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Cosmic ray effects on cloud cover and their relevance to climate change

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ABSTRACT

A survey is made of the evidence for and against the hypothesis that cosmic rays influence cloud cover. The analysis is made principally for the troposphere.

It is concluded that for the troposphere there is only a very small overall value for the fraction of cloud attributable to cosmic rays (CR); if there is linearity between CR change and cloud change, the value is probably $\sim 1\%$ for clouds below ~ 6.5 km, but less overall. The apparently higher value for low cloud is an artifact.

The contribution of CR to 'climate change' is quite negligible.

1. Introduction

It was initially claimed by Svensmark and Friis-Christensen (1997) and Svensmark (2007) that cosmic rays (CR) are a significant source of cloud condensation nuclei and, indeed, therefore a serious contributor to Global Warming. However, later work (e.g. by ourselves, Sloan and Wolfendale, 2008 and in later papers) claimed that the contribution was negligible. It seems likely, nevertheless, that it is finite, i.e. that there *are* mechanisms which lead to CR augmenting cloud cover (CC), albeit to a small degree.

In fact, very recent work by Dragic et al. (2010) shows a remarkably good correlation of 'DTR' (diurnal temperature range) for the average of 210 European meteorological stations with Forbush Decreases, and with CR GLE (Ground Level Enhancements). An effect on cloud cover is implied, although our view is that changes in solar irradiance, rather than CR-induced ionization, may well be responsible. Nevertheless, CR effects must be taken seriously.

The present work attempts to assess the actual magnitude of the fraction of cloud cover due to CR. We consider that the connection of CC and CR is described as

$$CC = CC_0(1-f+fr^s) \tag{1}$$

Here $r=I_{CR}/I_{CR}^0$ where I_{CR} is the variable CR intensity and I_{CR}^0 is the CR intensity under unperturbed space weather conditions. The parameters CC_0 and f are the total CC and its fraction caused by CR in these unperturbed conditions, i.e. for $r=1$. The parameter s determines the sensitivity of CC to CR variations.

Differentiation of expression (1) gives

$$d(CC) = CC_0 fsr^{s-1}\,dr \tag{2}$$

and

$$\frac{d(CC)}{CC} = \frac{fsr^{s-1}\,dr}{1-f+fr^s} = \frac{fsr^s}{1-f+fr^s} \times \frac{dr}{r} \tag{3}$$

If we denote the ratio $(d(CC)/CC)/(dr/r)$ as b then solving the equation

$$b = \frac{fsr^s}{1-f+fr^s} \tag{4}$$

we obtain

$$f = \frac{b}{sr^s + b(1-r^s)} \tag{5}$$

Since deviations of r from 1 rarely exceed 25% and as a rule $b \ll 1$ then for most cases one can roughly estimate the fraction f as

$$f \approx \frac{b}{s} \tag{6}$$

Usually, we can find from various observations just the value of b which we associate with the fraction f, assuming a linear dependence of CC on CR, i.e. $s=1$. The possible values of s will be discussed later in Section 4.

In all our work we are mindful of the fact that different types of cloud might be expected to have different sensitivities to the same CR changes. This aspect was discussed by us (Erlykin et al., 2009b) in

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connection with differences between stratiform and cumuliform clouds. In the present work we usually disregard the differences and deal only with aggregate values.

We are also mindful of the fact that we have used the ISCCP cloud data (Ref. 'ISCCP,'), about which there have been criticisms (e.g. Laut, 2003). In a recent publication (Erlykin et al., 2009c) we examined the problem in detail—the difficulty being mainly a droop in the LCC starting in about 1994. Our conclusion was that the droop was very probably real, and associated with Global Warming. We can see no way in which possible ISCCP errors can affect the results given here in any serious manner; nevertheless, those values in Fig. 2 which relied on the data are distinguished.

A more serious problem, rarely recognised, is the extent to which satellite-measured cloud cover represents the cloud content. Extra cloud droplets caused by CR or by solar irradiance (SI) changes might be expected to be mainly within existing cloud complexes and thus not affect the measured cloud cover but cause climatic change. It is possible that the work of Dragic et al. (2010) referred to earlier is indicative of such a process, at least for limited regions of the Earth's surface (Europe in this case).

An interesting result for a limited spatial region, and one for which ISCCP data were not used, is that Pudovkin et al. (1997). These workers analysed a variety of climatic parameters: pressure, temperature and wind, for Finland, at times of Forbush decreases. A significant effect was found, although whether or not CR or SI was responsible is an open question.

In what follows we continue to deal with CC, as measured, but remain mindful of its limitations.

