and Zonen CM5 pyradiometers, sampled automatically between 0855 and 0900UT at 1 Hz. The shade band diffuse irradiance was corrected using the isotropic sky assumption (e.g. Steven & Unsworth 1980).

measure of atmospheric cosmic ray ion production, the daily average neutron count rate (Simpson 2000). Neutrons are formed by cosmic rays, and the atmospheric cosmic ray ion production rate is closely related to the neutron count rate (Aplin *et al.* 2005). The neutron count rate (X) has been measured by the University of Chicago at Climax, Colorado (39.37° N, 253.82° E), since 1951. The principal characteristics of the Climax neutron data time series are strong solar modulations on 11 and 22 year cycles due to screening of the GCRs in the heliosphere, and occasional occurrences of sudden transient reductions (Forbush decreases), often around solar maximum due to transient ejections from the solar corona and/or co-rotating structures in the heliosphere. Solar modulation of the neutron count rate is asymmetric: for daily averages between 1958 and 2000, the median value is $4000\times10^2\ \mathrm{h}^{-1}$, and the skewness is 0.7.

3. Analysis of neutron and diffuse fraction data

(*a*) *Comparison between neutron data and the diffuse fraction at Jersey*

Clean air is one of the requirements for nucleation of new aerosol particles to occur, and Carslaw *et al.* (2002) suggested that marine air might provide a suitable environment for the formation of new particles from cosmogenic ions.

A UK Met Office site approximately representative of similar conditions, and where solar radiation measurements have also been made, is at Jersey. The solar radiation data from Jersey is available as hourly values between 1968 and 1994, from which daily mean values of DF have been calculated for estimating cloud changes.

A first comparison was the linear correlation between the Climax data daily averages and the daily mean Jersey DF. This gave $r=0.042$ (9086 points). Although this illustrates a highly significant ($p<0.001$) relationship between cosmic rays and clouds at Jersey, only a negligible ($<0.2\%$) part of the variance is explained. To investigate the nonlinearity of the relationship further, a more robust statistical approach is required, in which the daily mean DF values are compared with the daily mean neutron count rates.

Figure 2 shows the daily mean DF at Jersey plotted versus the Climax data for all days from 1968–1994. Figure 2*a* illustrates that the distributions of X and DF are both strongly negatively skewed and are far from being Gaussian. A robust local polynomial LOWESS fit (Cleveland 1981) is applied between the DF and Climax data (solid line in figure 2*a*), and emphasizes the nonlinear relationship present. It shows a piece-wise linear dependence of DF on X below a threshold $T=3600\times10^2\ \mathrm{h}^{-1}$, with little dependence for $X>T$. Although there is a large amount of variation in cloudiness for any particular value of cosmic ray count, there is a small yet statistically significant (at the 5% level), effect of cosmic ray counts on cloudiness. This can be seen in figure 2*b*, in the differences from the mean in the central (median) values of the notched boxplots. The notches indicate the 95% confidence limits on the medians and the width of the boxes is proportional to the square root of the number of values in each interval.

Two approaches are taken to investigate the robustness of the nonlinear relationship between the diffuse radiation fraction and the Climax data: (i) a comparison of the mean DF above and below a neutron count rate threshold, and (ii) a comparison of the change in likelihood of an overcast day above and below the threshold. For (i), a two sample Mann–Whitney test is used (Hollander & Wolfe 1973), which is well suited to an asymmetric distribution. For (ii), an odds ratio test is used to reject the null hypothesis that cosmic rays do not influence the odds of an overcast day occurring. Following the observational evidence from Reading (figure 1), an ‘overcast’ day is defined as a day with a daily mean $\mathrm{DF}>0.9$: because of the asymmetry in DF, a large fraction of days at Jersey (more than one-third) have $\mathrm{DF}>0.9$. The odds of an overcast day are defined as the probability of a day having $\mathrm{DF}>0.9$, divided by one minus this probability.

