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Short Communication

Observing Forbush decreases in cloud at Shetland

R. Giles Harrison*, Maarten H.P. Ambaum

Department of Meteorology, University of Reading, P.O. Box 243, Earley Gate, Reading RG6 6BB, UK

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ABSTRACT

Meteorological measurements from Lerwick Observatory, Shetland (60°09′N, 1°08′W), are compared with short-term changes in Climax neutron counter cosmic ray measurements. For transient neutron count reductions of 10–12%, broken cloud becomes at least 10% more frequent on the neutron minimum day, above expectations from sampling. This suggests a rapid timescale (~1 day) cloud response to cosmic ray changes. However, larger or smaller neutron count reductions do not coincide with cloud responses exceeding sampling effects. Larger events are too rare to provide a robust signal above the sampling noise. Smaller events are too weak to be observed above the natural variability.

1. Introduction

In assessing a possible physical effect of cosmic ray ionisation on clouds, a difficulty arises in separating radiative solar changes from cosmic ray changes, which are closely correlated. Radiative changes, particularly at ultraviolet wavelengths, may induce atmospheric circulation changes, ultimately influencing clouds (Gray et al., 2010), whilst cosmic rays may affect clouds directly through microphysical effects of ion formation or droplet charging (Harrison and Carslaw, 2003). Methods used previously to distinguish these effects include variation with latitude of cosmic ray ionisation (Sloan and Wolfendale, 2008), partial correlation analysis (Voiculescu et al., 2006) and characteristics of the cosmic ray power spectrum (Harrison, 2008).

A widely adopted approach to discriminate between the photon and particle effects utilises the sudden reductions unique to cosmic rays known as Forbush decreases (Bazilevskaya, 2000). Pudovkin and Veretenenko (1995) and Veretenenko and Pudovkin (1997) used Forbush decreases to attribute a change in winter surface solar radiation from stations between 60°N and 68°N to the cosmic ray enhancement of high cloud. Cloud reductions observed by satellites were also found at high latitudes using the Forbush approach by Kniveton (2004). Svensmark et al. (2009) reported global aerosol particle and cloud changes some days after large Forbush decreases, but this is contentious (Laken et al., 2009), and the global study of Calogovic et al. (2010) did not indicate a global cloud effect. Kristjánsson et al. (2008) found no effect in most regions globally, except for a marginal effect in a limited region.

A major difficulty that arises in the Forbush technique is the paucity of large Forbush decrease events that occurred during the satellite era of cloud measurements. For example, Kristjánsson et al. (2008) used 6 large (>10%) Forbush decreases, Svensmark et al. (2009) used primarily 5 events, and Calogovic et al. (2010) 6 events, but using different selection criteria. With such a small number of events to average, the effect of one large event or the selection method adopted can dominate the effects found, as emphasised by Laken et al. (2009). Event numbers can be increased if non-satellite cloud measurement methods are used, although this generally restricts studies to specific sites where alternative cloud data sources are available. For example, using surface solar radiation measurements to infer cloud changes (Harrison et al., 2008), statistical tests on data from UK meteorological sites showed a non-linear relationship between clouds and cosmic rays (Harrison and Stephenson, 2006), and a reduction in overcast days when neutron counter measurements of cosmic rays fell below a threshold value. One site in this study, Lerwick, Shetland (60°09′N, 1°08′W), showed reduced odds of an overcast day for low neutron counts. Subsequently a specific cosmic ray periodicity was observed in the cloudy day data, providing evidence for an ionisation effect on cloud there (Harrison, 2008). Independently, Voiculescu et al. (2006) identified Shetland as within a region where a positive relationship between low clouds and cosmic rays was expected.

In addition to a wide range of meteorological observations, the Lerwick geophysical observatory has a long series of atmospheric electricity measurements (Harrison, 2003; Harrison and Nicoll, 2008), which provides a useful context in which to assess cosmic ray induced changes. Consequently the Lerwick data series are examined further here, in terms of Forbush decreases, which,

* Corresponding author. Tel.: +44 118 3786690; fax: +44 118 3788905.
E-mail address: r.g.harrison@reading.ac.uk (R.G. Harrison).