2. Cosmic ray, cloud cover effects in the troposphere

2.1. The 11-year-cycle

From an examination of the magnitude of the CR, Low Cloud Cover (LCC) correlation as a function of vertical cut-off rigidity over the Globe, we (Sloan and Wolfendale, 2008) concluded that less than 23% (at the 2 standard deviation level) of the dip in LCC in Solar Cycle 22 was due to the solar modulation of the CR intensity. The result came from an examination of the manner in which the dip varied as a function of position on the Earth's surface. It is necessary to define the various 'cloud covers'. LCC denotes 'Low Cloud Cover' and relates to clouds below 3.2 km, MCC is 'Medium Cloud Cover' and is for clouds (the tops of the clouds) between 3.2 and 6.5 km. HCC is 'High Cloud Cover' and is for clouds above 6.5 km. The values come from the International Satellite Cloud Climatology Project (ISCCP).

The value of b relevant to these data will now be considered. Taking our (Sloan and Wolfendale, 2008) values, for Cycle 22 the peak to peak change of LCC was 1.3 % and the effective CR change was 7%. Thus, b follows as 0.18. A later analysis of CR-LCC long-term correlation for Cycle 22 gave the value $b=0.16\pm0.02$ with the correlation coefficient $c=0.54\pm0.05$ (Erlykin et al., 2009a).

In fact, when the next cycle (No. 23) is included, there is a slightly higher value of $b=0.22\pm0.03$ but with decreased correlation, $c=0.39\pm0.05$.

Even more important is the claim by us (Erlykin et al., 2009a) that the reason for the LCC, CR correlation is not causal but is that a correlated temperature variation (due to the correlated 11-year cycle change in solar irradiance) causes the mean cloud height to change and that some what should be LCC appears in the MCC or vice versa. Thus, LCC+MCC should be considered as the relevant cloud cover. Fig. 1 shows the situation for both LCC+MCC and LCC+MCC+HCC over the period for which satellite measurements have been made. Also shown is the CR intensity over the same period. It is evident that the correlations are extremely poor. A statistical analysis yields the results also shown in Fig. 1. Both correlation coefficients are consistent with zero within 2 standard deviations. The best-fit b values are negative but there is a positive one standard deviation (σ) limit, as shown, for LCC+MCC. For the summed cloud cover ($\Sigma CC \equiv LCC+MCC+HCC$) the 1σ upper limit is still negative but the 2σ limit is positive. It is evident that the response of the whole cloud cover to CR changes is somewhat negative, with only a small probability of being positive. This fact has been known for some time.

2.2. Forbush decreases

The well-known Forbush Decreases in CR intensity (denoted 'FD' and typically 3% for 2 or 3 days) caused by changes in the solar wind – and attendant CR modulation – following solar 'eruptions', should, if the CC, CR correlation is causal, give rise to CC reductions. Indeed, even if not causal but if both CR and CC changes are due to a third variable (solar irradiance, for example) then a correlation should result. Svensmark et al. (2009) have claimed such a correlation for CR FD and the liquid cloud fraction (LCF), but this has been disputed (by us, Laken et al., 2009 and by Calogovic et al., 2010).

Our own argument involved the demonstration that for the 6 strongest FD considered, the correlations could be by chance and, furthermore, the delays between CR decreases and the liquid cloud fraction decreases (which mirrored that of the LCC) were unphysically long.

It should be added that the apparently realistic FD decrease in the LCF for the mean of the 6 strongest FD came from adding widely disparate LCF patterns.

An interesting point in the 'FD-debate' is that the big FD events, e.g. the 'Special Event' of Laken et al. (2009) and the Bastille Day event of July 2000, are accompanied by strong solar acivity. Indeed, the LCF profile for the former correlates strongly (at the 7 standard deviation level) with the Mgii signal, a proxy indicator of UV. In fact, most FD are accompanied by changes in SI.

Notwithstanding the above, Laken (2010) and Laken and Kniveton (2011) have claimed a CR, CC correlation and, although the strongest argument is for stratospheric effects, to be considered later, there is evidence for the troposphere. The analysis involved identifying the 'time of onset' of the FD in a better fashion than previously. It showed that the peak probability for the signal (strongest in the Antarctic) was at -2 days for the stratosphere (10–180 mb). The signal fell by a factor 2 at days 0 and -4. This result suggested a mechanism other than direct CR ionization, perhaps in terms of solar irradiance, as discussed above, but CR cannot be ruled out in view of uncertainty in the identification as -2 days'.