Using (i) and separating the Jersey DF data at $T=3600\times10^2\ \mathrm{h}^{-1}$, the mean DF for days with neutron count rate above and below T are 0.731 and 0.699, respectively. Using the Mann–Whitney test because the DF data is skewed, the difference in the mean DF found is highly statistically significant at the 0.1% level.

For (ii), the odds of an overcast day at Jersey when the Climax neutron counts exceed T are 1.22 greater than the odds when neutron count rate are below T (odds of 0.469 and 0.383, respectively). The difference in odds is statistically significant at the 0.1% level, using an odds ratio test based on the asymptotic standard error (Stephenson 2000).

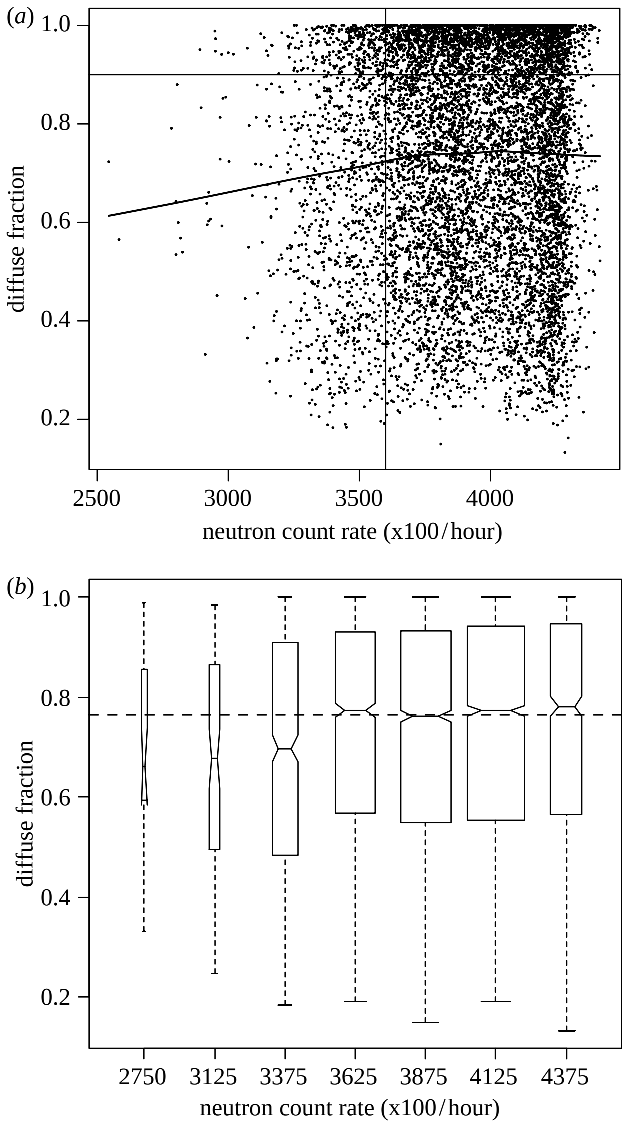

Figure 2. (*a*) Scatter plot of the daily mean diffuse fraction (DF) at Jersey versus Climax daily average neutron count rate (X), from 1968–1994, with a robust local polynomial LOWESS fit added (solid line). The thresholds in X and DF used in the analysis are marked. (*b*) Stacked notched box plot of Jersey DF in neutron count rate intervals. Notches indicate the 95% confidence limits on the medians, and the box width is proportional to the square root of the number of values in each interval.

A higher threshold neutron count rate can be chosen for the data at Jersey, as is evident from figure 2. Using a threshold of $T_{\text{med}}=4000\times10^2$ counts h^{-1} (the median neutron count rate), the mean DF above and below T_{med} are 0.733 and 0.722 respectively, which the Mann–Whitney test shows are significantly different at $p=0.002$. The odds ratio for overcast days above and below T_{med} is 1.15, which the odds ratio test shows is significant at $p=0.001$. Thus the Jersey diffuse radiation data also show a significant effect of cosmic rays if a higher neutron count threshold is used to separate the data.