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as for solar flares (Cobb, 1967), have been observed to modify surface atmospheric electricity parameters (Märcz, 1997).

Of the two physical mechanisms proposed to link cosmic rays with clouds (Carslaw et al., 2002; Carslaw, 2009), the potentially more likely mechanism to operate on cloudy days concerns cloud boundary electrification (Tinsley, 2000) associated with the global atmospheric electrical circuit (Rycroft et al., 2000, 2008). This hypothesis suggests that charging of horizontal cloud boundary droplets from the global circuit's vertical current density influences a droplet's microphysical properties, such as through changes in collection efficiency (Tinsley et al., 2000; Harrison, 2000; Tripathi and Harrison, 2002) or activation (Harrison and Ambaum, 2008, 2009). There is direct experimental evidence for horizontal cloud boundary charging (Nicoll and Harrison, 2009, 2010), and the global circuit current density is known to vary with solar activity (Markson and Muir, 1980). This solar modulation has been observed in Lerwick atmospheric electricity data in terms of cosmic ray changes observed in neutron counter data from Climax, Chicago (Harrison and Usoskin, 2010). Current density changes at Lerwick were proportionately larger than in the associated Climax neutron data changes. The above mechanisms operate on short timescales (<1 day). Changes to total solar irradiance during disturbed solar activity occur on much longer timescales (Woods et al., 2004) and any related atmospheric response is also expected to occur on longer timescales (Baldwin and Dunkerton, 2005). Any solar irradiance induced effects are therefore expected on timescales beyond those considered here.

Forbush decreases occurring during the long series of indirect cloud measurements from Lerwick are investigated further here, which yield larger specific events than just those associated with the satellite era, notably those from the late 1950s. Attention is given to the effect of sampling variability in the cloud measurements, and the removal of seasonal effects from the data to allow the maximum number of events from different seasons to be compared.

2. Methodology

2.1. Identification of cosmic ray decreases

Using daily averages of neutron data, day-to-day neutron changes were found using centred differencing. For a neutron count value N_i on day i, the % neutron change on the same day P_i is given by

$$P_i = 100\frac{N_{i+1} - N_{i-1}}{N_i}. \qquad (1)$$

This generates P_i values of both signs from stochastic fluctuations, but the distribution of P_i is asymmetric, with a long negative tail. The negative tail arises largely from Forbush decreases.

Fig. 1a shows time series of normalised daily neutron counter data centred on neutron counter decreases, for many decreases. (Multiple step decreases separated by less than 10 days have also been excluded.) The median of the superposed changes is given, which shows a more rapid onset than recovery, suggestive of a typical Forbush decrease in cosmic rays. Because of the centred decrease used to align the events, the minimum neutron count occurs on "day +1", following the maximum decrease day ("day 0"). Fig. 1b shows the cumulative distribution of neutron count decreases from the Climax neutron data series found using Eq. (1). The fall-off with larger decreases shows a steep power law behaviour ($\sim P^{-2.8}$), and demonstrates that few large decreases have occurred between 1952 and 2006. Quantitatively, using the power law fit, there are about 25 decreases 10% or greater, 7 events $\geq 15\%$ and 3 events $\geq 20\%$.

2.2. Meteorological data

The neutron counter decrease days are used to select days in the Lerwick meteorological records for further examination, to identify possible associated changes. As well as surface temperature, two quantities directly modulated by clouds are available over the long period of data, the diffuse fraction DF (i.e. the ratio of the diffuse to total surface solar radiation measured using thermopile solarimeters), and the duration of bright sunshine from a Campbell–Stokes recorder. DF, which is proportional to the cloud, is preferable, because of its good sensitivity which results from the ratio of two measurements, one (in the numerator) increasing with the cloud and the other (in the denominator) decreasing with the cloud (Harrison et al., 2008). By comparison, bright sunshine provides a much less quantitative measure, as the Campbell–Stokes burn threshold is poorly defined. However, the sunshine data used later to detect