'Apart from the excess in the stratosphere there is also a small signal in the troposphere—the region under study in this section. Here the results of relevance comprise contours of anomalous cloud changes (although still on 'day minus 2') as a function of latitude and altitude. We have integrated these as a function of height over the troposphere and for latitude bins. Interestingly, there is evidence for a variation of signal with vertical cut-off rigidity (VRCO), just as expected for a CR origin (i.e. higher values for small VRCO). The values of the mean b for three VRCO bands are:

- $6.0\pm2.5\%$ (0–2 GV),
- $7.5\pm2.5\%$ (3–6 GV) and
- $3.0\pm1.5\%$ (10–15 GV).

The overall mean value is $b=(5.5\pm2.0)\%$ for non-weighted averaging.

This value is presented in parenthesis in Fig. 2. Turning to the alternative view – that changes in solar irradiation of some form may

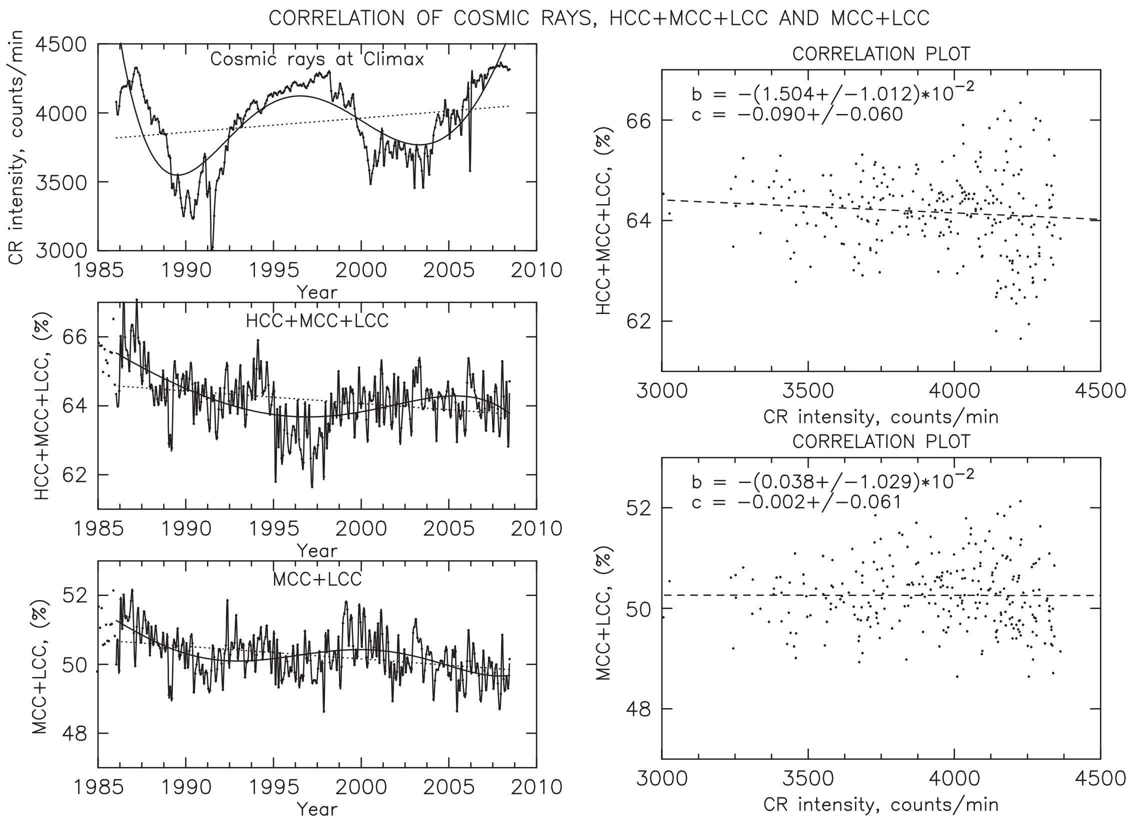

Fig. 1. Correlation of cosmic rays (Climax Neutron Monitor Rate), high cloud (HCC)+middle cloud (MCC)+low cloud (LCC), and MCC+LCC. The cloud data are from the analysis of Erlykin and Wolfendale (2010). Symbols *b* and *c* in the right panels relate to the ratio of relative variations of CC and CR: (*b*) (see text) and to the correlation coefficient between them: *c*.

be related to the FD events – the observed strongest correlation at −2 days favours this hypothesis.

We have made a specific search for correlation between the FD profile and that of solar irradiance, as exemplified by the 10.7 cm radio flux. Integrating each signal over time, within ±10 days of the FD minimum, we find a good correlation which can be consistent with zero only with a 1% probability. The time interval between the peak SI and FD (negative for FD) had a median of −1 day, i.e. the SI peak occured first. The spread in time intervals was such that 2/3 were between −2.5 days and +1.5 days.