(*b*) *Extension of the analysis to other UK sites*

Hourly surface solar radiation measurements obtained similarly to those at Jersey are also available for various periods between 1947 and 2000 from other UK Met Office sites: Aldergrove, Aberporth, Beaufort Park, Camborne, Cambridge, Eskdalemuir, Kew, Lerwick and Stornoway. A comparison between DF and the Climax data, similar to that made for the Jersey data, can be made for these other sites. Table 1 gives the changes in mean DF and odds of an overcast day for each of the sites using a neutron threshold $T = 3600\times10^2\ \text{h}^{-1}$. It lists the *p*-values associated with both the Mann–Whitney test for a change in the mean, and the odds ratio test for overcast days. All the stations have a greater DF when $X > T$ than when $X < T$. The results for the DF change are significant at the 5% level at all stations except Eskdalemuir. It is not clear why the behaviour at Eskdalemuir is different, but it may be related to rainfall, as Eskdalemuir has the highest annual rainfall of the sites considered (annual rainfall 1526 mm). This possibility is considered further in §5.

Figure 3*a* shows the mean DF for high Climax neutron count rates ($X > T$) versus the mean DF at low neutron count rates ($X < T$), for all the UK sites with long time series. The differences in the mean DF arise from climatological differences between the sites, however, the points all lie to the left of the 1 : 1 line, around which the points would cluster if the neutron change had no effect. Across the 10 UK sites, the gradient of the fitted line shows that the mean DF is 2% greater (1.02 ± 0.003) when $X > T$, than when $X < T$. Figure 3*b* shows the odds of an overcast day (DF > 0.9) at each site, plotted as figure 3*a* for high and low neutron count rates. Again all the points lie to the left of the 1 : 1 line, showing that the odds of an overcast day are greater at all stations when $X > T$ than when $X < T$. Taken across all the UK sites, the fitted line shows that the odds of an overcast day are 1.19 ± 0.04 greater when $X > T$ than when $X < T$.

Counting across the whole numbers of 22 year (Hale) cycles 1958–2000 in the Climax data, $X < T$ occurs about 13% of the time, which is an equivalent of 48 days annually with $X < T$. Because of the inverse solar modulation, the $X < T$ days frequently occur consecutively around solar maximum e.g. 30 September 1989 to 19 October 1990 (385 days), 30 April 1991 to 12 October 1991 (166 days) and 11 July 2000 to 18 August 2000 (39 days).

4. Transient changes in cosmic rays and diffuse fraction

The statistically significant increase in both DF and the odds of an overcast day indicate a positive effect of neutron counts on the cloud (or aerosol) amount present in the atmospheric column above the measurement. However, as the neutron flux is modulated by solar changes, it is possible that the cloud response could originate from another coincident solar effect on the atmosphere, such as the modification in atmospheric circulation arising from small changes in the sun's brightness occurring in phase with the solar cycle (Haigh 2003). One method of discriminating between a response to solar brightness and cosmic rays is to investigate the surface DF response to transient changes in the neutron

Table 1. Changes in diffuse fraction (ΔDF) and odds of overcast days, between high ($X > T$) and low ($X < T$) neutron count rates ($T = 3600 \times 10^2\ \mathrm{h}^{-1}$).

site	latitude °N	longitude °E	data start	data finish	data days	ΔDF (%)	p-value	overcast odds ratio	p-value
Aberporth	52.138	−4.570	1957	2000	14544	2.7	<0.001	1.21	<0.001
Aldergrove	54.650	−6.217	1976	2000	7549	1.1	0.08	1.11	0.08
Beaufort Park	51.389	−0.783	1965	2000	12582	2.8	<0.001	1.22	<0.001
Camborne	50.218	−5.326	1981	2000	5783	1.8	0.01	1.20	0.006
Cambridge	52.224	0.101	1957	1971	5327	5.0	<0.001	1.70	<0.001
Eskdalemuir	55.311	−3.205	1965	2000	12630	1.2	0.20	1.09	0.06
Jersey	49.217	−2.200	1968	1994	9086	4.7	<0.001	1.22	0.001
Kew	51.407	−0.313	1947	1980	10448	2.1	0.02	1.16	0.03
Lerwick	60.139	−1.184	1952	2000	16309	1.0	0.006	1.15	0.002
Stornoway	58.214	−6.318	1982	2000	6070	2.9	<0.001	1.28	<0.001