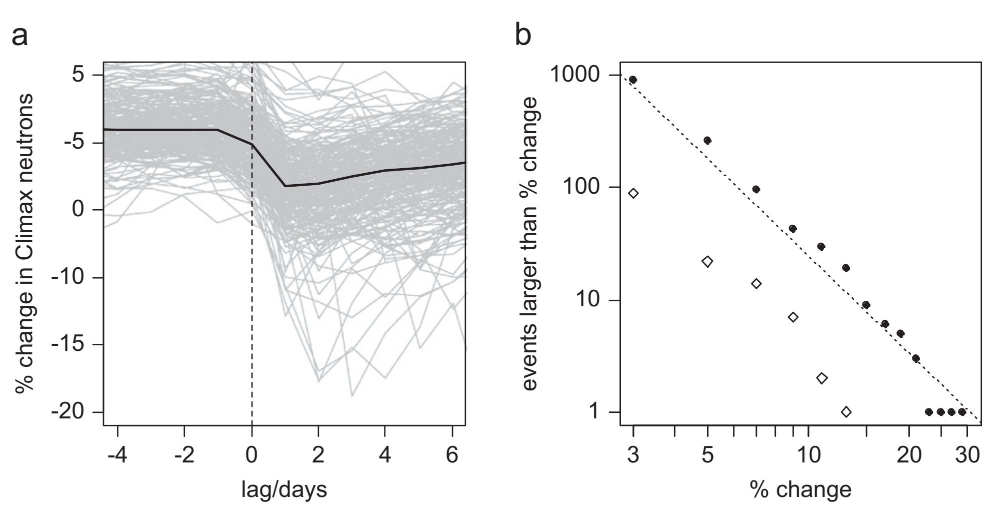

Fig. 1. Calculation of decreases in Climax neutron counts. Neutron decrease associated with a given day is found by subtracting the neutron count value on the day after ("day +1") from its value on the day before ("day −1"), normalised by the neutron count on the central day ("day 0"). (a) Decreases of neutron counts greater than 3% (grey lines), superimposed around each day 0, so that decreases and recoveries coincide. The median value of all episodes is shown (black line). (b) Cumulative distribution of neutron changes, using all Climax neutron data from 1952 to 2006 (positive changes hollow, negative changes solid.) A power law (dashed line) fitted by regression to the negative changes is also shown.

overcast days, to corroborate and extend the findings from the DF data.

Before the comparisons were made, the annual cycle in the meteorological quantities was first removed using a 90 day moving average derived over all the data (1952–1998 for DF, and 1952–2006 for temperature). This is necessary as neutron decreases can occur at any time of the year; any related changes in meteorological quantities can therefore be compared only after seasonal variations that could be larger have been removed.

3. Analysis

3.1. Neutron counter changes

Neutron count levels depend, amongst other factors, on the phase of the solar cycle, with an upper quartile to lower quartile variation at Climax of ~11%. Most Forbush decreases occur around solar maximum, but the absolute neutron count varies at different solar maxima. Consequently, for each threshold of percentage decrease, there will be a distribution of values of actual neutron count values showing the same percentage decrease. This range of values was assessed by plotting all the neutron counts available for each threshold value of neutron decrease P in Fig. 2, again aligned so that all the neutron decrease episodes are aligned around their respective day 0.

Fig. 2a–f summarise the distribution of neutron counts across the range of decreases on either side of day 0, specifically days −10 (Fig. 2a), −5 (Fig. 2b), +1 (Fig. 2c), +2 (Fig. 2d), +5 (Fig. 2e) and +10 (Fig. 2f), running left to right on each row of the figure. Fig. 2c shows the neutron decrease clearly on day 1, both in the general descent from left to right of all the individual values with the size of the decrease, and in the derived median value. To provide a context for the range of median values that could arise from sampling effects, the 95th percentile range obtained from repeated random samplings of the same number of daily values from the entire data series has also been plotted. (The number of daily values was given in Fig. 1b.) This generates a wedge shape, opening widest on the right hand side of the plot, where the number of samples (associated with the rare large changes) is the lowest. For day 1 (Fig. 2c), the median value lies well beneath he 95th percentile "sampling wedge", indicating that the change is much larger than that arising from sampling effects, for all threshold values of neutron decreases.