Finally, in this section, it can be remarked that the FD result of Dragic et al. (2010) referred to in Section 1. keep the possibility of a small 'FD-effect' alive. Studies of the variation with CR cut-off rigidity are awaited.

2.3. Positive cosmic ray excursions

Laken (2010) has made a similar analysis to that for Forbush Decreases but for positive CR excursions (i.e. Ground Level Enhancements) and, importantly, using the rate of change of CR intensity, and CC as the datum; the CR changes are similar in magnitude to those of FD but of opposite sign. Their origin is similar in the sense that both are caused by changes in the solar wind.

Again, the signals are greatest near the Poles, suggesting a genuine CR origin, a result strongly supported by the signals being coincident in time with the FD. Unfortunately, however, the data are insufficient to be sure about a significant effect within 70°N and 70°S, but the Global average can be estimated. It is $b=(1.0\pm1.0)\%$.

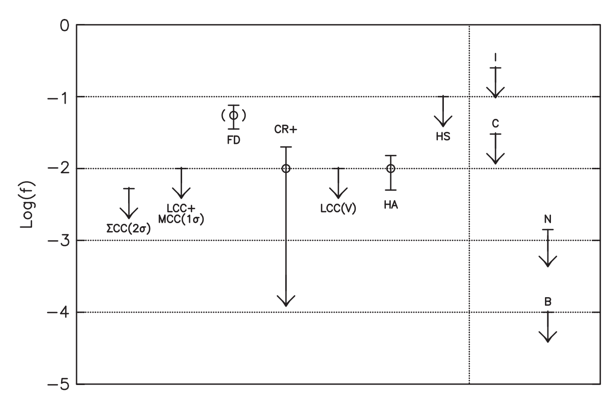

Fig. 2. The cloud fraction *f* attributable to cosmic rays (*f* coincides with the *b* value for the linear connection of CC and CR). Key:

- ∗ΣCC and LCC+MCC, *b* values are two and one standard deviation upper limits derived from Fig. 1, respectively.
- ∗ FD, from Forbush Decrease studies by Laken (2010) averaged over the troposphere (but uncertain—see text).
- ∗ CR+, from positive excursions of CR intensity lasting a day or so, from Laken and Kniveton (2011).
- ∗ LCC(V), from regional variations analysed by Voiculescu et al. (2006).
- HA, from Harrison and Ambaum (2008): changes to the IR flux below clouds.
- HS, from Harrison and Stephenson (2006): correlation of the number of overcast days with CR.

Other radiations:

- ∗ I, India (radon)
- C, Chernobyl (reactor accident)
- B, Nuclear weapon (15 Mt 'BRAVO')
- N, Nuclear bomb tests in 1961 and 1962.

The asterisk denotes use of the ISCCP data.

2.4. Rapid mid-latitude cloud change

A particularly interesting analysis has been made by Laken et al. (2010) involving concentration on particular latitude bands: 30°N–60°N and 30°S–60°S. Periods were chosen in which CC changed rapidly from one day to the next. Significant CR changes and mean surface temperatures were identified for these periods. Typically, peak cloud changes of 3% per day were associated with CR changes of also $\sim 3\%$ per day. This apparently strong CR effect on CC (100%!) is illusory if, as would need to be the case, the correlation is only strong for rapidly changing cloud cover, which occurs for only a small fraction of the time. The equivalent effect is at the 3% level, i.e. a little below the 'FD' point in Fig. 2.

Although CR effects are a possibility, there is the standard problem of the correlated SI changes (however, defined, Mgii, 10.7 cm, total solar irradiance TSI, etc.) being an alternative. This aspect has been examined in some detail by determining the correlation coefficients (c) of the Mgii index, CR and surface temperature, T. The values are as follows:

Mgii with CC, $c = -0.88$,
Mgii with T, $c = +0.78$,
CC with CR, $c = +0.77$.

In all cases the correlations are very significant—even the worst, CC with CR, is at the 0.3% level. A point against the CR hypothesis is that the time profiles of the rate of change of CR and of CC are dissimilar. However, there is also a worry with regard to the solar irradiance explanation, in that the UV (as indicated by Mgii) is absorbed in the stratosphere and does not reach the bulk of the clouds and it is surprising that there is such a good correspondence between the rate of change of CC and that of Mgii.

Our preferred explanation (see also Erlykin and Wolfendale, 2010; Erlykin et al., 2010) is still that solar radiation changes cause surface temperature changes and there, in turn, modify the cloud cover. The CR changes are incidental to solar wind variations associated with the solar radiation changes.