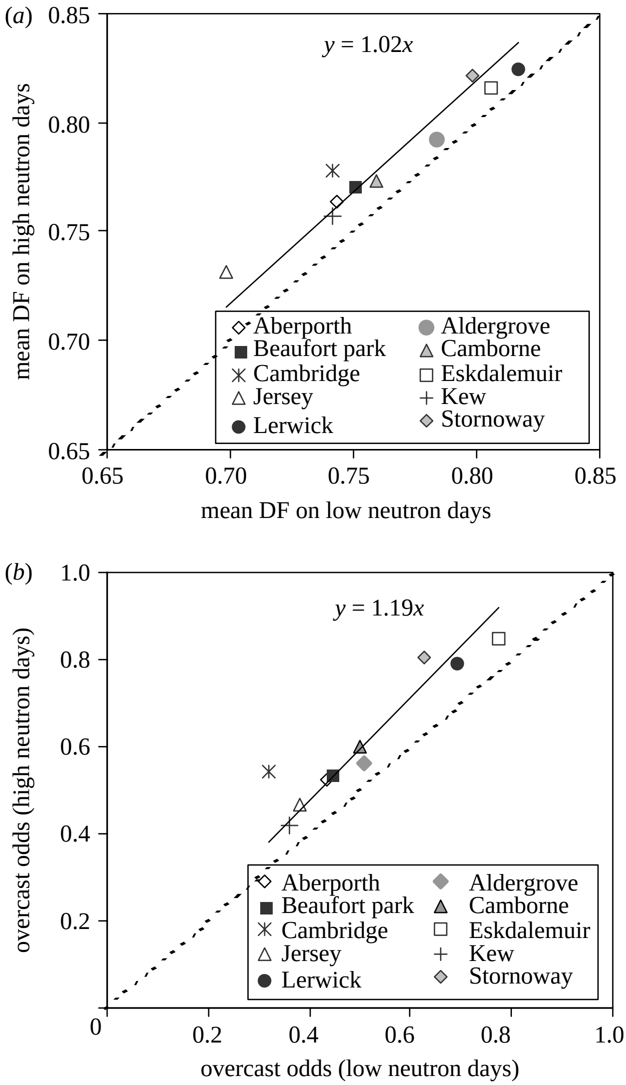

Figure 3. (*a*) Mean diffuse fraction DF for days having high neutron count rates ($X > 3600 \times 10^2\ \mathrm{h}^{-1}$) plotted against DF for days having low neutron count rates ($X < 3600 \times 10^2\ \mathrm{h}^{-1}$), for the UK radiation measurement sites. (*b*) Odds of an overcast day (defined as a day with DF > 0.9) for high neutron rates ($X > 3600 \times 10^2\ \mathrm{h}^{-1}$) plotted against the odds of an overcast day with low neutron rates ($X < 3600 \times 10^2\ \mathrm{h}^{-1}$). (The 1 : 1 line is shown dotted in each case.)

count rate, as such changes are unique to GCRs. Substantial (∼1 to 15%) sudden reductions (Forbush Decreases) occasionally occur, followed by a much slower recovery taking ∼10 days to months (Bazilevskaya 2000). An increase in the daily total surface radiation immediately following Forbush events has previously been reported and attributed to a reduction in cloud (Pudovkin & Veretenenko 1997).