The absence of effects on the days before the neutron decrease is illustrated in Fig. 2a (day −10) and b (day −5). On both these days, which are unaffected by the neutron decrease, the median values lie within the sampling wedge and there is no overall trend apparent in the individual values. In contrast, the days after the decrease, Fig. 2d (day 2), e (day 5) and f (day 10) all show median values remaining below the sampling wedge. This reflects the slow recovery of neutron values following each decrease, and forms the basis on which effects might be distinguished in the meteorological quantities of interest, such as clouds.

3.2. Meteorological changes

Fig. 2 extends the analysis to the meteorological data from Lerwick, using DF (Fig. 2g–l) and (Fig. 2m–r) maximum daily temperature T_{max}. As explained above, anomalies of DF and T_{max} were required for the analysis, found by obtaining the difference between the mean seasonal value of the quantity on the year day concerned and the actual measured value.

Fig. 2g and h shows the DF anomaly on days −10 and −5 before the neutron decrease. Both median lines lie within the sampling wedge as in the case for days 5 (Fig. 2k) and day 10 (Fig. 2l). For these days before and after the neutron decrease, the median value is not distinguishable from values that could arise from random sampling. On day 1 however, for decreases of about 10%, the median line falls outside the sampling wedge. This shows a DF anomaly reduction, i.e. a reduction in the proportion of diffuse radiation and, by implication, a reduction in cloud.

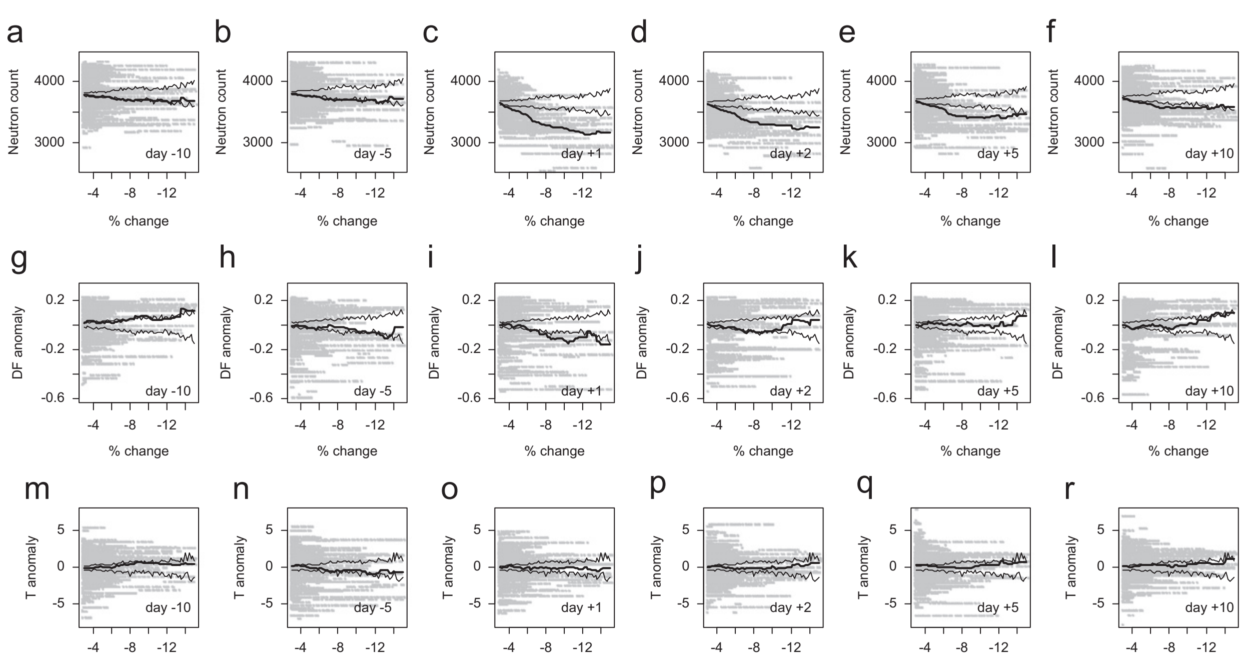

Fig. 2. Variations in daily mean neutron count rate ((a)–(f)), and daily anomalies at Lerwick in ((g)–(l)) diffuse fraction and ((m)–(r)) maximum daily temperature before and after neutron decrease days, as a function of size of neutron decrease on day 0. For each row, from left to right the plots represent days −10, −5, +1, +2, +5 and +10. In each case all available samples (grey points) are plotted at each neutron decrease, with the mean of the samples shown (thick black line). The thin black lines define the range (95th percentiles) of mean values obtained by randomly choosing the same number of days as there are event days at each value of neutron count decrease.