2.5. Regional variations of the CR, CC correlations

In important analyses, Usoskin et al. (2004) and Pallé et al. (2004) pointed out that the correlations varied over the Earth's surface. Voiculescu et al. (2006) made a comprehensive study of the correlations of CC with both CR and solar irradiance as exemplified by UV measurements (denoted UV) as a function of geographical coordinates (in $5^\circ \times 5^\circ$ bins) for all three sets of cloud data: LCC, MCC and HCC. A critical analysis of the results was made by us with the result that the only significant correlations were as follows:

- LCC CR (positive) UV (negative);
- MCC UV (positive); and
- HCC CR (negative).

Taking the UV first, it is quite possible that the alternate positive and negative correlation for MCC and LCC is due to the mechanism referred to in Section 2.1, i.e. the interchange of cloud between MCC and LCC because of surface temperature variations.

For cosmic rays, the LCC CR (positive) is the standard correlation first stressed by Svensmark and Friis-Christensen (1997) and interpreted differently by us. Nevertheless, the LCC CR (positive) map can be analysed and a value of b derived which is partly independent of the value already determined (the degree of independence arises because of the inclusion here of the UV signal).

The number of bins correlated with CR was 203 out of 2592, i.e. leading to $b = 7.8\%$. However, as with the analysis in Sloan and Wolfendale (2008), the distribution over the Earth is not as expected for CR, for reasons of 'VRCO'—vertical cut-off rigidity. Specifically, the correlated signal is high at middle latitudes but low in both the Equatorial and the Polar regions; the ratio is about a factor 8 between mid-latitudes and Equatorial/Polar regions. An upper limit to the genuine b follows as $b < 1\%$.

Consideration can be given to the HCC. Here, remarkably, in the sense that CR ionization variations are a maximum here, the correlation with CR is negative. This feature, contributes to the lack overall correlation of total cloud cover with CR in Fig. 1.

2.6. CC enhancement by CR-induced electrical effects

There is a wealth of literature on the electrical effects associated with CR (eg Rycroft, 2006; Tinsley, 2008—and references therein).

Here, we first examine the work of Harrison and Ambaum (2008) in which evidence was presented for an enhancement of cloud formation by droplet charging, the electric field distribution being perturbed by CR 'bursts' and leading to very highly charged cloud condensation nuclei.

The authors estimate that the enhancement of cloud formation by droplet charging leads to a positive contribution to the Global solar radiation budget of $(0.07 \pm 0.03)\,\mathrm{W\,m^{-2}}$. Thus, out of a total of $350\,\mathrm{W\,m^{-2}}$, the increase is 0.02%. The magnitude of the 'CR bursts' is not well defined, but is presumably of order 10%, for the periods of intense solar activity considered. The conversion from change in solar radiation is 0.1% change in SI gives $\sim 0.5\%$ change in MCC+LCC (from Erlykin and Wolfendale, 2010). Thus, if linearity is assumed, we have $b = (1.0 \pm 0.5)\%$, where the error is representative.

Another result of relevance is that of Harrison and Stephenson (2006). These workers found that overcast days were more common during periods of high CR intensity in comparison with those of low CR intensity. Derivation of b under these circumstances is difficult but an upper limit of $b < 10\%$ was derived.

Both values are given in Fig. 2.

It is appreciated that electric effects will be both cloud-type dependent, and spatially variable. Thus, the results reported here are even more uncertain if regarded as all-cloud, Global averages; however, there is no apparent way of finding more precise values, yet.

2.7. Indirect analysis using other sources of ionization

Cosmic rays are not the only source of ionization in the atmosphere, radon being significant at low altitudes, together with radioactive elements from nuclear power stations and, in the past, nuclear bombs. We have examined all three (Erlykin et al., 2009c) and determined upper limits to the 'efficiency for converting ions to cloud droplets', denoted η (in first order we can equate this to the 'b' used earlier).

A detailed survey of south-west India, where radon levels are particularly high (e.g. Karunakara et al., 2005) gave $\eta < 25\%$. A study of the Chernobyl accident in 1986 using fallout contours and cloud data gave $\eta < 3\%$. The corresponding b values are shown in Fig. 2.

A particularly stringent limit ($\eta < 0.01\%$) came from an analysis of the results of the 1954 BRAVO nuclear test of a 15 Mt bomb and this is indicated in Fig. 2. However, in view of the estimate having been made on the basis of estimated dose rate contours rather than observed rates we have re-examined the problem using the data on yearly bomb rates given by Harrison (2002).