Forbush events produce extreme minima in the Climax data, although large day-to-day changes are rare (6 days 1951–2000 with reductions from the previous day $\geq$10% and 26 with reductions $\geq$5%). The Climax minima can be used to search for associated changes in DF, by averaging the DF values from a composite of all the minima (Coles 2001), a procedure originally established for detection of solar disturbances on geomagnetic activity (Chree 1908). By averaging the DF over several cosmic ray decrease events, noise in the daily DF determinations at a site is reduced, increasingly the likelihood of detecting small changes. Results from this approach are shown in figure 4 for the two sites, Jersey and Cambridge, which show the largest DF sensitivity in table 1. Figure 4*a*,*b* show superposed epoch averages for Jersey, obtained by averaging before and after the 5 days with the biggest neutron reductions during the Jersey measurement series. The 95% confidence lines are given, to indicate when the change is significantly larger than the mean, which is marked as a straight line. In the composite of the neutron count rates around the neutron minima (figure 4*a*), the mean neutron count rate drops sharply and the 95% confidence line falls below the mean. Using the same days (figure 4*b*), the composite of the Jersey DF measurements also briefly drops sharply and significantly below the mean. Figure 4*c* and *d* show similar composites derived for Cambridge. As the Jersey and Cambridge data series have different durations, different calendar days are selected for the largest neutron minima from those used for figure 4*a*,*b*. Consequently the neutron minimum composite in figure 4*c* is different to the more rapid drop in figure 4*a*, with figure 4*c* showing a shallower response. A shallower response is also seen in the composite for Cambridge, and the DF falls significantly below the mean for several days. The transient cloud response at these sites shows that there is a direct effect of cosmic ray changes rather than an indirect effect mediated through solar-cycle related variations in climate.

5. Discussion

This study has found a small yet statistically significant effect of cosmic rays on daily cloudiness regionally that supports the global results from satellite data (Marsh & Svensmark 2000). The method used is independent of the satellite results, and uses data from different surface sites extending over a longer period. Likely physical mechanisms have been previously hypothesized (Carslaw *et al.* 2002; Harrison & Carslaw 2003), firstly ion-induced formation of aerosol and cloud condensation nuclei (Yu & Turco 2001) and, secondly, electrically enhanced freezing of supercooled droplets (Tinsley *et al.* 2000; Tripathi & Harrison 2002).

In a previous detailed case study using data from Kew, increases in DF and Climax neutron data occurred simultaneously with ion growth, which was associated with the first physical mechanism (Harrison 2005). The nonlinear behaviour in figure 2*a* supports this, as, in the low aerosol limit (Harrison & Carslaw 2003), ion number concentration n varies with ion production rate q as $n \propto q^{1/2}$. Assuming linear relationships between (i) X and q (Aplin *et al.* 2005), (ii) aerosol formed and n (Vohra *et al.* 1969) and (iii) DF and aerosol amount (Unsworth & Monteith 1972), DF in the non-overcast case would vary as $X^{1/2}$. A power law fit to the Jersey data (for $X < 3800 \times 10^2\ \mathrm{h}^{-1}$ and DF $<$ 0.9) gave DF $\propto X^{0.5 \pm 0.1}$. The transient DF response shown in figure 4 occurs within the daily timescale resolved: this is consistent with the modelling work of