Because the median lies outside the sampling wedge, the change is unlikely to arise from sampling effects. On day 2 the DF anomaly reduction has persisted, based on the similar shape of the median line in Fig. 2d and a possible recovery from Fig. 2i, but this is only suggestive as the median lies on the sampling wedge boundary.

Fig. 2m–r repeats the analysis of the DF anomaly for the T_{max} anomaly, but on all days before and after the decrease, nothing beyond random sampling can be identified in temperature.

3.3. Broken cloud measurements

The observed change in DF can be considered equivalently in terms of a change in the proportion of overcast days or days with broken clouds. Overcast conditions can be inferred independently from the surface measurements of DF or hours of bright sunshine. The Lerwick DF data series extends to 1998; hence an alternative measurement is needed if the solar events of 2003 are to be included. Although the Lerwick sunshine measurements still continue (1926 to present), they are not straightforward to interpret quantitatively. Sunshine data are, however, sufficient to identify days with or without sunshine and therefore to establish whether or not overcast or broken cloud conditions occurred. The Appendix shows that choosing threshold values of DF=0.85 and sunshine duration of 2 h leads to a broadly consistent definition of “overcast” conditions (DF $\geq$ 0.85, sunshine $<$ 2 h) and “broken cloud” (DF $<$ 0.85, sunshine $\geq$ 2 h) from the different data sets.

Using these criteria for matching the DF and sunshine data, Fig. 3 shows the number of broken cloud days as a proportion of the total number of days having a given magnitude neutron counter decrease, evaluated before and after the neutron counter decrease. For comparison, proportions of broken cloud days were found by randomly choosing the same number of days as there are neutron counter decrease days. As discussed earlier, large neutron counter decreases are rare; hence there is a wide spread of possible broken cloud proportions for large decreases as there are few days to average, in contrast to small neutron counter decreases, of which many more occur. If the neutron decrease days show atmospheric changes no larger than those found using a random selection of days, there is no positive evidence that the effects are caused by the neutron decreases (Ambaum, 2010).

For neutron counter decreases of 10–12%, the proportion of broken clouds on day 1 is greater than that expected using a random selection of days. This effect is apparent in both DF (Fig. 3b) and sunshine data (Fig. 3f). Whilst, for these magnitude neutron decreases the proportion of broken cloud days is much larger than the ~45% mean value found across all days (75% and 82% broken cloud in sunshine and DF data, respectively, for a decrease of 11%), a large amount (~65% in both cases) arises from sampling variations because there are rather fewer than all the available values used in finding the averages. Nevertheless, broken cloud days become more common at Lerwick on neutron decrease days of 10–12% beyond that expected from sampling effects.

3.4. Meteorological changes associated with large cosmic ray decreases

From the Fig. 3 analysis, neutron decreases of at least 10% seem necessary for an effect to appear in the DF data above that of sampling variability. For the 30 neutron decreases of 10% or more that occur between 1957 and 2005, Fig. 4a shows their variations with time, around day 0. The median value summarises the response, which shows a rapid onset followed by slow recovery. For the same decreases, variation with time of the anomalies in DF (Fig. 4b), daytime minimum temperature T_{min} (Fig. 4c) and daytime maximum temperature T_{max} (Fig. 4d) have also been found. All the available meteorological data (23 values on day 0 for Fig. 4b, 1957–1991, and 30 values on day 0 for Fig. 4c and d, 1957–2005) for the decreases are plotted as points associated with each day, with summary statistics in notched boxplots. In