This work showed that the yield from atmospheric nuclear tests was 160 Mt in 1961 and 320 Mt in 1962, with very little before and none since. Harrison found an apparent increase in the number of overcast days (i.e. extra cloud) at a particular location (Lerwick, Shetland). We consider that use of data from a single site is unwise and instead prefer to use data from a bigger region. Cloud cover over the USA (Barry and Chorley, 1988) has been examined and there is the possibility of extra cloud cover, amounting to as much as $\sim 2\%$ for about 5 years starting in 1962; this can be taken in order to estimate an upper limit for b. The phrase 'as much as' is used because there are clearly random trends even for an area the size of the USA. Allowing for loss to the stratosphere leads to an average production rate of ~ 35 ions $cm^{-3}\,s^{-1}$, a value some 15 times the average production rate from CR. The upper limit to b follows as $b < 0.14\%$.

3. The stratosphere

3.1. Forbush decreases and cosmic ray transients

Many observers have identified strong effects in the stratosphere due to cosmic rays. These are largely connected with solar flare particles. Examples include the enhancement of stratospheric aerosols (Shumilov et al., 1996); ozone, wind and temperature responses Krivolutsky et al. (2006), changes in pressure, temperature and wind (Pudovkin et al., 1997) as already mentioned, and general large increases in ionization following strong solar particle events (Usoskin et al., 2009). In all cases, effects are observed only in Polar regions (it will be noted that the tropopause is very low in these regions, at ~ 300 mb).

To the above can be added studies of CR effects on stratospheric cloud cover following Forbush Decreases and transient CR increases by Laken (2010). However, the extent to which stratospheric clouds are affected by CR is problematical because of difficulties with the use of ISCCP data in Polar regions. As Todd and Kniveton (2004) have pointed out, during the polar night no visible data are available and even when they are the temperature inversion means that the surface temperatures are often lower than those of the overlying atmosphere. Our analysis of the data of Laken (2010) yielded finite results for both FD and Ground Level Enhancements are the sub-one per-cent level but it is considered unsafe to use them. Further uncertainties arise from the role of SI variations: the majority of CR changes are, understandably, associated with SI, and other related solar emission changes.

3.2. Volcanism, geomagnetic variability and climate variability

Kuznetsov and Kuznetsova (2006) and Kuznetsova and Kuznetsov (2008) have made an interesting suggestion and, although it relates to the difficult area of changes several hundred years ago, it will be considered here. The suggestion is that during geomagnetic field 'excursions' present in the (long) period after a 'super volcano' the undoubted increase in CR intensity was responsible for a big change in cloud cover, with consequent change in temperature. Certainly, there are correlations between the Earth's surface temperature and ice core dust deposits and these are perturbed by field excursions.

The argument is that the CR rate is considerably enhanced during an excursion not only because of the reduced interplanetary magnetic field but also because of the release of the particles from the Van Allen belts. At 1 GeV the CR intensity is increased by a factor 10^4 and this causes charging of the volcanic dust with consequent coagulation and rain out.

We have examined the correlation of surface temperature with geomagnetic field both during excursions and between excursions. There is indeed a difference that can be attributed to the claimed effect but quantification is difficult because of a variety of uncertainties, most noticeably the length of time for which the radiation-belt enhancement lasts. Our best estimate for b is $10^{-4} < b < 10^{-2}$.

Notwithstanding the great uncertainty at present, the method may hold promise in the future.

4. Sensitivity of ionization change to cloud cover change and the fraction of cloud cover caused by cosmic rays

In the Introduction we connected the CR intensity and CC by the expression (1) which includes the sensitivity parameter s. The value of s determines also the fraction f of CC caused by CR—see expressions (5) and (6). In the conventional causal CR, CC correlation it is the ionization caused by CR which enhances the probability of condensation nucleus production. Although in our earlier work (Erlykin et al., 2009a) we adopted $s = 1/2$, i.e. $n \propto \sqrt{q}$, where n is the CR-initiated cloud density and q is the ionization rate, here we adopt $s = 1$, i.e. $n \propto q$ for several reasons.

(i) Our earlier work (Sloan and Wolfendale, 2008) gave $n \propto q^s$ with $s = 0.77 \pm 0.38$, i.e. consistent with either $s = 0.5$ or 1.
(ii) Experimental measurements of the ionization produced by CR in the stratosphere gives support to $s = 1$ (Bazilevskaya et al., 2008).
(iii) The more important results come from the effect of CR changes on the 'electrical circuit', which would be expected to be linear.

An examination of Fig. 2 shows that the majority of b estimates are just upper limits. Both of the two finite points denoted (CR+) and (HA) give an estimate of $b \approx 1\%$. Using the assumed linear connection between CR and CC we can conclude that the fraction f of CC caused by CR (see expression (6)) does not exceed 1%.

On the other hand we cannot exclude the existence of a positive feedback effects (e.g. an proposed effect of upward convection flows on the reduction of LCC with growing surface temperature) which makes the sensitivity s higher than 1. For example, the best non-linear fit of the LCC-CR plot in Solar Cycle 22 gives formally $s = 8.65 \pm 0.46$ (Erlykin et al., 2009a). If it is true our estimate of the fraction f has to be even lower than 1%.