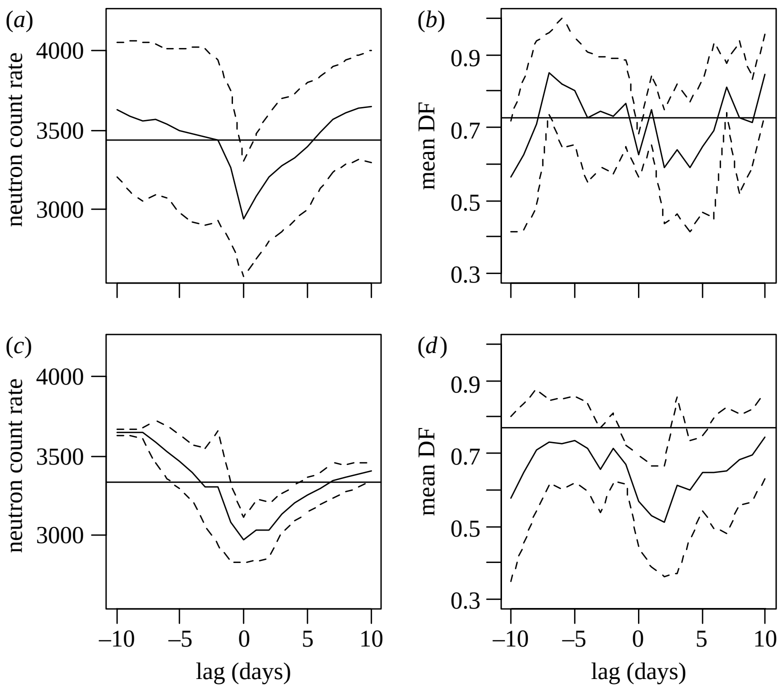

Figure 4. (*a*) Composite of Climax neutron count rate before and after the 5 days having the largest neutron minima during the Jersey measurements (1968–1994), with the mean and 95% confidence limits (2 s.e.) on the mean. (*b*) Composite of Jersey DF for the same days as (*a*) with mean and 95% confidence intervals shown. (*c*) and (*d*) as (*a*) and (*b*), but for the solar radiation data from Cambridge (1957–1971).

Yu & Turco (2001), who showed that the growth of ions to particles sufficiently large to act as cloud condensation nuclei had a timescale of about 8 h.

The possibility that rainfall influences particle formation was suggested in §3*b*. Aerosol and trace vapours are scavenged by precipitation and frequent precipitation events will prevent substantial aerosol populations forming (Carslaw *et al.* 2002). Charged aerosols are also preferentially removed over neutral aerosol (Tinsley *et al.* 2000; Tripathi & Harrison 2002). The effect of precipitation processes may be evident in the DF response to cosmic ray changes, as Eskdalemuir, where the effect is small (1.2%), has substantial annual rainfall, but the sites showing the biggest DF sensitivity have much lower rainfall (Cambridge 552 mm yr^{-1} and Jersey 860 mm yr^{-1}).

Changes in DF and the frequency of overcast days represent changes in the weather and the atmospheric energy balance. The decrease in the proportion of direct solar radiation associated with an increase in DF will lead to a local reduction in daytime surface temperature. Further, because the net global effect of cloud is cooling (Hartman 1993), any widespread increase in the overcast days could also reduce temperature. At Reading, the measured sensitivity of daily average temperatures to DF for overcast days is −0.2 K per 0.01 change in DF (for 1997–2004). Consequently the inverse relationship between GCR and solar activity will lead to cooling at solar minimum. This might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al.* 2003), which neglect a cosmic ray effect.

In summary, our data analysis confirms the existence of a small, yet statistically robust, cosmic ray effect on clouds, that will emerge on long time scales with less variability than the considerable variability of daily cloudiness.

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Appendix A. Data sources and processing

Climax neutron data were obtained as daily averages[1]. The solar radiation data were obtained as hourly values through the British Atmospheric Data Centre (BADC)[2], with supplementary material obtained from the Met Office Publication *The Observatories Yearbook*, published annually until 1967. Radiation values were originally recorded using the *M*et *O*ffice *D*ata *L*ogging *E*quipment ('MODLE'), and a shade band correction applied (Painter 1981; HMSO 1982). For each station, the 'MODLERAD' hourly data files were processed to find the hourly DF, when both the total (S_g) and diffuse (S_d) irradiance values were available, if the conditions ($S_g > 0$, $S_d > 0$, $S_d \le S_g$) were all met. The hourly DF values were used to calculate the daily average DF, and the number of hours' data averaged also recorded. Data for each day were only analysed further if the Climax daily averages fulfilled $2000 \times 10^2\ \mathrm{h}^{-1} < X < 6000 \times 10^2\ \mathrm{h}^{-1}$, and the daily DF averages contained 3 h of measurements or more.

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