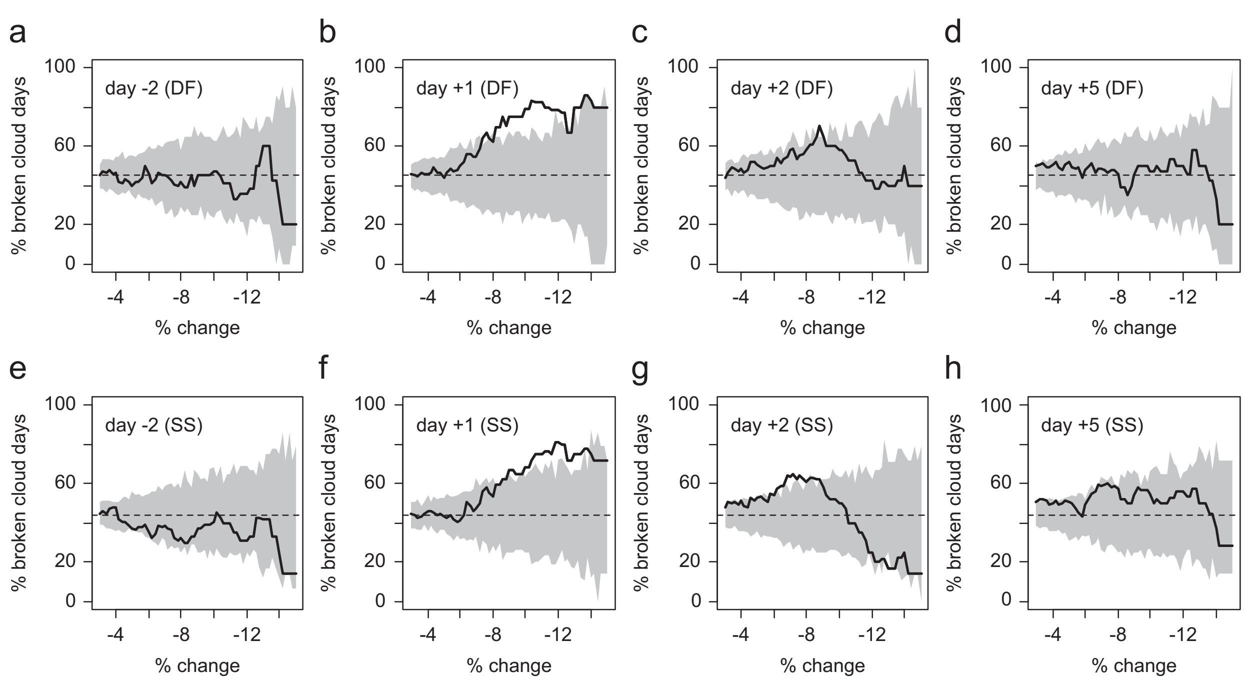

Fig. 3. Proportion of broken cloud days at Lerwick determined from diffuse fraction ((a)–(d)) and sunshine hours ((e)–(h)) measurements, against size of neutron count decreases. This is evaluated around the neutron count decrease day, as 2 days earlier ((a) and (e)), the day after ((b) and (f)), 2 days later ((c) and (g)) and 5 days later ((d) and (h)). Grey shading shows the range (95th percentiles) of broken day proportions found by randomly choosing the same number of days as there are event days at each value of neutron count decrease.