The majority of the points in Fig. 2 are independent of one another, although many use the same set of cloud data (ISCCP). Such 'errors' in the data are not expected to give problems for all except the LCC, MCC and ΣCC results. Even here, however, we have given reasons why such problems should be slight.

5. Conclusions

Concerning the troposphere, it seems that there is a finite influence of CR on cloud cover at the level of $f \simeq 1\%$, a result that is mainly for clouds below about 6.5 km, although when averaged over the entire atmosphere it is smaller than this. The reason for the difference is presumably that CR effects on clouds at different altitudes are different in sign and there is cancellation when summed. There is, presumably, a dependence of f on cloud type (see Erlykin et al., 2009b), which is also playing a role. The origin of the negative correlation of HCC, CR is not understood; it is clearly opposite to expectation for an ionization mechanism, and one doubts its veracity.

Disregarding the latter fact and taking an average *f* value of 1%, the temperature change consequent upon the changing CC given by the maximum CR change that could be allowed over the last 50 years can be calculated. Over this period the mean CR intensity appears to have fallen by less than 0.6%, using the data of Bazilevskaya et al. (2008), so that if the conversion, ΔCR to ΔCC and thereby to ΔT is known, ΔT can be calculated. Here, we adopt the conversion $\Delta CC = 11.3\%$ corresponds to $\Delta T = 0.5\,^{\circ}C$ from the work of Erlykin and Wolfendale (2010). The increase in temperature predicted is 0.002 °C, a value quite negligible in comparison with the Global Warming in this period (~0.5 °C) and the conclusion is that cosmic rays have a negligible effect on climate.

All the above is not to say that CR have no effect on atmospheric conditions at all, for certain regions, principally at high latitudes and altitudes, there is an effect, however, averaged over the Globe their effect is very small.

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References

Barry, R.G., Chorley, R.J., 1988. Atmosphere, Weather and Climate. Routledge, London and New York.

Bazilevskaya, G.A., Usoskin, I.G., Flueckiger, E.O., Harrison, R.G., Desorgher, L., Butikofer, R., Krainev, M.B., Makhmutov, V.S., Stozhkov Yu, I., Svizzhevskaya, A.K., Svirzhevsky, N.S., Kovaltsov, G.A., 2008. Cosmic ray induced ion production in the atmosphere. Space Sci. Rev. 137, 149.

Calogovic, J., Arnold, F., Beer, J., Desorgher, L., Flueckiger, E.O., 2010. Sudden cosmic ray decreases: no change of global cloud cover. Geophys. Res. Lett. 37, L03802.

Climax Neutron Monitor Data were taken from: 〈ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS/climax.tab〉.

Dragic, A., Anicin, I., Banjanac, R., Udovocic, V., Jokovoc, D., Puzovich, J., 2010. Forbush decreases—clouds relation in the Neutron Monitor Era. In: Proceedings of the European Cosmic Ray Symposium, Turku, submitted to ASTRA (private communication).

Erlykin, A.D., Gyalai, G., Kudela, K., Sloan, T., Wolfendale, A.W., 2009a. On the correlation between cosmic ray intensity and cloud cover. J. Atm. Solar-Terr. Phys. 71, 1794.

Erlykin, A.D., Sloan, T., Wolfendale, A.W., 2009b. The search for cosmic ray effects on clouds. J. Atm. Solar-Terr. Phys. 72, 955.

Erlykin, A.D., Gyalai, G., Kudela, K., Sloan, T., Wolfendale, A.W., 2009c. Some aspects of ionization and the cloud cover, cosmic ray correlation problem. J. Atm. Solar-Terr. Phys. 71, 823.

Erlykin, A.D., Wolfendale, A.W., 2010. Global cloud cover and the Earth's mean surface temperature. Surv. Geophys. 31, 399.

Erlykin, A.D., Sloan, T., Wolfendale, A.W., 2010. Correlations of clouds, cosmic rays and solar radiation over the Earth. J. Atm. Solar-Terr. Phys. 72, 151.

Harrison, R.G., 2002. New directions: radiolitic particle production in the atmosphere. Atm. Environ. 36, 159.

Harrison, R.G., Ambaum, M.H.P., 2008. Enhancement of cloud formation by droplet charging. Proc. R. Soc. A 464, 2561.

Harrison, R.G., Stephenson, D.B., 2006. Empirical evidence for a non-linear effect of galactic cosmic rays on clouds. Proc. R. Soc. A 462, 1221.