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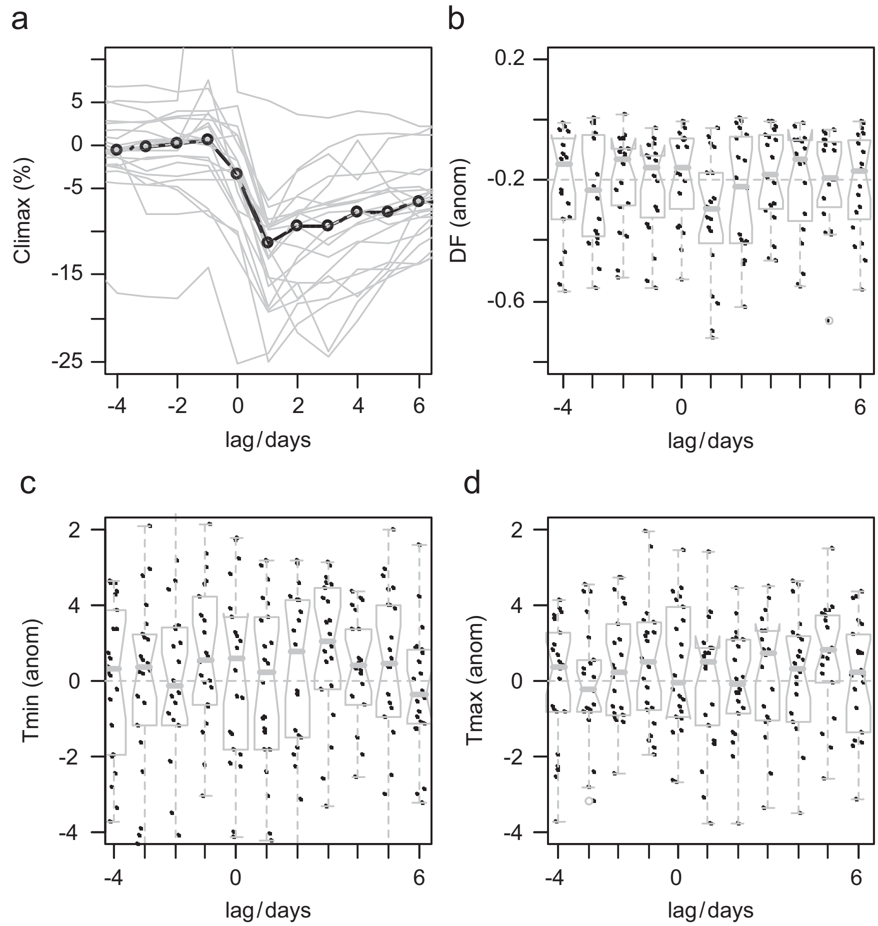

Fig. 4. Changes in Lerwick meteorological data around Climax neutron counter decreases 10% or greater. (a) Neutron counter changes of 10% or greater (grey lines), with median change (black line). Anomalies in (b) diffuse fraction DF, (c) daily minimum temperature T_{min} and (d) daily maximum temperature T_{max} on the same days as for (a), plotted as points on each day. The points have been offset slightly by a small (random) horizontal displacement for clarity. Outline boxplots (grey lines) summarise the distribution properties for each day's data, showing median (thick line), 95% confidence limits (notches), inter-quartile range (box edges) and outlier estimates (whiskers).

Fig. 4b a median DF anomaly reduction of 0.1 is clearly apparent on day 1, which, as the notches on the boxplot show, is greater than that expected from variability at the 95% confidence level. For subsequent days no such change is evident. This may be because, rather than being proportional to the stimulus itself, it is possible that the response observed is actually to the change (i.e. a differential response). However, to the best of our knowledge, no theories have been proposed to justify such a differential response. Alternatively, the noise in the system may be swamping evidence of a proportional recovery.

In the T_{min} anomaly, no change is apparent on day 1 or the other days (Fig. 4c), but in T_{max} (Fig. 4d), there is a median temperature anomaly of 0.5 °C, although the estimated 95% confidence interval on this median is of the same magnitude. Both T_{max} and DF are daytime measurements, and the evident daytime increase in temperature would not be inconsistent with a break in cloud cover. Following a reviewer's suggestion, the calculations of Fig. 4 were repeated for the 7 largest events of 15% or more. While this does produce a noticeable change in DF just by eye, the accompanying increased scatter illustrates the need to include more events, such as those yielded by the 10% threshold adopted.

4. Conclusions

Whilst the use of Forbush decreases to separate the natural variability in clouds from changes potentially induced by cosmic rays is appealing and useful in principle, in practice it is limited by the rarity of large Forbush decreases and therefore there is a need for a long cloud data series. The use of surface solar radiation measurements as a cloud proxy does allow more events to be considered, and there is consistency between this work and that of Veretenenko and Pudovkin (1997) in finding reduced cloudiness shortly after Forbush events. Whilst the responses found exceed those attributed to sampling effects, to avoid confusion between overcoming the sampling uncertainty with the likelihood of a specific cosmic ray effect, the conventional description "significant" has not been applied (Ambaum, 2010).