ISCCP: the data were obtained from the International Satellite Cloud Climatology Project: 〈http://isccp.giss.nasa.gov〉, maintained by the ISCCP research group at NASA Goddard Institute for Space Studies, New York.

Karunakara, N., Somashekarappa, H.M., Rajashekara, K.M., Siddapa, K., 2005. Indoor and outdoor radon levels and their diurnal variations in the environs of southwest coast of India. Int. Congr. Ser. (Elsevier) 1276, 341.

Krivolutsky, A.A., Klyuchnikova, A.V., Zakharov, G.R., Vyushkova, T., Yu Kuminov, A.A., 2006. Dynamical response of the middle atmosphere to solar event of July 2000: three dimensional model simulations. Adv. Space Res. 37 (8).

Kuznetsov, V.V., Kuznetsova, N.D. 2006. The Earth's palaeoclimate response to cosmic rays exposure during geomagnetic field excursions. In: Proceedings of the Geocosmos-2006, vol. 112.

Kuznetsova, N.D., Kuznetsov, V.V., May 2008. Implications of volcanism and geomagnetic field polarity reversals into the climate variability. In: Proceedings of the Seventh International Conference 'Problems of Geocosmos'. St Petersburg, Russia, pp. 26–30.

Laken, B.A., 2010. Modelling the impact of daily timescale GCR variations on Earth's climate. PhD Thesis, University of Sussex: 〈http://benlaken.com/publications.html〉.

Laken, B.A., Kniveton, D.R., 2011. Forbush decreases and Antarctic cloud anomalies in the upper troposphere. J. Atmos. Solar–Terr. Phys., 73, 371. doi:10.1016/j.jastp.2010.03.008.

Laken, B.A., Kniveton, D.R., Frogley, M.R., 2010. Cosmic rays linked to rapid mid-latitude cloud changes. Atmos. Chem. Phys. Discussions 10, 18235.

Laken, B.A., Wolfendale, A.W., Kniveton, D.R., 2009. Cosmic ray decreases and changes in the liquid water fraction over the oceans. Geophys. Res. Lett. 36, L23803.

Laut, P., 2003. Solar activity and terrestrial climate: an analysis of some purported correlations. J. Atm. Solar-Terr. Phys. 65, 801.

Pallé, E., Butler, C.J., O'Brien, K., 2004. The possible connection between ionization in the atmosphere by cosmic rays and low level clouds. J. Atm. Solar-Terr. Phys. 66, 1779.

Pudovkin, M.I., Veretenenko, S.V., Pellinin, R., Kyro, E., 1997. Meteorological characteristic changes in the high latitudinal atmosphere associated with Forbush decreases of the galactic cosmic rays. Adv. Space Res. 20, 1169.

Rycroft, M.J., 2006. Electrical processes coupling the atmosphere and the ionosphere : an overview. J. Atm. Solar-Terr. Phys. 68, 445.

Shumilov, O.I., Kasatkina, E.A., Henriksen, s., Vashenyuk, E.V., 1996. Enhancement of stratospheric aerosols after solar proton event. Ann. Geophys. 14, 1119.

Sloan, T., Wolfendale, A.W., 2008. Testing the proposed causal link between cosmic rays and cloud cover. Environ. Res. Lett. 3, 024001.

Svensmark, H., 2007. Cosmoclimatology: a new theory emerges. News Rev. Astron. Geophys. 48, 18.

Svensmark, H., Friis-Christensen, E., 1997. Variations of cosmic ray flux and global cloud coverage—a missing link in solar–climate relationships. J. Atm. Solar-Terr. Phys. 59, 1225.

Svensmark, H., Bondo, T., Svensmark, J., 2009. Cosmic ray decreases affect atmospheric aerosols and clouds. Geophys. Res. Lett. 36, L15101.

Tinsley, B.A., 2008. The global atmospheric electric circuit and its effect on cloud microphysics. Rep. Prog. Phys. 71, 066801.

Todd, M.C., Kniveton, D.R., 2004. Short-term variability in satellite-derived cloud cover and galactic cosmic rays: an update. J. Atm. Solar-Terr. Phys. 66, 1205.

Usoskin, I.G., Tylka, A.J., Kovaltsov, A., Dietrich, W.F., 2009. Ionization effect of strong polar particle events: low middle atmosphere. In: Proceedings of the 31st ICRC, Lodz, p. 1.

Usoskin, I.G., Marsh, N., Kovaltsov, G.A., Mursala, K., Gladysheva, O.G., 2004. Latitudinal dependence of low cloud amount on cosmic ray induced ionization. Geophys. Res. Lett. 31, L16109.

Voiculescu, M., Usoskin, I.G., Mursala, K., 2006. Different response of clouds to solar input. Geophys. Res. Lett. 33, L21802.