On the assumption of a cosmic ray ionisation effect on clouds, the detection of a cloud change could be seen as a signal to noise problem. A measure of the day-to-day variability in cloud ("noise"), which needs to be overcome by a Forbush decrease effect ("signal"), is the spread of values in the Lerwick DF. Since the DF distribution is non-normal, the inter-quartile range (IQR) is used to measure its spread, scaled to be equivalent to one standard deviation as IQR/1.349. This spread is 0.18, or ~20% when normalised by the median DF (0.875). Neglecting the linkage efficiency between Forbush decreases and cloud changes, Fig. 1b shows that there were only 3 neutron decreases $\geq$20% between 1952 and 2006. For the DF anomaly change observed in the 23 events of 10% or greater in Fig. 4b, the mean neutron decrease was 13.2%. The associated DF variability would be reduced through averaging by $\sqrt{23}$, i.e. to ~4%, and therefore if detection is assumed to have occurred the signal to noise ratio achieved (13.2%/4%) is 3.1. For comparison, if just the three large

(> 20%) events were used (mean neutron decrease 23.4%) the DF variability would only be reduced by $\sqrt{3}$, giving a signal to noise ratio of 2. Alternatively, using the 137 events with changes from 3% to 5% (mean neutron decrease 3.7%), the signal to noise ratio is 2.1.

This provides a basis with which to understand the appearance of an effect in the middle range of neutron decreases as evident in Figs. 2i, 3b and f. Smaller signal to noise ratios therefore result either from the actual decreases themselves being small, or for the larger decreases, from insufficient reduction of cloud variability through averaging of only a few events. The signal to noise ratio is, in practice, a consequence of the competition between rapid fall-off in abundance of large events and the number of events needed to reduce cloud variability by averaging. The need to use averaging and/or event selection to detect cloud changes resulting from Forbush decreases underlines that the effect is small compared with natural variability. Whilst there may be circumstances in which the atmospheric cloud variability is reduced and therefore when smaller changes may be detectable, in general obtaining a signal to noise ratio >1 will require averaging, either temporally or spatially.

Acknowledgements

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Appendix. Matching of sunshine and diffuse fraction measurements

DF and sunshine measurements are independently obtained at the Lerwick site. However they are sufficiently different in their operation – one arising from a threshold measurement and the other a continuous variable – that an exact correspondence is not expected. As they both respond to solar radiation, some matching is possible. Fig. A1 shows daily sunshine hours and DF measurements from Lerwick, plotted against each other. Choosing threshold values of DF = 0.85 and 2 sunshine hours divides the two sets of data approximately similarly, to give 54.9% of DF values (DF ≥ 0.85) against 45.1% (DF < 0.85) and 55.1% of sunshine values (sunshine < 2 h) against 44.9% (sunshine ≥ 2 h). These threshold values provide criteria to select days with "overcast" (DF ≥ 0.85, sunshine < 2 h) and "broken cloud" (DF < 0.85, sunshine ≥ 2 h) conditions from the different data sets.

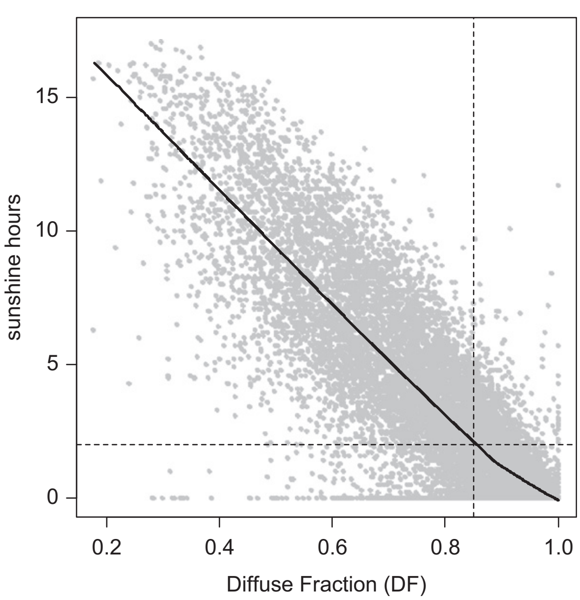

Fig. A1. Relationship between daily averaged diffuse fraction (DF) and daily total of bright sunshine hours at Lerwick. A locally weighted (lowess) fit was added (thick line), illustrating that 2 h of bright sunshine corresponds approximately to daily DF = 0.85, which are used as common threshold values for "broken cloud".

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